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Experimental characterization and modeling of thin-layer drying of mango slices

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Abstract

Convective air drying characteristics of mango slices at different drying temperatures (60°C, 70°C and 80°C), at an air velocity of 0.5 m/s and for constant sample thickness (3 mm) were investigated. Results indicated that drying took place in the falling rate period. Drying time decreased considerably with increased drying temperature. Three mathematical models; namely, Newton (Lewis), Henderson and Pabis, and Page were selected to describe and compare the drying characteristics of mango slices. Comparisons were based on the coefficient of determination (R^2), sum square error (SSE), root mean square error (RMSE) and reduced-chi square (χ^2). Among the tested models, the Page model achieved the best fit. Moisture transfer from mango slices was described by applying the Fick's diffusion model. Effective moisture diffusivity (D_{eff}) values increased with increasing drying temperature and were found to range from 4.97 x 10^{-10} m^2/s to 10.83 x 10^{-10} m^2/s. The temperature dependence of the effective diffusivity was described by the Arrhenius-type relationship and the activation energy for the diffusion of the moisture associated with the mango slice was found to be 37.99 kJ/mol.

Introduction

Mango (*Mangifera indica* L.) is one of the tropical and subtropical fruit of great importance for both economical and nutritional point of view. It is considered to be a good source of carbohydrates, vitamin C and very rich source of pro-vitamin A. In spite of its excellence, the perishable nature of this fruit and its short harvest season severely limit its utilization. Drying may be an interesting method in order to prevent fresh fruit deterioration.

Drying is one of the most widely used primary methods of food preservation. The objective drying is the removal of water to the level at which microbial spoilage and deterioration reactions are greatly minimized (Akpinar and Bicer, 2004). It also provides longer shelf-life, smaller space for storage and lighter weight for transportation (Ertekin and Yaldiz, 2004). Sun drying is the most common method used to preserve agricultural products in tropical and subtropical countries. However, being unprotected from rain, wind-borne dirt and dust, infestation by insects, rodents and other animal, products may be seriously degraded to the extent that sometimes become inedible and the resulted loss of food quality in the dried products may have adverse economic effects on domestics and international markets. Therefore, the drying process of agricultural products should be undertaken in closed equipment (solar or industrial dryer) to improve the quality of the final product. The drying process takes place in two stages. The first stage happens at the surface of the drying material at a constant drying rate and is similar to the vaporization of water into the ambient. The second stage drying process takes place with decreasing drying rate (Midilli and Kucuk, 2003). When the drying process is controlled by the internal mass transfer, mainly in the falling rate period, modeling of drying is carried out through diffusion equations based on Fick's second law.

Drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously (Sahin and Dincer, 2005). From engineering point of view, it is important to develop a better understanding of the controlling parameters of this complex process. Mathematical models of drying processes are used for designing new or improving existing drying systems or even for the control of the drying process. Many mathematical models have been proposed to describe the drying process, of them thin-layer drying models have been widely in use.

Several thin-layer drying models available in the literature for explaining drying characteristics of agricultural products. These models can be categorized as theoretical, semi-empirical and empirical. Moreover, the drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behavior, and for optimizing the drying parameters. Many investigators have carried out mathematical modeling and experimental studies on the thin-layer drying of various vegetables and fruits. For example, potato

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slices (Aghbashlo *et al*., 2009), onion slices (Arslan and Özean, 2010), sweet cherry (Doymaz and Ismail, 2011) and banana (da Silva *et al*., 2013). However, there is limited information and research on drying kinetics of mango slices in the literature. Therefore, the objectives of this study were: (a) to investigate the thin-layer drying characteristics of mango slices, (b) modeling of the thin-layer drying of mango slices by testing three drying models and (c) to estimate the effective diffusivity coefficient and energy of activation for mango fruit.

Materials and Methods

Raw material

Fresh mangoes, var. Kent, from Mali, were purchased at a local supermarket in Goettingen, Germany and stored in a refrigerator at 4 ± 0.5°C. Prior to drying, samples were taken out of the refrigerator and left for 5 days for post-harvest ripening at 25 ± 2ºC and 50% relative humidity (Pott *et al*., 2005). The fruits were then washed, manually peeled using a stainless steel knife, and sliced using an electric food-slicer (Krups variotronic, Germany) to a thickness of 3 mm.

Drying experiments

The drying experiments were performed in a convective air oven (Heraeus: UT 6120, Germany) at temperature of 60, 70 and 80°C. The oven is consisted of heating unit, temperature control unit, drying chamber and centrifugal fan that has a fixed air velocity of 0.5 m/s. The average initial moisture content of the mango fruit was 82.5 ± 0.4% (w.b.), as determined using a precision air-oven method, at a temperature of 135°C for 2 hours until constant weight was reached, according to the standard method of AOAC (2000) and moisture content on wet basis (w.b.) was calculated by the following equation:

$$MC_{wb} = \frac{W_w}{(W_w + W_d)} x100\% \qquad (1)$$

Where:
MC_{wb} = moisture content, percent, wet basis
W_w = weight of water, g
W_d = weight of dry matter, g

Moisture content on wet basis was converted to moisture content on dry basis by the following equation:

$$MC_{db} = \frac{MC_{wb}}{(100 - MC_{wb})} \qquad (2)$$

Where: MC_{db} = moisture content, decimal, dry basis

Prior to starting the experiments, the oven was adjusted to the selected temperature for about half an hour to reach thermal stabilization. Then the samples were uniformly spread in a single layer of 3mm thickness on a tray. Representative samples of sliced mango for moisture content determination were placed in a circular wire mesh of 10 cm diameter and placed onto the centre of the tray. For measuring the mass of the sample at any time during experimentation, the circular wire mesh with sample was taken out of the drying chamber and weighed on a digital balance and placed back into the drying chamber every 30 min during the drying process. The digital top pan balance (Sartorius, Goettingen, Germany) of ±0.001 g accuracy, was kept near to the drying unit and weight measurement process took less than 10 seconds time. The drying process was stopped when the moisture content decreased to about 9 ± 0.2% (w.b). All the experiments were replicated three times at each drying temperature and the average values were used for the drying characteristics of mango slices.

Mathematical modeling of drying curves

The moisture ratio (MR) and drying rate of mango slices during drying experiments were calculated using the following equations:

$$\text{MR} = \frac{M - Me}{Mo - Me} \qquad (3)$$

Where: MR is the dimensionless moisture ratio; M, M_0 and M_e are the moisture content at any time, initial moisture content and equilibrium moisture content, respectively. However, MR was simplified according to Pala *et al.* (1996) and Doymaz (2004) as:

$$\text{MR} = \frac{M}{Mo} \qquad (4)$$

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \qquad (5)$$

Where, M_t, and M_{t+dt} are the moisture content at t and moisture content at t+dt (kg water /kg dry matter), respectively, t is drying time (hr).

The drying curves were fitted to three well-known thin layer drying models that are widely used in most food and biological materials; namely, Newton (Lewis), Henderson and Pabis, and Page models. These models are generally derived by simplifying the general solution of Fick's second law. Henderson and Pabis model is the first term of a general series solution of Fick's second law. The model was used to predict the drying characteristics of corn (Henderson and Pabis, 1961) and is expressed as follows:

$$MR = a\exp(-kt) \qquad (6)$$

Newton (Lewis) model is a special case of the Henderson and Pabis Model where the intercept is unity and is used to describe the drying of barely (Bruce, 1985) and grape seed (Roberts *et al*., 2008). This model is expressed as:

$$MR = \exp(-kt) \quad (7)$$

Page model is an empirical modification of Newton (Lewis) model to overcome its shortcoming it was successfully used to describe the drying characteristics of some agricultural products (Singh *et al*., 2006; Hassan-Beygi *et al*., 2009; Doymaz and Ismail, 2011). This model is expressed as follows:

$$MR = \exp(-kt^n) \quad (8)$$

In the proposed models, a and n are the drying coefficients and k is the drying constant (hr^{-1}).

Statistical analysis

Non-linear regression analysis was used to evaluate the parameters of the selected models. The goodness of fit of the three selected drying models to the experimental data was determined using four statistical parameters, namely; coefficient of determination (R^2), sum square error (SSE), reduced chi-square (χ^2) and root mean square error (RMES). These parameters can be calculated by using the following equations:

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2 \quad (9)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2}{N-n} \quad (10)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2} \quad (11)$$

Where:
$MR_{exp.}$ = Experimental moisture ratio
$MR_{pred.}$ = Predicted moisture ratio
N = Number of observations
n = Number of constants

The higher R^2 values and the lower χ^2, SSE and RMSE values are goodness of fit (Sacilik *et al*., 2006; Hassan-Beygi *et al*., 2009).

Determination of effective moisture diffusivity and activation energy

Effective moisture diffusivity describes all possible mechanisms of moisture movement within the food, such as liquid diffusion, vapor diffusion, surface diffusion, capillary flow and hydrodynamic flow. A knowledge of effective moisture diffusivity is necessary for designing and modeling mass-transfer processes such as dehydration, adsorption and desorption of moisture during storage. The drying data in the falling rate period are usually analyzed by Fick's diffusion equation (Crank, 1975).

Fick's second equation of diffusion was used to calculate effective moisture diffusivity of mango slices, considering a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution as follows:

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff} t}{4L^2}\right) \quad (12)$$

Where:
$8/\pi^2$ = the shape factor and depends on the geometry of the drying material ($4/\pi^2$ for a cylinder and $6/\pi^2$ for the sphere).
D_{eff} = the effective diffusivity, m^2s^{-1}
L = half-thickness of slab, m
n = positive integer

For long drying times, the Eq. (12) can be simplified as Eq. (13) by taking the first term of the series solution and expressed in a logarithmic form as follows (Doymaz, 2012):

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (13)$$

The effective moisture diffusivity was obtained by plotting the experimental data in terms of ln(MR) versus drying time (hr). From equation (13), a plot of ln(MR) versus time gives a straight line with a slope of (k) in which:

$$k = \frac{\pi^2 D_{eff} t}{4L^2} \quad (14)$$

The dependence of the effective moisture diffusivity on temperature is generally described by the Arrhenius equation (Simal *et al*., 2005):

$$D_{eff} = D_o \exp\left(\frac{-E_a}{RT}\right) \quad (15)$$

Where:
D_o = the pre-exponential factor of the Arrhenius equation, m^2/s
E_a = activation energy, $kJmol^{-1}$
R = universal gas constant, $kJmol^{-1}K^{-1}$
T = absolute temperature, K

Eq. (15) can be rearranged into the form of Eq. (16) as follows:

$$\ln D_{eff} = \ln(D_0) - \frac{E_a}{RT} \quad (16)$$

A plot of $\ln D_{eff}$ as a function of the reciprocal of absolute temperature 1/T will produce a straight line with slope equal to ($-E_a/R$), from which the parameter E_a can be estimated.

The activation energy (E_a) was calculated by plotting the natural logarithm of D_{eff} versus the reciprocal of the absolute temperature (T_{abs}). Activation energy is a measure of the temperature sensitivity of D_{eff} and it is the energy needed to initiate the moisture diffusion within the mango slices.

Results and Discussion

Drying characteristics of mango slices

The drying characteristics of mango slices are shown in Figures 1 and 2. The initial moisture content of mango slices before drying was about 82.5 ± 0.4% w.b. (mean ± std. deviation). As expected, the drying temperature had a significant effect on drying characteristics of the mango slices. The moisture content decreased continuously with time and an increase in temperature resulted in reduced drying time. The longest and shortest drying times were recorded at 60°C (7 hr) and 80°C (3hr), respectively. The time required to reduce the moisture content of mango slices from 82.5 ± 0.4% (w.b.) to a final 9 ± 0.2% (w.b.) were 3, 5 and 7 hour at 80°C,70°C and 60°C, respectively, as shown in Figure 1.

Figure 2 shows moisture ratio of the mango slices plotted versus drying time. From the figure it is clear that moisture ratio decreased considerably with increasing drying time. The time required to reduce the moisture ratio to any given level was dependent on the drying temperature, being highest at 60°C and lowest at 80°C. It was observed that the main factor influencing drying kinetics was the drying temperature, as noted in other studies (Belghit *et al*., 2000; Koulia *et al*., 2002). Thus, a higher drying temperature produced a higher drying rate and consequently the moisture content decreased faster. This is due to increase of air enthalpy to the mango slices and subsequent acceleration of water migration within the mango slices.

Figure 3 shows the effect of the three temperatures on the drying rate of mango slices. From the figure it can be observed that there is no constant rate drying period in the drying process of mango slices, and all the drying process occurs in the falling rate period. This indicates that diffusion is the dominant physical mechanisms governing moisture movement within the mango slices. Similar results have been reported for the drying studies on raw mango slices (Goyal *et al*., 2006), apricots (Doymaz, 2004) and yacon slices (Shi *et al*., 2013).

Table.1. Values of the drying constants and drying coefficients of the selected models

Model	Drying temperature (°C)	Drying constants	Drying coefficients
Newton (Lewis)	60	$k = 0.644 hr^{1}$	-
	70	$k = 0.864 hr^{1}$	-
	80	$k = 1.264 hr^{1}$	-
Henderson & Pabis	60	$k = 0.624 hr^{1}$	a = 1.104
	70	$k = 0.853 hr^{1}$	a = 0.963
	80	$k = 1.36 hr^{-1}$	a = 1.233
Page	60	$k = 0.601 hr^{1}$	n = 1.071
	70	$k = 0.851 hr^{1}$	n = 1.069
	80	$k = 1.004 hr^{1}$	n = 1.285

k = drying constant (hr^{-1}); a = drying coefficient and n = drying coefficient

Table.2. Statistical results obtained from the selected thin layer drying models

Model	T (°C)	R^2	SSE	RMSE	χ^2
Newton (Lewis)	60	0.991	0.001297	0.02419	0.00139
	70	0.995	0.000676	0.01533	0.00074
	80	0.979	0.00374	0.03948	0.00437
Henderson & Pabis	60	0.991	0.001614	0.03043	0.00186
	70	0.996	0.001205	0.02190	0.001326
	80	0.972	0.008498	0.0525	0.011897
Page	60	0.994	0.000717	0.019246	0.000828
	70	0.998	0.000261	0.010784	0.000287
	80	0.999	3.61×10^{-5}	0.0051	5.05×10^{-5}

T = temperature (°C); R^2 = coefficient of determination; SSE = sum square error; RMSE = root mean square error and χ^2 = reduced chi-square.

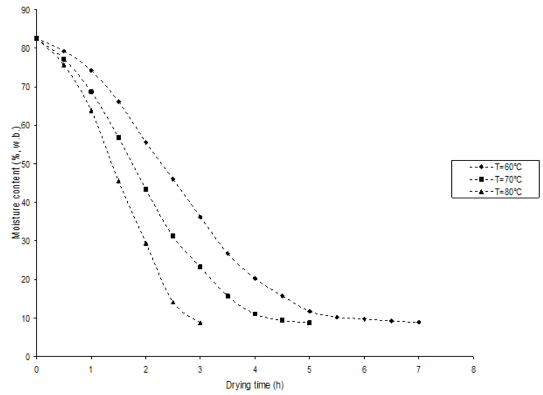

Figure 1. Effect of drying temperature on the moisture content of mango slice

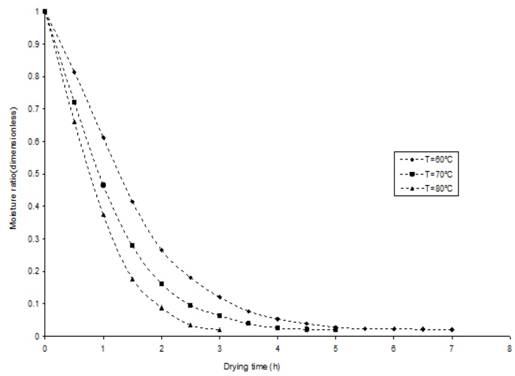

Figure 2. Effect of drying temperature on the moisture ratio of mango slices.

Fitting of the drying models

Table 1 shows values of the drying constants and drying coefficients of the selected models. From the table it is clear that drying constant (k) is temperature function. It is increased with increasing drying temperature. The fitting of the three thin-layer drying models to experimental data were compared in terms of the four statistical parameters; R^2, χ^2, SSE and RMSE. The statistical analysis values are

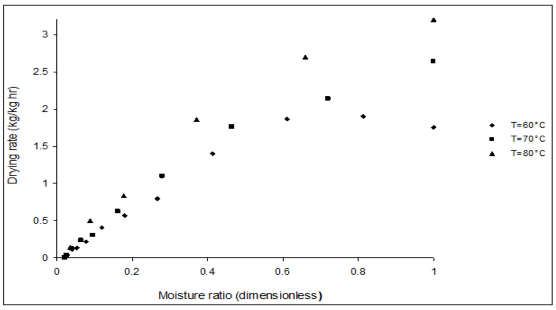

Figure 3. Drying rates versus the experimental moisture ratio of mango slices

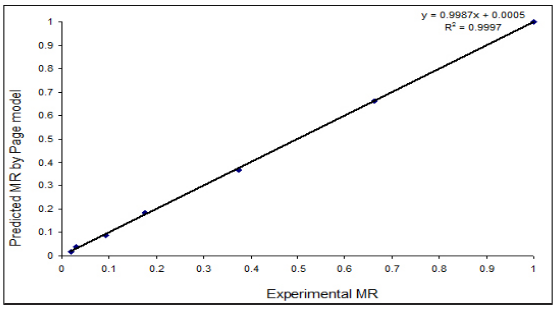

Figure 4.Predicted MR versus Experimental MR by Page model at 80°C

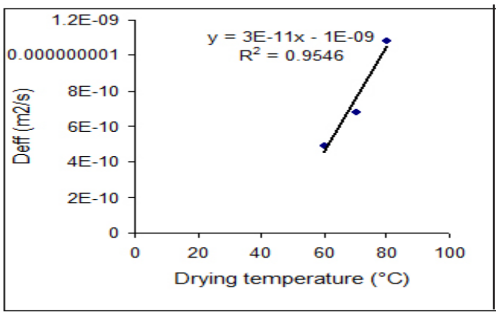

Figure 5. Effect of drying temperature on the effective diffusivity of water in mango slices

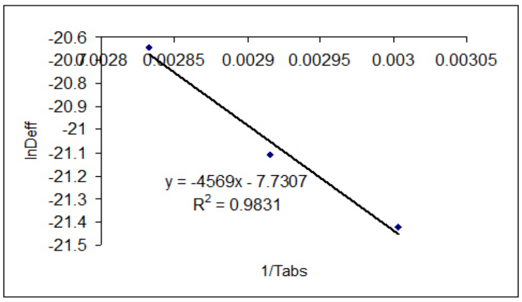

Figure 6. Arrhenius-type relationship between effective diffusivity and temperature.

summarized in Table 2.

In all cases, the R^2 values for the models were greater than 0.95, indicating a good fit (Doymaz and Ismail, 2011). The R^2 values varied between 0.972 and 0.999, SSE values between 3.61 x 10^{-5} and 0.0085, RMSE values between 0.0051 and 0.0395, and χ^2 values between 5.05 x 10^{-5} and 0.0119. These values show that the three tested drying models predict thin layer drying process of mango slices adequately. Generally, Page model gave a higher R^2 and lower SSE, RMSE and χ^2 values (Table 2). Thus, the Page model could be selected to represent the thin-layer drying characteristics of mango slices.

Figure 4 shows the plotting of the experimental data with the predicted ones using Page model for mango slices at 80ºC. The scatter diagram shows that the observations are clustered along the linear regression line which means the adequacy of this model in describing the drying characteristics of mango slices. Similar findings were reported by Goyal *et al.* (2006) for raw mango slices, Doymaz and Ibrahim (2011) for sweet cherry, Aghbashlo *et al.* (2009) for potato slices and Doymaz (2012) for persimmon slices.

Effective moisture diffusivity

The determined values of the effective moisture diffusivity (D_{eff}) for the different temperatures are shown in Figure 5. The diffusivity values were found to be 4.97 x 10^{-10}, 6.79 x 10^{-10} and 10.83 x 10^{-10} m^2/s at 60, 70 and 80ºC, respectively. It is clear that effective diffusivity values for mango slices increases greatly with increasing drying air temperature. When samples were dried at higher temperature, increasing heating energy increases the activity of water molecules leading to higher moisture diffusivities. The values of effective moisture diffusivity obtained from this study lie within the general range from 10^{-11} to 10^{-9} m^2/s for food materials (Madamba *et al.*, 1996). The values of the effective moisture diffusivity (D_{eff}) are consistent with the reported values of 2.27 to 4.97 x10^{-10} m^2/s for the drying of apple in the temperature range 40-60ºC (Sacilik *et al.*, 2006), 2.62 to 4.97 x 10^{-10} m^2/s for the drying of raw mango (cv. Dasehari) slices in the temperature range 55-60ºC (Goyal *et al.*, 2006), 3.32 to 90.0 x 10^{-10} m^2/s for berberis fruit at 50-70ºC (Aghbashlo *et al.*, 2008) and 6.27 to 35.0 x10^{-10} m^2/s for orange slices at 40-80ºC (Raffie *et al.*, 2010).

Activation energy

The activation energy (E_a) was found to be 37.99 kJ/mol (Figure 6.). The activation energy value obtained from this study lies within the general range of 12.7 to 110 kJ/mol for various food materials (Zogzas *et al.*, 1996). It is higher than activation energies of 27.0 kJ/mol for kiwifruit drying in the temperature range 30-90ºC (Simal *et al.*, 2005) and 30.0 kJ/mol for yacon drying (Shi *et al.*, 2013), and lower than the activation energies of 40.95 kJ/mol for fig drying (Xanthopoulos *et al.*, 2009) and 43.05-49.17 kJ/mol for sweet cherry drying (Doymaz and Ismail, 2011). But similar to activation energies of 30.46-43.26 kJ/mol in the temperature range 50-70ºC for persimmon slices drying (Doymaz, 2012).

Conclusions

Drying curves were greatly affected by the drying temperature. Increased in drying temperature caused a decrease in the drying time. Drying of mango slices occurred in the falling rate period, which indicates that moisture removal from the product was governed by internal diffusion phenomenon. According to statistical analysis applied to the three drying models, Page model was found to be the most suitable model for describing the thin-layer drying characteristics of mango slices. The effective diffusivity coefficients increased with increasing drying temperature, which ranged from 4.97 x 10^{-10} to10.83 x 10^{-10} m^2/s over the temperature range (60 to 80ºC). The activation energy for the mango slices was estimated to be 37.99 kJ/mol.

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