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Evaluation of a suitable thin layer model for drying of pumpkin under forced air convection

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Abstract

The thin layer drying kinetics of pumpkin slices *(Cucurbita moschata)* were experimentally investigated in a convective hot air dryer. In order to select the appropriate model for predicting the drying kinetics of pumpkin *(Cucurbita moschata)*, twelve thin layer semi theoretical, theoretical and empirical models, widely used in describing the drying behaviour of agricultural products were fitted to the experimental data. The Page and Two term exponential models showed the best fit under certain drying conditions. The Hii *et al.* (2009) model, which was adopted from a combination of the Page and Two term models was compared to the other 11 selected thin layer models based on the coefficient of determination (R^2) and sum of squares error *(SSE)*. Comparison was made between the experimental and model predicted moisture ratio by non-linear regression analysis. Furthermore, the effect of drying temperature and slice thickness on the best model constants was evaluated. Consequently, the Hii *et al.* (2009) model showed an excellent fit with the experimental data ($R^2 > 0.99$ and SSE < 0.012) for the drying temperatures of 50, 60, 70 and 80 °C and at different sample thicknesses of 3 mm, 5 mm and 7 mm respectively. Thus, the Hii *et al.* (2009) model can adequately predict the drying kinetics of pumpkin.

Introduction

Pumpkin is a cultivar of the squash plant with round, smooth, slightly ribbed skin and deep yellow to orange colouration (Michael, 1990). The three most common varieties are *Cucurbita pepo, Cucurbita maxima* and *Cucurbita moschata.* Pumpkin is also rich in carotene, vitamins, minerals and pectin (Krokida *et al*., 2003). The chemical composition as well as the antioxidants content makes pumpkin an important food product for human consumption and industrial utilisation (Guiné and Barroca, 2012). Just as in most fruits, pumpkins are very sensitive to microbial spoilage, even under refrigerated conditions. Thus, it is best if they are preserved in order to increase shelf life (Doymaz, 2007). This is especially true as the perishable nature of pumpkin tends to limit its utilisation, hence the need to be processed by drying.

Drying is the most commonly used method of food preservation which involves the removal of moisture from a material to a level at which microbial and enzymatic activities are greatly minimised (Henríquez *et al.*, 2014). The mechanism responsible for this process in fruits and vegetables is diffusion, which is due to the simultaneous heat and mass transfer that occurs in the material during a falling rate period (Diamante *et al.*, 2010; Tzempelikos *et al*., 2014; Udomkun *et al*., 2015).

The rate of the heat and mass transfer depends on the drying conditions of temperature, relative humidity, air velocity and material thickness (Pandey *et al.*, 2010; Jangam, 2011). Thus, there is a need to apply appropriate drying technique that will describe the drying process accurately. The most common drying technique used for most biological and agricultural products is thin layer convective drying (Sacilik, 2007; Kadam *et al.*, 2011).

Thin layer convective hot air drying technique enables the effective control and uniform distribution of drying air and temperature conditions over the material (Da Silva *et al*., 2015), thereby improving the overall quality of the final product. Thin layer drying curve models are often employed to evaluate the drying process of food products and may be categorised into three groups, namely; theoretical, semi-theoretical and empirical models (Erbay and Icier, 2010). The semi-theoretical and empirical models have been applied and found best at describing the drying process and predicting the drying kinetics

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of numerous agricultural foods (Meisami-asl *et al*., 2010; Rayaguru and Routray, 2012). These categories of models provide a greater extent of drying curve fitting and better prediction of drying behaviours (Ozdemir and Devres, 2000; Panchariya *et al*., 2002; Erbay and Icier, 2010). Nonetheless, most of the empirical model parameters are liable to inappropriate physical interpretations and cannot be applied to all agricultural and food products (Simal *et al.*, 2000; Simal *et al*., 2005).

However, the semi-theoretical models, which are generally derived from Fick's second law, Newton's laws of cooling and Newton's law of fluid momentum, provide better understanding of the transport processes and show a better fit to the experimental data than other categories of models (Janjai *et al*., 2010). Thus, the semi-theoretical models can provide an appropriate estimation of the drying kinetics for agricultural and food products.

Previous studies have reported different models used in predicting the drying kinetics of agricultural and food products (Table 1), yet, none of these models have been found applicable over a wide range of drying conditions and products (Aghbashlo, 2009). Thus, the present study was undertaken to investigate the most suitable mathematical empirical and theoretical thin layer model for the prediction of the drying kinetics of pumpkin *(Cucurbita moschata).*

The objective of this study is therefore to understand the drying behaviour of pumpkin in order to select a suitable model that will estimate the effects of drying conditions on the drying kinetics. In addition, the study intends to show the effect of these conditions on the model constants.

Materials and Methods

The pumpkin *(Cucurbita moschata)* samples used were purchased locally from different shops located in Serdang, Selayang, Ipoh, Kajang, and Penang regions of Malaysia. A total of 76 samples (36 for training and 30 for validation) of pumpkin fruits with an average weight of 1.9 kg per piece were used in the experiments. The samples were stored in a cold room at a temperature of 10°C (± 2) during the drying duration which lasted for two weeks. A total of 12 experimental runs were carried out in three replications. The experiments were conducted in the Bio-System laboratory of the Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra, Malaysia.

Convective hot-air dryer

The dryer used was a NFC-3D Series Electric Convection Oven with an operating voltage of 380V/220V, a power of 4.5 kW and a frequency of 50Hz. It consists of five basic units including a fan which provided the desired drying air velocity, electrical heaters that were responsible for controlling the temperature of the drying air, a drying chamber, a dehumidifier that controlled the relative humidity of the drying chamber, and a system unit where all the data was stored automatically. In addition there was an electric control panel containing electrical circuits, wire connections, Internet and universal serial bus (USB) ports (for data collection). The exterior dimensions were 860 mm x 111 mm x 500 mm with a tray size of 600 mm x 40 mm x 20 mm. A single door opened at the front in order to allow the insertion or removal of the drying tray. The dryer consisted of an air velocity control button that had just two levels of speed. The actual velocity was measured using a vane anemometer sensor with an accuracy of ± 0.03 m/s, placed opposite to the blowing fan and 1 cm above the drying tray.

Preparation of samples

Before the drying process commenced, 36 samples were selected from a total of 76. The samples were washed, hand peeled and sliced into thin layer slab pieces of thickness 3 mm, 5 mm and 7 mm respectively The peeled sliced samples were labelled and dried at four (4) different temperature levels with an average relative humidity of 45% ± 3% and a constant air velocity.

Experimental procedure

For the first experimental treatment, 36 samples were selected and portions from each piece were sliced into thin layers of the required dimension. Before the commencement of each set of experimental runs, the dryer was brought up to temperature to attain a stable state equilibrium condition by running it empty for about 45 minutes. For each experimental run, the drying of the pumpkin started with an initial moisture content of 76.4% (wet basis) and continued until a constant weight (to three decimal places) of each sample was observed. A total of thirty six (36) runs were conducted with four (4) levels of air temperature (50, 60, 70 and 80°C) and three (3) levels of slice thickness at a constant air velocity of 1.16 m/s. Each experimental run was completed in triplicate and the average values were taken. A 30 minute time interval was adopted for the collection of experimental data.

Moisture content determination

The oven dry method described by ASAE (2005) was used to determine the average initial moisture

Table 1. Thin layer drying models

Model number	Model name	Model	Products	Reference
1.	Lewis (Newton)	$MR=\exp(-kt)$	Strawberry; Papayas	El-Beltagy *et al*., 2007; Udomkun *et al*., 2015
2.	Page Model	$MR = \exp^{-kt^n}$	Quinces; Mango	Akoy, 2014; Tzempelikos *et al*., 2014
3.	Modified Page	$MR = \exp(-Kt)^n$	Castor seeds; Aloe vera	Ojediran and Raji, 2011; Vega *et al*., 2007
4.	Henderson and Pabis	$MR=a\exp(-kt)$	Pumpkin (*C. moschata*); Apple (*Golab*); Pumpkin (*C. pepo*)	Hashim *et al*., 2014; Meisami-asl *et al*., 2010; Sacilik, 2007
5.	Logarithmic Model	$MR= a\exp(-kt) + c$	Beetroot; Stone apple	Kaur and Singh, 2014; Rayaguru and Routray, 2012
6.	Midilli Model	$MR = a\exp^{-kt} + bt$	Spearmint; Yacon; Pepper	Ayadi *et al*., 2014; *Shi*, *et al*., 2013; Darvishi and Hazbavi, 2012
7.	Modified Midilli	$MR = \exp^{-kt} + bt$	Jackfruit; Oil palm	Gan and Poh, 2014; Noor *et al*., 2014
8.	Demir *et al*. Model	$MR = a\exp(-Kt)^n + b$	Green table olives	Demir *et al*., 2007
9.	Two-Term Model	$MR=a\exp(-k_1t)+b\exp(-k_2t)$	Squash seeds; Pumpkin *(C.Pepo)*	Chayjan, *et al*., 2013; Sacilik, 2007
10.	Wang and Singh	$MR = 1 + at + bt^2$	Paddy; Mabonde Banana	Manikantan *et al*., 2014; Omolola *et al*., 2014
11.	Aghbashlo model	$MR= \exp\left(-\frac{K_1 t}{1+K_2 t}\right)$	Apple; Carrots	Seiiedlou *et al*., 2010; Aghbashlo *et al*., 2009
12.	Hii *et al*. Model	$MR = a\exp(-K_1t^n) + b\exp(-K_2t^n)$	Cocoa; Carrot pomace	Hii, *et al*., 2009; Kumar et al., 2012

a, b, c, k, k_1, k_2, and n are model constants

content of the samples. The samples were initially weighed using an electronic balance having a sensitivity of 0.001 g and placed in an air oven for 24 hr at 103°C ± 2°C. After 24 hours, the samples were taken out of the oven and weighed to determine the final individual weight. The average values of the initial mass and final mass were used to calculate the moisture content expressed on a wet basis as shown in Equation 1. The process was repeated three times and the average was calculated.

$$\text{Moisture content (MC)} = \frac{W_i - W_f}{W_i} \times 100 \text{(\% wet basis)} \quad (1)$$

Where W_i is the average initial weight of the sample and W_f is the average final weight of the sample.

Kinetic modelling

The thin layer equations are important tools in mathematical or kinetic rate modelling (Erbay and Icier, 2010). Thin layer kinetic modelling follows the rate of change principle which can be determined by combining the rate of reaction with the material balance for the system (Brooker *et al*., 1974; Henríquez *et al*., 2014).

The boundary conditions used in this study were:

$$t = 0,\ M_t = M_0 \quad (2)$$

$$t > 0,\ z = 0, \frac{dM}{dt} = 0 \quad (3)$$

$$t > 0, z = L,\ M_t = M_e \quad (4)$$

$$t > 0, T = T_a \quad (5)$$

$$L = \frac{h}{2} \quad (6)$$

For the pumpkin slab slices used, Equation 2 (the first boundary condition) states that all sample slices have uniform initial moisture content. The mass transfer with regard to the centre of the sample slices is symmetric, (inflection point) (Equation 3), thus there is negligible shrinkage. The third condition states that when the diffusion path occurs on both sides of the slices, the samples instantaneously reach equilibrium with the surrounding air (Akpinar, 2006).

The experimental data obtained for the different conditions were modelled in the form of the moisture ratio (MR) versus time.

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (7)$$

According to Aghbashlo *et al*. (2009) the value of M_e is negligible as the relative humidity is not constant throughout the entire experiments, thus the moisture ratio was calculated according to the ANSI/ ASAE standard as:

$$MR = \frac{M_t}{M_o} \quad (8)$$

$$M_t = M_o \exp^{-kt} \quad (9)$$

Therefore, $MR = \frac{M_t}{M_o} = \exp^{-kt}$ (first order exponential model) (10)

where M_t is the moisture content at any time *t*, M_o is the initial moisture content of the sample, M_e is the Equilibrium moisture content, *k* is the drying rate coefficient (reciprocal minutes), *t* is the time (minutes), z is the direction of sample thickness (mm), T is the Drying air temperature (°C), T_a is the Ambient temperature (°C), L is the half thickness of the slice (mm) and h is the slice thickness (mm).

The preliminary analysis of the drying data at 50°C, 60°C, 70°C and 80°C for the slices of 3 mm thickness showed that the Page model was best suited for predicting the drying kinetics of pumpkin. However, an increase in the slice thickness to 5 mm and subsequently 7 mm resulted in different fitting results, with the Two Term model as the most appropriate under these conditions.

Thus, both models could not give a consistent best fit for all drying conditions. However, the Hii *et al.* (2009) model (Equation 11), which is a combination of the Page and Two-Term model was adopted to describe the drying behaviour under all conditions investigated. The model is more of a modification of the Two Term model with the assumption that n > 1 for all drying conditions.

$$MR = a\exp(-K_1 t^n) + b\exp(-K_2 t^n) \quad (11)$$

Where a, K_1, b, K_2 and n are model constants

Furthermore, the experimental data was regressed non-linearly using Scientific Data Analysis and Graphing Software (SIGMAPLOT 12.0) and fitted to all the selected models.

Statistical design and data analysis

The data collected was analysed at the 95% confidence level using Scientific Data Analysis and Graphing Software (Sigma plot 12.0). The statistical design employed used a factorial 3 × 4 arrangement (thickness x temperature x time x Moisture Ratio), with 12 runs completed in triplicate which amounted to a total of 36 experimental units. The mean values of all levels were used for the mathematical modelling.

The goodness of fit of the thin layer models to the experimental data was evaluated using the coefficient of determination *(R^2)* and the sum of squares error *(SSE)* such that the higher the value of R^2 and the lower the SSE value, the better was the goodness of fit (Yaldiz *et al.*, 2001; Ertekin and Yaldiz, 2004; Rayaguru and Routray, 2012; Tahmasebi *et al.*, 2014).

R-squared *(R^2)* is also known as the coefficient of determination, or the coefficient of multiple determination for multiple regression and measures how close the statistical data could fit the regression line. The higher the value of R-squared, the better the model fits the data (Draper and Smith, 1998). This is computed mathematically as:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N} (MR_{pre} - MR_{exp,i})^2} \right] \quad (12)$$

SSE is also known as the sum of squares error, which measures the differences between each observation and the mean of the group. It can be used as a measure of variation within a cluster. Mathematically, it can be written as:

$$SSE = \left[\frac{\sum_{i=1}^{N} (S_{exp,i} - S_{pre,i})^2}{N} \right] \quad (13)$$

where *MRpre,i* is the *ith* predicted moisture ratio, *MRexp,i* is the ith experimental moisture ratio, S_{pre} is the predicted sum of squares, S_{exp} is the experimental sum of squares and N is number of observations.

Furthermore, the relationship between the best model(s) constants and the drying conditions of temperature and slice thickness was determined by multiple regression analysis of the combinations of different simple linear, logarithmic and power equations (Menges and Ertekin, 2006; Meisami-asl *et al.*, 2010).

Linear: $Y = a_1 + a_2X$ (14)

Logarithmic: $Y = a_1 + a_2 \ln X$ (15)

Power: $Y = a_1 X^{a_2}$ (16)

Exponential: $Y = a_1 \exp^{a_2 X}$ (17)

Where a_1 and a_2 are the model constants.

Results and Discussion

In order to select a suitable model to predict the dying kinetics of pumpkin, the experimental moisture content data was used. The moisture content data for each drying process was estimated as a non-

Table 2. The statistical comparison of selected models with the Hii *et al.* (2009) model for drying curve prediction

Model name	Slice thickness (mm)	Drying air temperature							
		50 °C		60 °C		70 °C		80 °C	
		R^2	*SSE*	R^2	*SSE*	R^2	*SSE*	R^2	*SSE*
Lewis Model	3	0.9685	0.0562	0.9455	0.0790	0.9506	0.0770	0.9719	0.0546
	5	0.9838	0.0320	0.8425	0.0969	0.9788	0.0384	0.9893	0.0296
	7	0.7796	0.1019	0.7608	0.1139	0.9450	0.0594	0.9453	0.0767
Page Model	3	**0.9974**	**0.0167**	**0.9990**	**0.0112**	**0.9991**	**0.0107**	**0.9979**	**0.0154**
	5	0.9877	0.0286	0.9452	0.0588	**0.9928**	**0.0231**	**0.9962**	**0.0183**
	7	0.9818	0.0302	0.9415	0.0580	0.9888	0.0277	0.9504	0.0762
Modified Page Model	3	0.9685	0.0582	0.9455	0.0822	0.9506	0.0805	0.9719	0.0570
	5	0.9838	0.0329	0.8425	0.0997	0.9788	0.0397	0.9893	0.0309
	7	0.7796	0.1048	0.7608	0.1172	0.9450	0.0614	0.9453	0.0801
Henderson and Pabis Model	3	0.9726	0.0543	0.9484	0.0769	0.9575	0.0746	0.9745	0.0543
	5	0.9841	0.0326	0.8835	0.0857	0.9805	0.0381	0.9899	0.0300
	7	0.7865	0.1032	0.8268	0.0997	0.9479	0.0598	0.9453	0.0801
Logarithmic Model	3	0.9764	0.0523	0.9571	0.0762	0.9631	0.0729	0.9781	0.0528
	5	0.9854	0.0322	0.8849	0.0878	0.9811	0.0389	0.9903	0.0308
	7	0.9353	0.0585	0.8381	0.0994	0.9563	0.0569	0.9612	0.0707
Midilli Model	3	0.9746	0.0543	0.5767	0.2393	0.9606	0.0753	0.9763	0.0550
	5	0.9848	0.0329	0.8837	0.0883	0.9806	0.0394	0.9900	0.0313
	7	0.8599	0.0861	0.8296	0.1020	0.9502	0.0607	0.9598	0.0720
Modified Midilli Model	3	0.9710	0.0558	0.3614	0.2814	0.9545	0.0772	0.4781	0.2459
	5	0.9846	0.0321	0.3767	0.1983	-0.7901	0.3647	0.6935	0.1652
	7	-1.7139	0.3679	-0.7207	0.3144	0.9478	0.0599	0.0296	0.3372
Demir *et al.* Model	3	0.9764	0.0544	0.9571	0.0799	0.9631	0.0768	0.9781	0.0557
	5	0.9854	0.0332	0.8849	0.0907	0.9811	0.0405	0.9903	0.0325
	7	0.9353	0.0605	0.8381	0.1027	0.9563	0.0592	0.9612	0.0745
Two-Term Model	3	0.9726	0.0587	0.9652	0.0516	**0.9963**	**0.0243**	**0.9939**	**0.0293**
	5	0.9861	0.0324	0.9698	0.0464	**0.9960**	**0.0185**	**0.9977**	**0.0159**
	7	**0.9902**	**0.0236**	0.9713	0.0432	**0.9939**	**0.0222**	0.9453	0.0885
Wang and Singh Model	3	0.9035	0.1019	0.9019	0.1103	0.9313	0.0948	0.8953	0.1101
	5	0.8470	0.1012	0.5998	0.1589	0.6475	0.1618	0.7519	0.1486
	7	0.0173	0.2214	0.4232	0.1820	0.4970	0.1858	0.9647	0.0643
Aghbashlo Model	3	0.9890	0.0344	0.9712	0.0598	0.9771	0.0548	0.9899	0.0341
	5	0.9879	0.0285	0.9071	0.0765	0.9873	0.0307	0.9937	0.0237
	7	0.9653	0.0416	0.8942	0.0780	0.9777	0.0391	0.9631	0.0658
Hii *et al.* Model	3	**0.9976**	**0.0182**	**0.9990**	**0.0130**	**0.9996**	**0.0082**	**0.9980**	**0.0180**
	5	**0.9992**	**0.0081**	**0.9922**	**0.008258**	**0.9980**	**0.0138**	**0.9985**	**0.0138**
	7	**0.9972**	**0.0131**	**0.9958**	**0.0040**	**0.9993**	**0.0006**	**0.9985**	**0.0052**

dimensional moisture ratio (Equation 8), due to the assumption of a uniform initial moisture content for all the samples (Equation 2) (Akpinar, 2006; Ronoh *et al*., 2009). The average initial moisture content of the pumpkin samples was found to be 76.4 (% wet basis). Twelve thin layer drying models were compared according to their statistical indicators of R^2 and *SSE* as listed in Table 2. Furthermore, the best model describing the thin layer drying characteristic of pumpkin was chosen as the one with the highest R^2 value and the lowest SSE value.

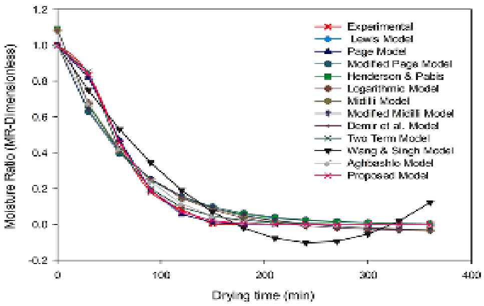
From the results presented in Table 2, the Hii *et al.* (2009) and Page model gave the best fit at all temperature levels for a thickness of 3 mm, while the Hii *et al*. (2009) and the Two Term model showed the best fit at all temperature levels for a thickness of 5 mm and 7 mm based on R^2 and *SSE* values. The R^2 values of the Hii *et al.* (2009) model ranged from 0.9922 to 0.9996 and *SSE* values from 0.0006 to 0.0182. Thus, the Hii *et al.* (2009) model satisfactorily represented the experimental values of the moisture ratio of Pumpkin *(Cucurbita moschata)*. The individual constants of the three best models are presented in Table 3.

The drying experiment at 70°C was an example which showed the highest values of R^2 at all thickness levels. The results of fitting each of the drying models are shown in Figure 1 for thicknesses of 3, 5 and 7 mm respectively. As expected, the drying process took place during the falling rate period. The figure shows

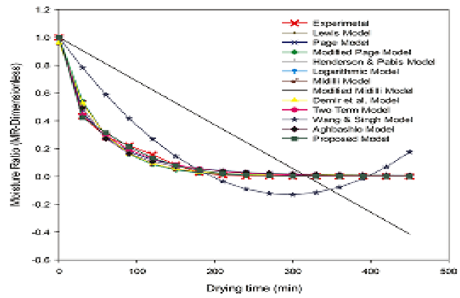
Table 3. Drying kinetic constants of the best models under different drying conditions

Model Name	Temperature (°C)	Model constant		
		3 mm	5 mm	7 mm
Page Model	50	k=0.0009; n=1.6167	k=0.0166; n=0.8775	k=0.3631; n=0.3309
	60	k=0.0001; n=2.0834	k=0.0997; n=0.5563	k=0.1650; n=0.4592
	70	k=0.0003; n=1.9355	k=0.0631; n=0.7346	k=0.1424; n=0.5656
	80	k=0.0014; n=1.6059	k=0.0535; n=0.7910	k=0.0042; n=1.1668
Two-Term Model	50	a=0.5758; k_1=0.0146; b=0.4927; k_2=0.0146	a=0.1167; k_1=194.7387; b=0.8833; k_2=0.0080	a=0.7249; k_1=0.0761; b=0.2756; k_2=0.0035
	60	a=0.5937; k_1=0.0165; b=0.4964; k_2=0.0165	a=0.4531; k_1=57.4963; b=0.5469; k_2=0.0059	a=0.5355; k_1=194.7387; b=0.4645; k_2=0.0049
	70	a=-0.7641; k_1=194.7387; b=1.7641; k_2=0.0243	a=0.3286; k_1=194.7387; b=0.6714; k_2=0.0138	a=0.5182; k_1=194.7387; b=0.4818; k_2=0.0107
	80	a=-0.5620; k_1=194.7387; b=1.5620; k_2=0.0257	a=0.2692; k_1=194.7387; b=0.7308; k_2=0.0168	a=0.0054; k_1=194.7387; b=0.9946; k_2=-0.0095
Hii *et al.* Model	50	a=0.5163; k_1=0.0007; b=0.4676; k_2=0.0007; n=1.6604	a=0.6992; k_1=5.6780E-005; b=0.2994; k_2=1.8957E-006; n=2.3257	a=0.8060; k_1=0.0004; b=0.1940; k_2=4.7488E-007; n=2.4570
	60	a=0.5458; k_1=0.0001; b=0.4496; $k_2$0.0001; n=2.1067	a=0.6317; k_1=2.263; b=0.3683; k_2=1.082E-7; n=2.908	a=0.6775; k_1=2294e+3; b=0.3225; k_2=6.011e-8; n=2.940
	70	a=0.5552; k_1=0.0001; b=0.4437; k_2=3.0573E-005; n=2.3015	a=0.5060; k_1=176.6749; b=0.4940; k_2=0.0008; n=1.5350	a=0.7722; k_1=0.000018; b=0.2278; k_2=2.626e-8; n=3.390
	80	a=0.5158; k_1=0.0013; b=0.4795; k_2=0.0013; n=1.6161	a=0.5158; k_1=0.0013; b=0.4795; k_2=0.0013; n=1.6161	a=0.4673; k_1=0.0014; b=0.4480; k_2=0.0014; n=1.3736

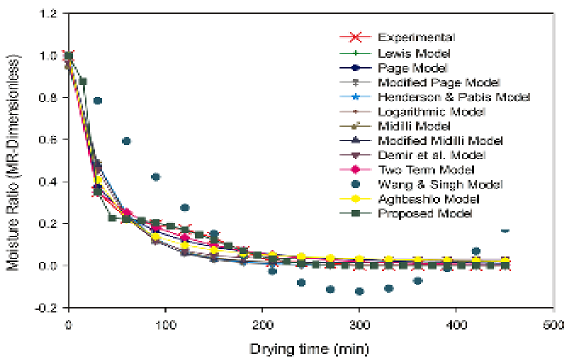
a,b, c are drying model constants; k,k_1,k_2 are kinetic coefficient constants; n is the model number constant



(a) 3mm@70 degrees



(b) 5mm@70 degrees



(c) 7mm@70 degrees

Figure 1. Comparison of models for different thickness levels at 70°C

that the moisture ratio of the samples decreased as the drying time increased. An increase in the sample thickness from 3 to 7 mm as shown in Figure 2a to 2d resulted in an increase in the total drying time of about 60% at 50°C, 50% at 60°C and 30% at 70°C. As the drying temperature was raised to 80°C, there was not much difference in the total drying time at all thickness levels. More so, for example, for a 3 mm sample thickness, a safe moisture content under 2% was reached after 270 minutes when drying at 50°C and 150 minutes at a drying temperature of 80°C. Consequently, a decrease in the drying time of about 44.4% was observed as the temperature increased from 50 to 80°C. Thus, an increase in the drying temperature resulted in a decrease in the drying time. The increase in the total drying time at the lower drying temperatures was as a result of the longer time required for moisture to travel from the internal

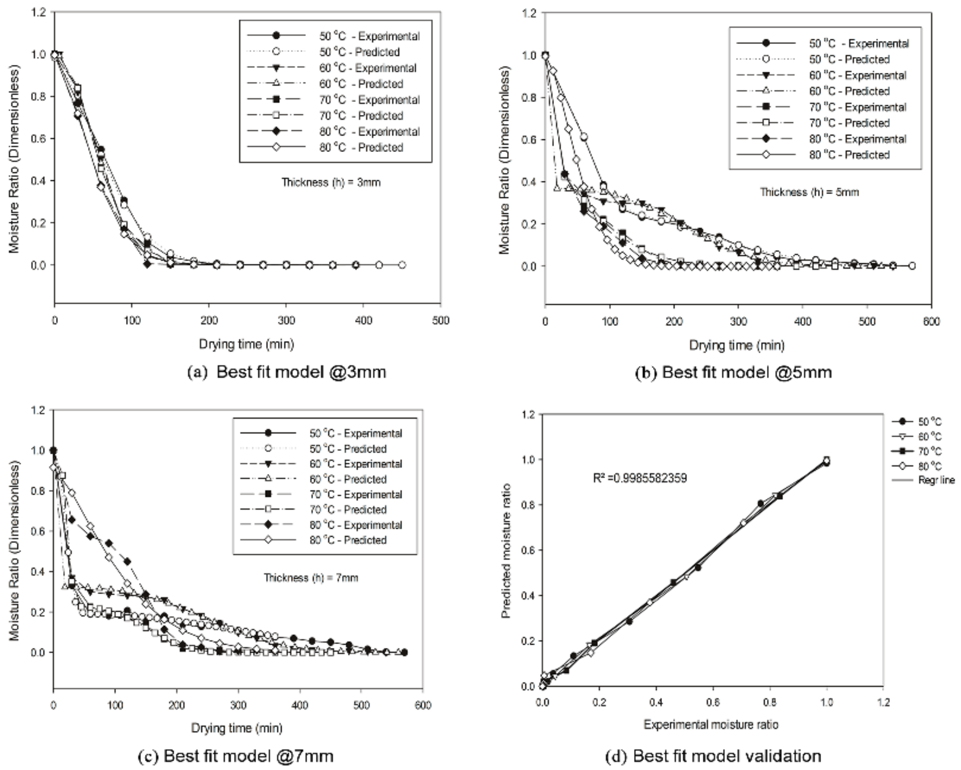


Figure 2. Variations and validation of Hii *et al.* (2009) model under different drying conditions

portion to the surface pores for large thickness slices (7 mm). This compares to the 3 mm slice thickness which had a reduced distance of moisture travel, hence an increase in the drying rate. Similar results have been reported by various authors (Krokida *et al.*, 2003; Arévalo-Pinedo and Murr, 2006; Doymaz, 2007; Jittanit, 2011; Hashim *et al.*, 2014).

Further, the Hii *et al*. (2009) model gave the best fit and consistency for the experimental drying curve under all drying conditions. On the other hand, both the Page and the Two term models showed a good fit to the experimental drying curve under certain conditions.

It is appropriate to note that all the other models closely followed the above mentioned models, except for the Wang-Singh and the modified Midilli models. The behaviour of the Wang-Singh model further showed that the empirical model was not appropriate for predicting the drying behaviour of fruits and vegetables as reported previously by Demir *et al.* (2007).

Furthermore, Figure 2a-c show the variations between the experimentally determined moisture ratio and the Hii *et al*. (2009) model predicted moisture ratio at different drying temperatures for thicknesses of 3, 5 and 7 mm respectively. According to the results, the Hii *et al*. (2009) model predicted drying curve was in conformity with the experimental drying curve under all drying conditions tested.

The effects of temperature and slice thickness on the model constants (Table 3) were also investigated by multiple regression analysis. All possible combinations were regressed (Equation 14 to Equation 17). The multiple combinations of the parameters that gave the highest coefficient of determination (R^2) were eventually included in the final model. Based on this, the relationship between the drying air temperature, slice thickness and the Hii *et al.* (2009) model constants are presented as follows:

$$a = 0.761 + 0.0369h - 0.00530T \qquad R^2 = 0.778 \tag{18}$$

$$b = 0.297 + 0.00454T - 0.0405h \qquad R^2 = 0.832 \tag{19}$$

$$K_1 = 0.1528 exp^{2.6163h} \; r = 0.684 \tag{20}$$

$$K_2 = -0.00501 + 0.000393T - (8.84E-006T^2) + (615E-008T^3)\; R^2 = 0.8970 \tag{21}$$

$$n = -10.581 + 0.427T - 0.00344T^2 \qquad R^2 = 0.679 \tag{22}$$

The multiple combinations of the model constants and the drying conditions of temperature and sample thickness were used to validate the Hii *et al.* (2009) model by comparing the experimental moisture ratio values with the predicted values, and these values fitted along a linear line (Figure 2d). Thus it can be concluded that the Hii *et al.* (2009) model is valid for the predicting the drying kinetics of pumpkin within a drying temperature range of 50°C to 80°C and a thickness range of 3 to 7 mm at an air velocity of 1.16 m/s.

Conclusion

In order to determine a suitable model for predicting the drying kinetics of pumpkin, the drying rate was experimentally investigated using an automated laboratory scale convective hot air dryer at different temperature and material thickness levels. The results of fitting the experimental data to 12 selected thin layer models showed that the Hii *et al.* (2009) model resulted in an excellent fit for all drying temperatures of 50, 60, 70, and 80°C and sample thicknesses of 3, 5 and 7 mm. These results clearly show that the Hii *et al*. (2009) model was most suitable for predicting the drying curve of pumpkin. At all drying temperatures tested, the value of R^2 was higher than 0.99 and the *SSE* value was less than 0.0120. Also, the relationship between the drying conditions and the model constants can be predicted as a function of both polynomial and exponential equations. The Hii *et al.* (2009) model was further validated by comparing the predicted moisture ratio against the experimental moisture figures. The data points were identified to lie on a straight line, showing the suitability of the model in describing the drying kinetics of pumpkin at a temperature range of 50°C to 80°C and a sample thickness of 3 mm to 7 mm. Therefore, the Hii *et al.* (2009), Page and Two term models can be applied in describing the drying behaviour and predicting the drying kinetics of pumpkin *(Cucurbita moschata).*

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