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Research Article

Mathematical Modelling of Thin Layer Mangoes (*Mangifera indica* L.) Drying Process

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Abstract

This study was conducted to investigate the effect drying process on hot-air drying kinetics of mangoes (Mangifera indica L.) slices and to evaluate the best model predicting the drying kinetics. The experimental study was carried out in an electric dryer at 40 °C, 50 °C and 60 °C, 0.6 m/s with two configurations (vertical airflow batch drying and vertical countercurrent airflow drying). To estimate and select the appropriate drying model, seven different models were applied to the experimental data and compared. The performances of these models were compared using the coefficient (R^2), reduced chi square (χ^2) and root mean square error (RMSE) between the observed and predicted moisture ratios. The analysis of results showed that the vertical countercurrent airflow drying permits us to obtain best quality of products in terms of moisture ration. Among the models used, the Midilli et al., model was found to best explain thin layer drying of mangoes slices as compared to the other models over the experimental temperature range. By increasing the drying air temperature, the effective moisture diffusivity values increased from 5.018×10^{-10} to 7.395×10^{-10} m^2/s for vertical airflow batch drying and from 3.698×10^{-10} to 7.660×10^{-10} m^2/s for vertical countercurrent airflow drying. The activation energy was calculated using an exponential expression based on Arrhenius equation and E_a = 16.86 kJ/mol and D_o= 3.28×10^{-7} m^2/s for vertical airflow batch drying and E_a = 31.51 kJ/mo and D_o= 6.55×10^{-5} m^2/s for vertical countercurrent airflow drying.

***Keywords**: activation energy, effective diffusivity, drying process, models.*

Introduction

Mango fruit (*Mangifera indica* L.) is one of the most important seasonal fruits of Cameroon and subtropical countries. It contains high amounts of sugars and considerable amounts of vitamin C and provitamin A. Mango fruit is highly perishable and must be consumed within a few days after harvesting. Because of inadequate methods of preservation, substantial quantity of harvests is lost each season. Drying can constitute an efficient solution of preservation (Dissa *et al.*, 2008).

This process improves the food stability, since it reduces considerably the water and microbiological activity of the material and minimizes physical and chemical changes during its storage. Generally to improve the efficiency of the drying process, products are sliced before drying. Thin-layer drying equations as a function of drying conditions are used to estimate drying time of several products and also to generalize drying curves. Many mathematical models have been developed and used to describe the drying process of food products in different drying conditions (Doymaz, 2004; Velic *et al.*, 2004; Karim and Hawlader, 2005; Simal *et al.*, 2005; Kuitche *et al.*, 2007; Kashaninejad *et al.*, 2007; Meisami-asl *et al.*, 2009; Ghatrehsamani *et al.*, 2012; Rayaguru and Routray, 2012).

Studies focusing on the mangoes behavior during the drying process have been reported by several researchers in the literature. Among others, Nieto *et al.,* (2001) studied the influence of pre-treatments by blanching and/or osmotic dehydration with glucose syrups on air drying kinetics of mango during the falling rate period. An exponential correlation which allowed determining mango diffusivity as a function of thickness and drying temperature are developed in case of batch process drying (Jaya and Das, 2003). Touré and Kibangu-Nkembo (2004) studied the free convection sun-drying of cassava, banana and mango and established an expression linking slices initial moisture content to the maximal temperature difference between drying air and each product. Goyal *et al.,* (2006) studied the thin-layer drying kinetics of raw mango slices at 55, 60 and 65°C air temperature. Mercer (2012) presented a comparative study of the kinetics of mango drying in open-air, solar, and forced-air dryers. Omayma and Khaled (2012) presented the characteristics of dried mango slices as affected by pre-treatments and drying type. Aremu *et al.,* (2013) studied the effect of slice thickness and temperature on the drying kinetics of mango *(mangifera indica* L.*)* in a batch dryer. Takamte *et al.*, (2013) conducted a numerical simulation of thin-layer mangoes drying at 40, 50 and 60 °C by control external

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Table 1: Thin layer mathematical models

Models	Expressions	References
Newton	$MR = \exp(-kt)$	Lewis (1921)
Page	$MR = \exp(-kt^n)$	Page (1949)
Henderson et Pabis	$MR = a.\exp(-kt)$	Henderson et Pabis (1961)
Logarithmique	$MR = a.\exp(-kt) + c$	Yagcioglu *et al*. (1999)
Two term	$MR = a.\exp(-kt) + b.\exp(-k_1 t)$	Henderson, (1974)
Diffusion approximative	$MR = a.\exp(-kt) + (1-a)\exp(-kbt)$	Kasem (1998)
Midilli*et al.*,	$MR = a.\exp(-kt^n) + bt$	Midilli*et al.*, (2002)

conditions. Most of the above mentioned studies applied for the same drying process (horizontal or vertical airflow batch) at different level air velocity and drying temperature.

The present study was therefore undertaken to investigate the thin layer drying characteristics of mangoes slices in a convective dryer at vertical airflow batch and vertical countercurrent airflow drying. Also the experimental data were fit to propose the best mathematical model to estimate the constant parameters for calculating the effective diffusivity and activation energy for drying mangoes (*Mangifera indica* L.).

Materials and methods

Fully-ripened mangoes (*Mangifera indica* L.) were collected to the local market, washed, manually peeled and transversely cut into 3 mm slices using a stainless steel knife. Drying experiments were conducted at 40, 50 and 60°C (± 2°C). The air velocity of dryer was fixed at 0.6 m/s. Two configurations (vertical airflow batch drying and vertical countercurrent airflow drying) were used to study effect of drying process. Each experiment was terminated when the weights of the samples were stabilized up to 2 decimal points. The initial moisture content of fresh slices and the final moisture content of dried samples were determined by hot air oven method at 105ºC for 24 h. Each experimental run was conducted in triplicate and the average of the results was analyzed.

Drying analysis and evaluation of thin layer drying models

Based on the initial moisture content from oven drying, the weight loss was used to calculate the moisture content. The drying characteristic curves were plotted after analyzing the experimental data. The moisture content was converted to moisture ratio (MR) using the following equation

$$MR=\frac{X-X_{eq}}{X_0-X_{eq}} \quad (1)$$

where MR is moisture ratio, X the average moisture content of the product, X_0 the initial moisture content, Xeq the equilibrium moisture content.

Empirical models

In order to estimate and select the appropriate drying model among different semi-theoretical and/ or empirical models, mathematical modeling was carried out to describe the drying curve equation of stone apple slices and to determine the parameters of the thin layer drying models by fitting experimental data to the model equation. The thin layer drying equations mentioned in Table 1 were tested to select the best model.

The non-linear regression analysis was performed using the TableCurve V5.1. of CIRAD of Montpellier – France. Although the coefficient of determination (R^2) was one of the primary criterions for selecting the best model to describe thin-layer drying curves of slices, the statistical test methods such as the reduced chi- square (χ^2), root mean square error (RMSE) as described by Equation (2) and (3) were also used to evaluate the goodness of fit of the models. The lower chi- square (χ^2) and RMSE values and the higher R^2 values, were chosen as the basis for goodness of fit (Akpinar *et al*., 2003; Midilli and Kucuk, 2003).

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

$$MSE=\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2 \quad (3)$$

Effective water diffusivity determination

The water diffusivity of mangoes is evaluated by using the simplified mathematical Fick's second law. Assuming one-dimensional moisture transfer, homogenous and parallelepipedic shape for the mangoes' samples, uniform initial moisture distribution, and the analytical solution of Fick's equation (4) is (Crank, 1975):

$$\frac{X-X_{eq}}{X_{cr}-X_{eq}}=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2}{4}\frac{D.t}{l^2}\right] \quad (4)$$

Where X_{cr} is the critical water content, *l* the half thickness of the slice, t is the drying time (s), *D* the water diffusivity, n the Fourier's series number and γ the shape factor equal $\frac{8}{\pi^2}$ to for a parallelepiped. In convective drying of solids, this solution is valid only for the falling rate period when the drying process is controlled by internal moisture diffusion for slice moisture content below the critical value. Therefore, the diffusivity must be identified from Eq. (5) by setting the initial moisture content to the critical value X and by setting the drying time to zero when the mean moisture content of the sample reaches that critical moisture content.

For a long diffusion time, the crank equation for slab which involved a series of exponents can be simplified to Equation 6 using the first term.

Table 2: Statistical results of different thin layer models for vertical airflow batch drying

Models	T (°C)	a x 10^{-2}	b x 10^{-2}	k x 10^{-3}	n x 10^{-2}	c x 10^{-2}	k_1x 10^{-3}	R^2	RMSE x 10^{-3}	χ^2
Newton	40	-	-	2.1413	-	-	-	95.135	1.535	3.214 x 10^{-3}
	50	-	-	2.7575	-	-	-	91.358	5.017	5.017 x 10^{-3}
	60	-	-	3.1767	-	-	-	91.627	5.165	5.165 x 10^{-3}
Page	40	-	-	8.8790	76.1936	-	-	98.668	0.917	9.165 x 10^{-4}
	50	-	-	15.5926	69.6815	-	-	97.500	1.520	1.520 x 10^{-3}
	60	-	-	15.0813	72.2142	-	-	96.123	2.506	2.505 x 10^{-3}
Henderson and Pabis	40	92.9245	-	1.8945	-	-	-	96.168	2.637	2.637 x 10^{-3}
	50	91.3483	-	2.3806	-	-	-	92.926	4.302	4.302 x 10^{-3}
	60	93.4725	-	2.8734	-	-	-	92.394	4.916	4.915 x 10^{-3}
Logarithmic	40	85.1829	-	3.1777	-	15.7043	-	99.966	0.025	2.462 x 10^{-5}
	50	81.8748	-	4.29763	-	18.1384	-	99.986	0.009	9.142 x 10^{-6}
	60	84.8029	-	4.86591	-	16.5363	-	99.728	0.184	1.845 x 10^{-4}
Two term	40	92.683	7.7131	2.84197	-	-	0.56102	99.982	0.013	1.333 x 10^{-5}
	50	82.6816	17.2445	4.23514	-	-	0.04639	99.986	0.009	9.301 x 10^{-6}
	60	92.2995	7.9286	4.16998	-	-	0.69742	99.819	0.129	1.233 x 10^{-4}
Diffusion approximative	40	93.1835	23.4922	2.78646	-	-	-	99.980	0.014	1.431 x 10^{-5}
	50	82.5808	0.8863	4.2511	-	-	-	99.986	0.008	8.883 x 10^{-6}
	60	92.382	17.7252	4.13409	-	-	-	99.818	0.123	1.398 x 10^{-4}
Midilli et al	40	100.134	1.18	2.59764	0.292	-	-	99.980	0.015	1.465 x 10^{-5}
	50	100.428	1.44	5.05428	92.8427	-	-	99.970	0.020	1.966 x 10^{-5}
	60	100.383	1.49	4.34724	97.7915	-	-	99.818	0.129	1.297 x 10^{-4}

Table 2: Statistical results of different thin layer models for vertical countercurrent airflow drying

Modèles	T (°C)	a x 10^{-2}	b x 10^{-2}	k x 10^{-3}	n x 10^{-2}	c x 10^{-2}	k_1x 10^{-3}	R^2	RMSE x 10^{-3}	χ^2
Newton	40	-	-	1.73735	-	-	-	97.123	1.488	1.488 x 10^{-3}
	50	-	-	2.45188	-	-	-	97.917	1.706	1.706 x 10^{-3}
	60	-	-	3.58378	-	-	-	97.951	1.124	1.227 x 10^{-3}
Page	40	-	-	5.65768	81.395	-	-	99.341	0.350	3.497 x 10^{-4}
	50	-	-	7.84922	80.7884	-	-	99.220	0.446	4.461 x 10^{-4}
	60	-	-	9.34959	83.0548	-	-	99.541	0.288	2.747 x 10^{-4}
Henderson and Pabis	40	93.7946	-	1.60277	-	-	-	98.019	1.052	1.052 x 10^{-3}
	50	93.4305	-	2.25817	-	-	-	97.813	1.250	1.250 x 10^{-3}
	60	94.8951	-	3.36313	-	-	-	98.517	0.932	9.379 x 10^{-4}
Logarithmic	40	84.0783	-	2.60497	-	16.3145	-	99.988	0.006	6.362 x 10^{-6}
	50	85.4901	-	3.58404	-	14.6389	-	99.856	0.024	2.454 x 10^{-5}
	60	86.313	-	5.02017	-	0.13705	-	99.981	0.012	1.253 x 10^{-5}
Two term	40	90.8293	9.1586	2.37354	-	-	4.32048	99.997	0.001	1.507 x 10^{-5}
	50	93.1614	6.3941	3.19322	-	-	0.823	99.981	0.011	1.139 x 10^{-5}
	60	93.2105	6.4392	4.56833	-	-	1.104	99.991	0.006	6.026 x 10^{-5}
Diffusion approximative	40	90.8014	18.0597	2.37533	-	-	-	99.997	0.001	1.333 x 10^{-6}
	50	92.6847	21.421	3.26095	-	-	-	99.979	0.012	1.257 x 10^{-5}
	60	92.5589	19.4236	4.66007	-	-	-	99.990	0.006	6.724 x 10^{-6}
Midilli et al	40	100.074	0.0110	2.38372	98.5913	-	-	99.997	0.001	1.816 x 10^{-6}
	50	99.5354	0.0136	3.10195	99.71	-	-	99.982	0.010	1.088 x 10^{-5}
	60	99.8539	0.0177	4.71692	98.4663	-	-	99.993	0.005	5.037 x 10^{-6}

$$MR = \frac{X - x_{eq}}{x_{cr} - X_{eq}} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}.t}{4l^2}\right) \quad (5)$$

where, MR is the moisture ratio, D_{eff} (m^2/s) is the effective moisture diffusivity,

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\pi^2 \frac{D_{eff}}{4l^2}.t\right) \quad (6)$$

can be put in the general form $K.t + b = 0$ and K is the gradient of $\ln(MR) = f(t)$

where : $K = \dfrac{\pi^2 D_{eff}}{r^2}$

Activation energy was thus identified from diffusivity according to Arrhenius dependence as:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

Where D_o is the diffusivity coefficient at infinite temperatures and E_a the activation energy of the (kj/mol), R the gaz constant, T temperature in °K.

Results and discussion

Figure 1 present the evolution of the moisture ration of mango slices in two study configurations.

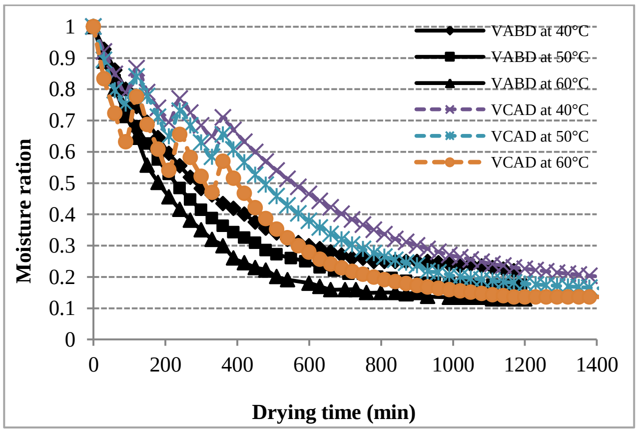

Figure 1: Effect of drying principle on mangoes slices drying time at 40°C, 50°C and 60°C

In the experimental temperature range, the higher hot air temperature led to the faster drying rate and the shorter

Table3: Effective diffusivities of mangoes slices at different temperatures and drying process

Drying process	Temperature (°C)	Diffusivity (m^2/s)
Vertical airflow batch drying	40	5.018×10^{-10}
	50	6.339×10^{-10}
	60	7.395×10^{-10}
Vertical countercurrent airflow drying	40	3.698×10^{-10}
	50	5.018×10^{-10}
	60	7.660×10^{-10}

drying time. As the drying air temperature rises, the transfer rate of moisture from the internal of the drying mangoes to its surface and the vaporization potential of moisture at the surface increased, resulting in the higher drying rate. Moreover, we observed that the drying time varies with the drying principle. The similar results are presented by (Meisami-asl et *al.*, 2009; Takamte *et al.*, 2014; Edoun, 2014).

The moisture ratio calculated from the drying data at different temperatures was fitted to the thin layer models given in Table 1. The statistical results from models are summarized in Tables 2 and 3. The best model describing the thin-layer drying characteristics of mangoes was chosen as the one with the highest R^2 values and the lowest and RMSE values. The R^2 for Logarithmic, Two terms, Diffusion approximative and Midilli models were above 0.99 but for Newton, Page, Henderson and Pabis model that value was above 0.90. During the vertical airflow batch drying, Two term model gives the highest value of R^2 and the lowest values of χ^2 and RMSE and during the vertical countercurrent airflow drying the Midilli model gives the best statistical results at different temperature.

In the case of vertical airflow batch drying, the effect of temperature on the drying constants of the Two term model was taken into account by developing the relation between these constants and the drying temperature. The regression equations relating the constants of the selected model and the drying temperature are the following:

$$MR = a.\exp(-kt) + b.\exp(-k_1 t) \quad (8)$$

where :

$a=0.000980965T^2 - 0.0982883T+3.28882$
$b= -0.000942365T^2+0.0943443T-2.18886$
$k= -0.00000729165T^2+0.000795566T-0.017314$
$k_1= -0.0000058283T^2+0.00057601T-0.0142761$

The same developing are done for vertical concurrent airflow drying and the regression equations relating the constants of midilli model and the drying temperature are the following:

$$MR = a.\exp(-kt^n) + b.t \quad (9)$$

where :

$a=0.000042855T^2-0.00439555T+1.10799$
$b= 0.000000085T^2-0.00000505T+0.000176$
$k= 0.0000044837T^2-0.00033171T+0.0084782$
$n= -0.00011812T^2+0.0117495T-0.704925$

Effective moisture diffusivity

Effective diffusivities (D_{eff}) of mangoes at three different temperatures was evaluated by plotting ln(MR) vs time and the data was presented in Table 3. Values of D_{eff} was calculated for the two drying principle and the efficient diffusivity of mangoes slices ranged form 5.018×10^{-10} to 7.395×10^{-10} m^2/s for vertical airflow batch drying and from 3.698×10^{-10} to 7.660×10^{-10} m^2/s for vertical countercurrent airflow drying. These values are within the general range 10^{-9} to 10^{-11} m^2/s for drying of food materials (Maskan *et al.*, 2002). The effective moisture diffusivity increased as drying air temperature was increased. The similar results are presented in the literature (Kuitche *et al.*, 2007; Kadam *et al.*, 2001; Aremu *et al.*, 2013).

Activation energy

Activation energy is the minimum energy required to initiate moisture diffusion from a product. Figure 2 presents $\ln(D_{eff}) = f(1/T)$ respectively for vertical airflow batch drying and vertical countercurrent airflow drying. From the slop of the straight lines described by the Arrhenius equation, E_a = 16.86 kJ/mol and $D_0 = 3.28 \times 10^{-7}$ m^2/s for vertical airflow batch drying and E_a = 31.51 kJ/mol and D_0 = 6.55×10^{-5} m^2/s for vertical countercurrent airflow drying. We observe that the activation energy of mangoes slices was lower at vertical airflow batch drying as compared to that at vertical countercurrent airflow drying.

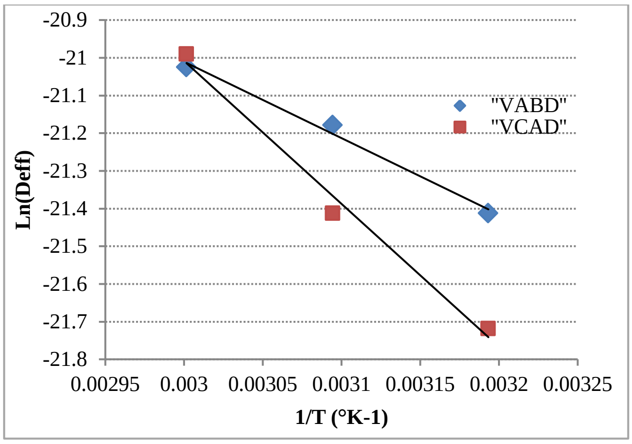

Figure 2: Evolution of $\ln(D_{eff})$ with 1/T for the different temperatures

Conclusion

Drying of mangoes slices study was carried to determine the effect of drying process (vertical airflow batch drying and vertical countercurrent airflow drying) and drying air temperature on drying kinetics. The results show that the increase in drying air temperature decreased the drying time in both the drying process. Midilli et al. thin layer drying equation represented the thin layer drying behaviour of mangoes slices in the two cases. Efficient moisture diffusivity of mangoes slices ranged form 5,018 x 10^{-10} to 7,395 x 10^{-10} m^2/s for vertical airflow batch drying and from 3,698 x 10^{-10} to 7,660 x 10^{-10} m^2/s for vertical countercurrent airflow drying.. Activation energy was 16,86 kJ/mol and 31,51 kJ/mol respectively for vertical airflow batch and vertical countercurrent airflow drying.

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