Solar drying of roselle (*Hibiscus sabdariffa* L.): Effects of drying conditions on the drying constant and coefficients, and validation of the logarithmic model

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Abstract: In previous research articles on solar drying of Roselle (karkade), statistical analyses on twelve thin-layer drying models proved the superiority of the logarithmic model. This article investigated the effects of the drying conditions on the drying constant (*k*), coefficients, and drying rate. Validation of the model as well was presented. The rate constant (*k*) was highly affected by the drying temperature. It increased linearly with the temperature. Air velocity to a lesser extent influenced (*k*). Coefficient (*a*) showed a positive relation with both drying-air temperature and velocity. In contrast to coefficient (*a*), parameter (*c*) showed an inverse relation with the drying temperature and a moderate dependence on the air velocity. The drying rate was highly influenced by the drying temperature. Raising the temperature increased the drying rate. Furthermore, two criteria were applied to validate the developed model.

Keywords: roselle, drying constant, coefficients, rate, logarithmic model, model validation

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1 Introduction

Drying is a complex thermal process in which unsteady heat and moisture transfers occur simultaneously (Sahin and Dincer, 2005). Drying not only affects the water content of the product, but also alters other physical, biological, and chemical properties such as enzymatic activity, microbial spoilage, viscosity, hardness, aroma, flavor, and palatability of the foods (Barbosa-Canovas and Vega-Mercado, 1996; Özbek and Dadali, 2007). The drying kinetics of food is a complex phenomenon and requires dependable models to predict the drying behaviour (Kingsly and Singh, 2007). Madamba, Driscoll and Buckle., (1994) stated that mathematical modelling and simulation are often used to study the drying process, validate mechanisms, and optimize the operating parameters and conditions. They are also used for designing new or improving existing drying systems or even for the control of the drying process. The drying constant k is the most suitable value for purposes of design, optimization, and any other situation in which a large number of iterative model calculations are needed. On the other hand, the classical partial differential equations, which analytically describe the two prevailing transport pathways during drying (internal-external and heat-mass transfer), require a lot of time for their numerical solution and thus are not attractive for iterative calculations (Krokida, Foundoukidis and Maroulis, 2004). Many mathematical models have been proposed to describe the drying processes; though, thin-layer drying models are widely used (Doymaz, 2007). The models have to be sufficiently accurate and capable of predicting the water

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removal rates and describing the drying performance of each product under common drying conditions. Semi-theoretical models are derived directly from the general solution of Fick's law by simplification. The empirical models are derived from statistical relations. They directly correlate moisture content with time, having no physical connection with the drying process itself (Babalis et al., 2006). These types of models (empirical and semi-empirical) are valid in the specific ranges of temperature, air velocity, and humidity for which they are developed. These thin-layer drying equations contribute to the understanding of the drying characteristics of agricultural materials (Midilli and Kucuk, 2003), the prediction of the drying time, and the generalization of drying curves (Goyal et al., 2007). In Part I of this work, statistical analysis proved the superiority of the logarithmic model to the others. Consequently, the objectives of the present section are to study the effects of the drying conditions on the drying constant, drying coefficients, and drying rate; and to validate the developed logarithmic model.

2 Mathematical modeling

2.1 Thin-layer drying models

Twelve thin-layer drying models, namely, Newton, Page, Modified Page, Modified Page II, Henderson and Pabis, Modified Henderson and Pabis, Logarithmic, Simplified Fick's diffusion, Two-term, Two-term exponential, Verma et al., and Diffusion approach were presented in Part I. The fitness of each model was statistically measured.

2.2 Moisture content (MC)

Moisture content (MC) on dry basis (%) (Ceylan et al., 2007; Saeed et al., 2008a) is given by:

$$\%\ MC_{db} = \frac{W_w}{W_d} \times 100 \tag{1}$$

2.3 Moisture ratio (MR)

Moisture ratio (MR) (Özbek and Dadali, 2007; Shivhare et al., 2000; Saeed et al., 2008b) is given by:

$$MR = \frac{M - M_e}{M_o - M_e} \tag{2}$$

2.4 Drying rate

Drying rate (Ceylanl. Aktas and Dogˇan, 2007; Doymaz, 2007; Saeed., Sopian and Zainol Abidin, 2008b) is given by:

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{3}$$

2.5 Logarithmic model

Logarithmic model (Togrul and Pehlivan, 2002; 2003; Wang et al., 2007) is given by:

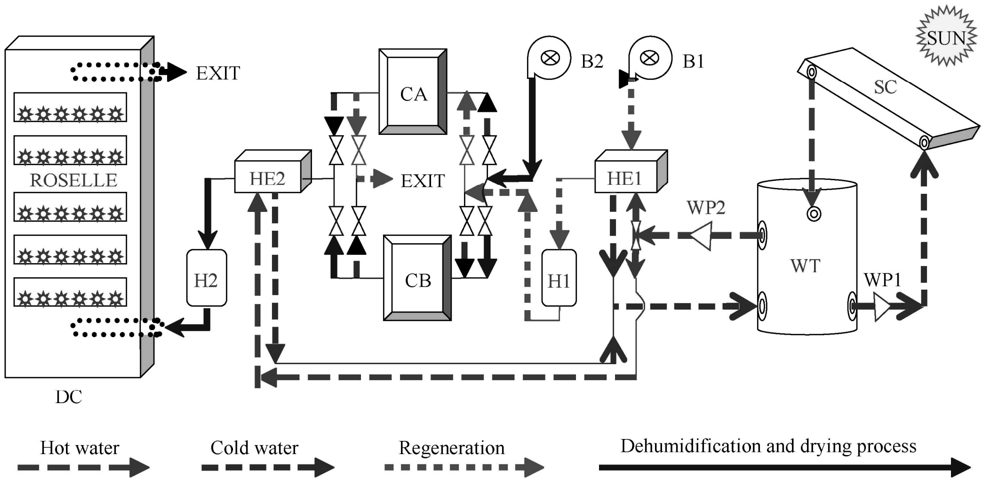
$$MR = \text{a. exp } (-c\ (t/L^2)) \tag{4}$$

3 Drying experiments

Thin-layer drying experiments with Roselle were carried out in a solar-assisted dehumidification drying system designed for drying of agricultural products. A flat-plate solar collector (five panels connected in parallel, 9.86 m^2), auxiliary electric air-heaters, and a cabinet-type drying chamber (100 cm ×100 cm ×240 cm L, *W*, and *H*) were used. The distance between the shelves could be adjusted according to different heights. The configuration of the system's components is shown in Figure 1. Dry and wet bulb temperatures were measured online using T-type thermocouples (-270℃ to 400℃). The solar radiation is measured using Eppley pyranometer (model 8-48 Eppley Radiometer, the Eppley Laboratory, USA). The thermocouples and the pyranometer were connected to a Fuji Micro-jet recorder (type PHA, Fuji Electric Co., Ltd, Tokyo, Japan). A digital thermometer-anemometer-data logger device (model DTA4000, Pacer Industries, Inc., USA), was used to measure the drying air velocity (accuracy of ±0.2% and 1.0% for temperature and air velocity). Water flow rate was measured by Aalborg WF-meters (Aalborg instruments and controls, NY, USA), 3.4-45 L/min, with ±5% accuracy, and 100 psi max working pressure. Two silica gel columns were used alternatively for the dehumidification and regeneration processes (25 cm× 25 cm×125 cm: *L*, *W*, and *H*), the silica gel height is about 85 cm (42.5 kg silica gel/column). A digital balance (Shimadzu; model UX2200H, Capacity of 2200 g, readability of 0.01 g; from Shimadzu Co., Japan) was used to weigh Roselle samples. The data was transferred to personal computer at the 5th minute. A convective oven (Venticell, MMM, Medcener, Germany) was used to determine the initial and final moisture content at 105℃ (Ruiz, 2005). Five average temperatures (35, 45, 55, 60, and 65℃) and two average air velocities (1.5 and 3.0 m/s) were considered. An approx. 10 kg of fresh Roselle's calyces (variety Arab) were used in each run. The seed capsules were removed before commencing the drying experiments. Samples of ≈0.2 kg of whole (uncut) Roselle's calyces were suspended to digital balance. Fresh and dried Roselle are shown in Figure 2. Twelve thin-layer drying models were fitted to the experimental data using non-linear regression based on the minimization of the sum of squares using least squares Levenberg-Marquardt algorithm (Doymaz, 2007; Saeed, Sopian and Zainol Abidin., 2006; 2008a) in order to find the model that best describes the solar-drying behavior of Roselle.

4 Results and discussion

As it was shown in Part I, the drying air temperature was the main factor that affected the solar-drying kinetics of Roselle. The drying air velocity had minor effects on the drying processes compared to that of air temperature. Moreover, results of statistical analysis showed the advantages of logarithmic model in describing the drying behaviour of Roselle. At this stage of the series study, Part II discusses the effects of the drying variables on the drying constant (k), drying coefficients, and the drying rate, as well as, validation of the developed drying model.



B = air blower; CA = column A; CB = column B; DC = drying chamber; H = heater; HE = heat exchanger; SC = solar collector; WP = water pump; WT = water tank

Figure 1 Regeneration (column A) and dehumidification (column B)

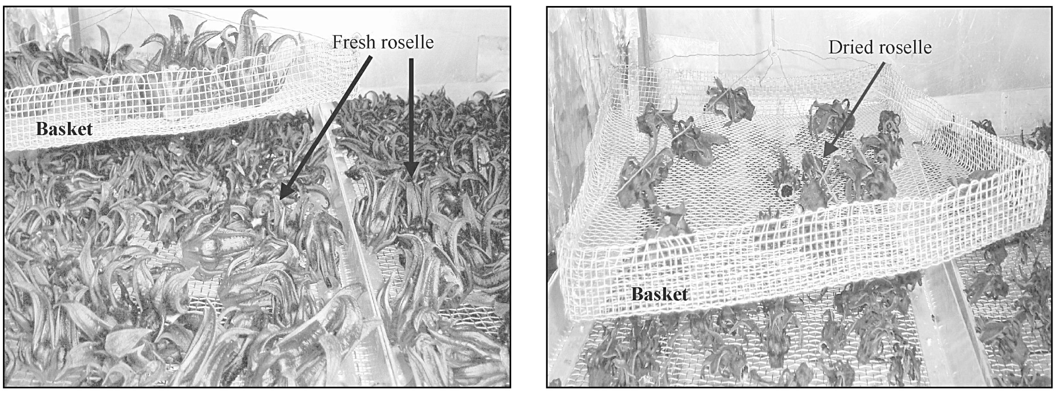


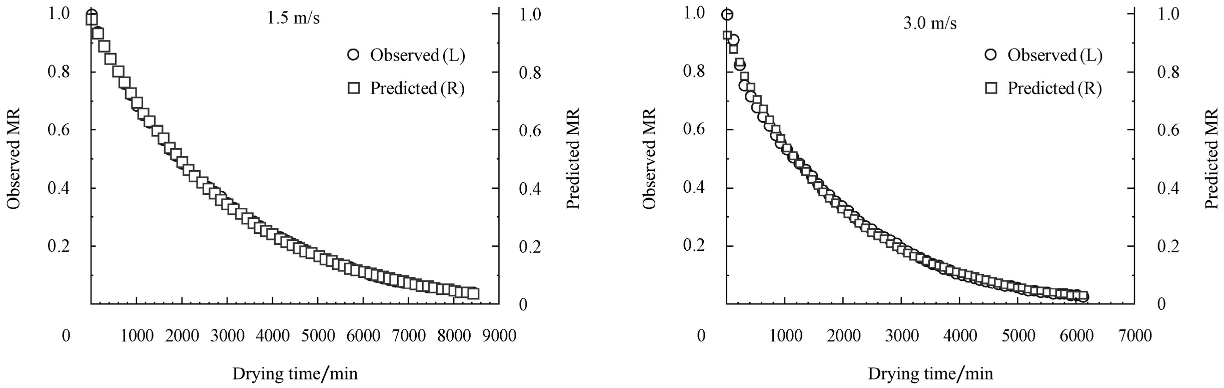
Figure 2 Fresh (left) and dried Roselle (right)

4.1 Observed and predicted moisture content

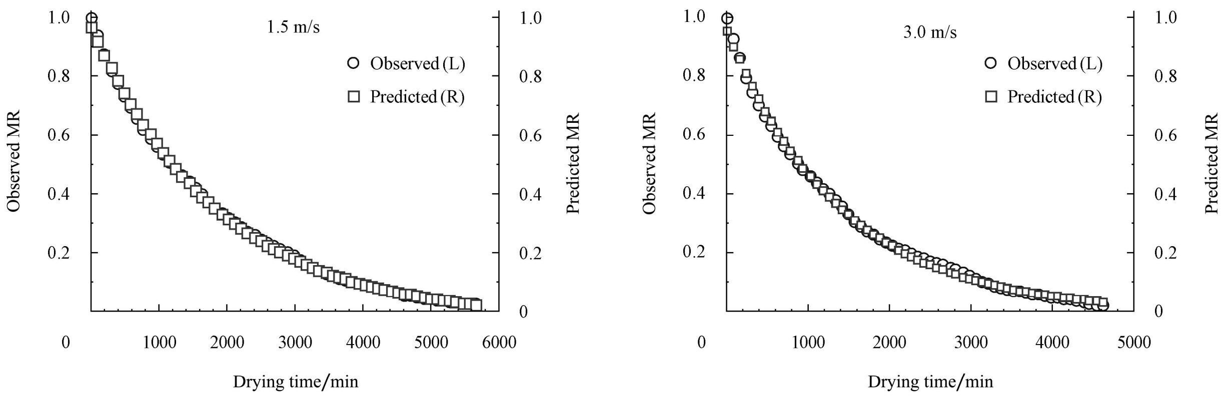
The Roselle's calyces (karkade) were dried from the average initial moisture content of 9.88db to an average final moisture content of 0.19db. Figure 3 presents the plotting of the observed ($MR_{obser.}$) and predicted (MR_{pred}) moisture contents, against the drying time (min), at different drying conditions, where the moisture content is expressed as dimensionless moisture ratio (MR). It was obvious that the logarithmic model predicted well the drying curves of Roselle, as the lines of the observed and predicted data were identical for most of the drying time. The model was found satisfactorily described the drying behaviour of several agricultural products, such as drying of rosehip (Erenturka Gulaboglua and Gultekin., 2004); thin-layer drying kinetics of plum (Goyal et al., 2007); solar drying of shelled and unshelled pistachios (Midilli and Kucuk, 2003); drying of hull-less seed pumpkin (Sacilik., 2007); and thin-layer solar drying of Sultana grapes (Yaldiz, Ertekin and Uzun, 2001).

4.2 Drying constants and coefficients

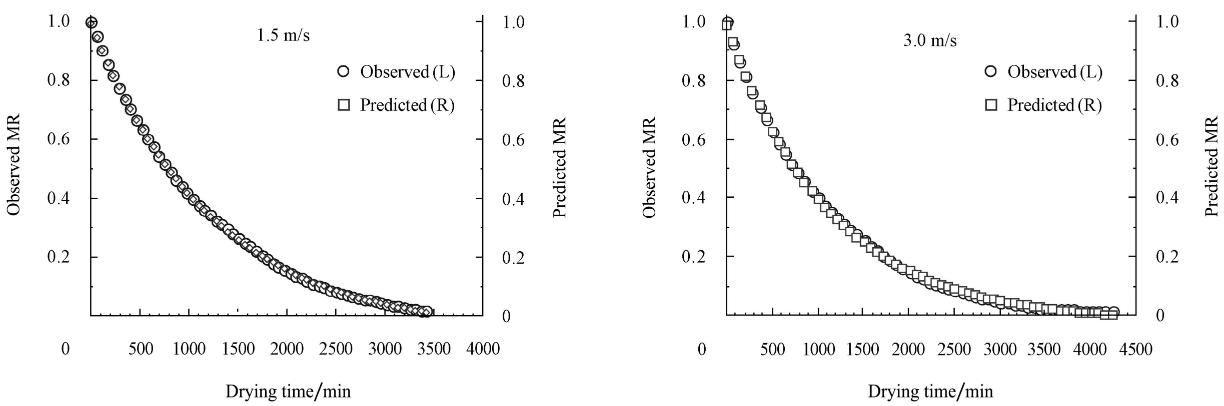
Table 1 presents the constants and coefficients resulted from statistical analyses on twelve drying models. It is showed the average values produced by different models. The average values of the whole models were 0.0020, 0.0008, -0.0025, 1.0173, 0.8938, 0.2263, -0.0241, 0.0305, 0.0013, and -0.8742, for k, k_0, k_1, n, a, b, c, g, h and l, respectively.



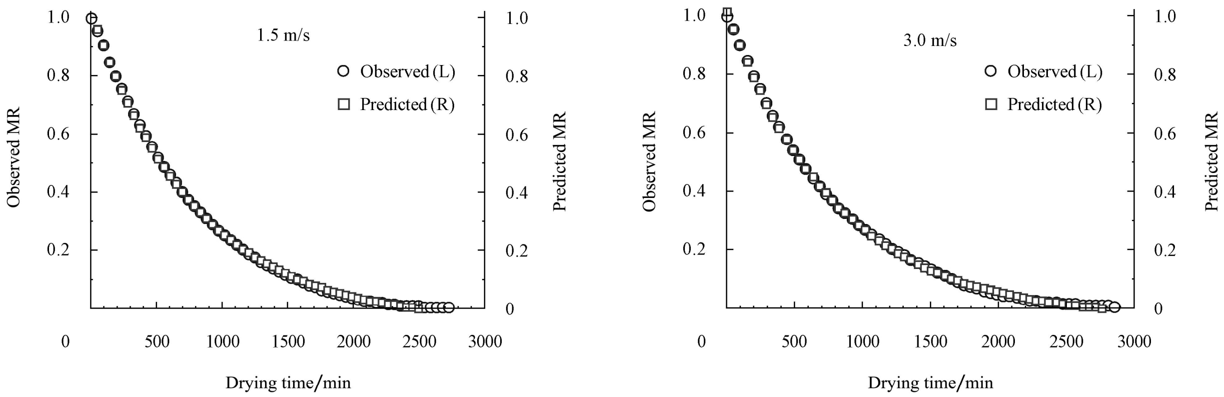
a. 35℃



b. 45℃



c. 55℃



d. 65 ℃

Figure 3 $MR_{obser.}$ and MR_{pred} vs. time at 35℃, 45℃, 55℃ and 65℃

Table 1 Constants and coefficients resulted from statistical analyses of the fitted twelve drying models

Model Name	k	k_0	k_1	n	a	b	c	g	h	l
Newton	0.00085									
Page	0.00077			1.01729						
Modified Page	0.00085			1.01729						
Modified Page II	0.00618			1.01729						-2.08952
Henderson and Pabis	0.00086				0.99581					
Modified Henderson and Pabis	0.00083				0.85311	0.19703	-0.04559	0.00132	0.00132	
Simplified Fick's diffusion	0.00078				1.00873		-0.02674			
Logarithmic					0.99581		0.00013			0.34112
Two-term		0.00083	-0.00252		0.71980	0.28601				
Two-term exponential	0.00275				1.08141					
Verma et al.	0.00082				0.97594			0.05968		
Diffusion approach	0.00546				0.52016	0.19598				
Average	0.00201	0.00083	-0.00252	1.01729	0.89385	0.22634	-0.02407	0.03050	0.00132	-0.87420

Where, k_0, k_1, n, a, b, c, g, h and l are empirical coefficients and k is the drying constant.

The values of (k), (a), and (c) resulted from fitting of logarithmic model, at different drying air conditions, were presented in Table 2. The average values of the drying constant k and coefficients (a) and (c) obtained from logarithmic model were 0.000783, 1.008733 and -0.026738, respectively. The values are in agreement with other researcher's findings, e.g. drying of kiwi: a = 1.10600, c=-0.07579; avocado: a=1.06874, c= -0.06075; banana: a=0.98749, c=-0.02023 (Ceylanl et al., 2007). However, researches with higher values included solar drying of hull-less seed pumpkin: k = 0.1508, a = 0.9088, c = 0.0939 (Sacilik et al., 2007); solar drying of apricots: k=0.02399, a=1.0185; c=-0.09565 (Togrul and Pehlivan, 2002); drying of single apricot: k = 0.0035, a = 1.0984, c= -0.0926 (Togrul and Pehlivan, 2003); drying of figs: average values k= 0.049425, a= 1.021977, c= -0.03416 (Xanthopoulos et al., 2007); drying of apple pomace k = 0.00298, a=2.112955, c=-1.068815 (Wang et al., 2007).

Table 2 Drying constant k, coefficient (a) and (c) resulted from fitting f logarithmic model at different drying conditions

T/℃	Air vel./m • s^{-1}	k	a	c
35	1.5	0.000338	0.999396	-0.018150
	3.0	0.000516	0.939910	-0.010500
45	1.5	0.000532	0.993992	-0.025240
	3.0	0.000713	0.959027	-0.001660
55	1.5	0.000803	1.051420	-0.055990
	3.0	0.000873	1.011140	-0.023700
65	1.5	0.001253	1.064960	-0.044690
	3.0	0.001232	1.050020	-0.033970

4.3 Effects of drying conditions on the drying constants and coefficients

4.3.1 Drying constant (k)

Drying constant data in the literature are scarce due to the variation in composition of the materials and the variation of the experimental conditions (Krokida

Foundoukidis and Maroulis, 2004). The drying-air temperature greatly influenced (p = 0.004) the drying rate constant.

Similar results were reported by others (Tarigan et al., 2007). As the drying temperature is raised from 35℃ to 65℃, the values of the drying constant were increased from 4.27×10^{-4} to 1.24×10^{-3}. On the other hand, drying air velocity has less influence on the drying constant. Similar results were found by Pangavhane，Sawhney and sarsavadia, (1999), and Rapusas and Driscoll, (1995).

Figure 4a shows plotting of the drying constant against the drying-air temperature at different air speeds. The linearity of (k) is obvious with the drying air temperature (r^2= 0.965). Several investigators correlated the drying constant (k) with the air temperature (Panchariya Popovic and Sharma, 2002; Simal et al., 2005; Togrul and Pehlivan, 2002). The results of correlation of (k) with the temperature were given as follows:

$$k_{1.5} = -0.00902 + 0.00003016T \quad r^2 = 0.964 \qquad (5)$$

$$k_{3.0} = -0.00663 + 0.00002308T \quad r^2 = 0.966 \qquad (6)$$

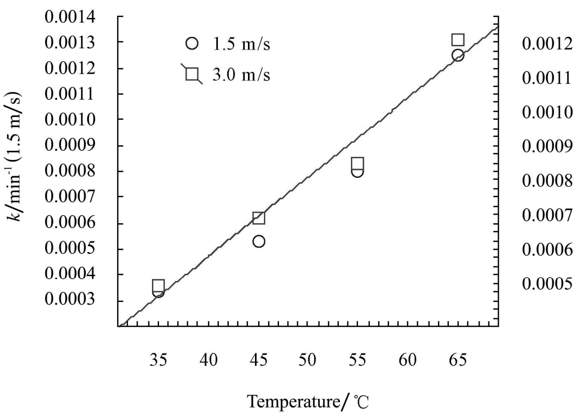


Figure 4a Drying constant (k) vs. temperature (°C)

Furthermore, the two sets of the data points representing the values of (k) at 1.5 m/s and 3.0 m/s air velocities coincide each other indicating that the effect of air velocity is small (p =0.697) compared to that of air temperature. However, (Jayas et al., 1991) concluded that air velocity significantly affected (k). Nevertheless, drying at 3.0 m/s resulted in slightly higher values of (k) than that of 1.5 m/s (Figure 4a).

Moreover, two Arrhenius models were used in the literature to relate the dependence of the drying rate constant on the drying-air temperature. According to Azzouz et al. (2002), the drying constant is a function of the absolute temperature of the grain, and it could be described with an Arrhenius type of equation. This relationship is represented by the following equations:

$$k = k_0 \exp(-E / R \cdot T) \qquad (7)$$

$$k = A \exp(-B / T) \qquad (8)$$

Where in Equation (7) (Gupta et al., 2002) and Equation (8) (Shivhare et al., 2000, Tarigan et al., 2007): k_0, E, R, A, and B are coefficients, k is the drying constant (min^{-1}), and T is the temperature (K). Figures 4b and 4c show the Arrhenius plots relating the drying constant and the inverse of the absolute temperature. The fitting was performed using Equation (7) and (8), respectively:

$$k = (83.2301) \exp(-(0.0000644)/(0.0000000171)T) \quad (R^2 = 0.995) \qquad (9)$$

$$k = (0.00000000751) \exp(-(-0.03551)/T) \quad (R^2 = 0.997) \qquad (10)$$

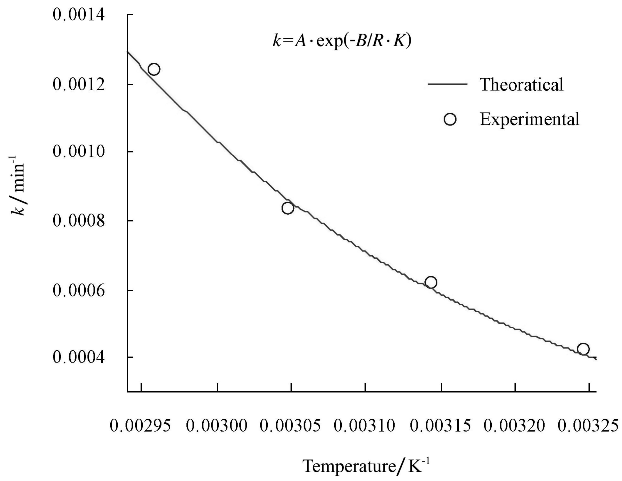


Figure 4b k vs. temperature (K): eq. (4)

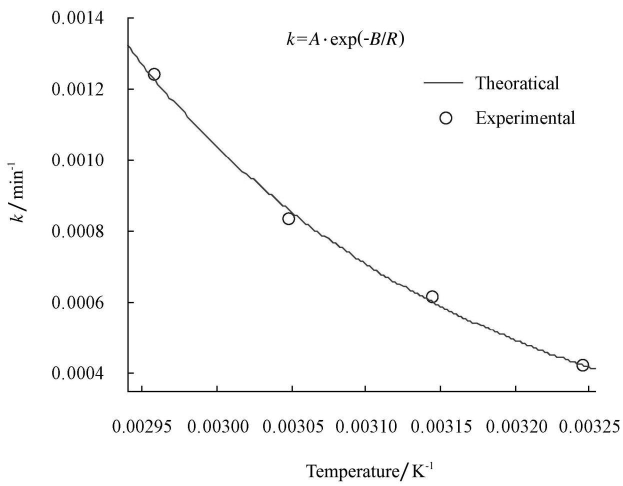


Figure 4c k vs. temperature (K): eq. (5)

The values of R^2 from Equation (9) and (10) are higher compared to previous works on different products (drying of unshelled kernels of candlenuts: stored = 0.976 and fresh = 0.98 (Tarigan et al., 2007).

4.3.2 Coefficient (*a*)

The coefficient (*a*) was found to have a positive relationship with the drying temperature; it increased linearly with the drying temperature (p=0.093). Figure 5 shows how the drying conditions affect coefficient (*a*). The equations of straight-line fitting generated high value for r^2 = 0.973 at air velocity of 3.0 m/s compared to 0.831 for 1.5 m/s. This indicated that the linearity was enhanced with higher air velocity. The equations are given as:

$$a_{1.5} = 0.90038200+0.00254120T\ (r^2 = 0.831) \quad (11)$$

$$a_{3.0} = 0.79880275+0.00382443T\ (r^2 = 0.973) \quad (12)$$

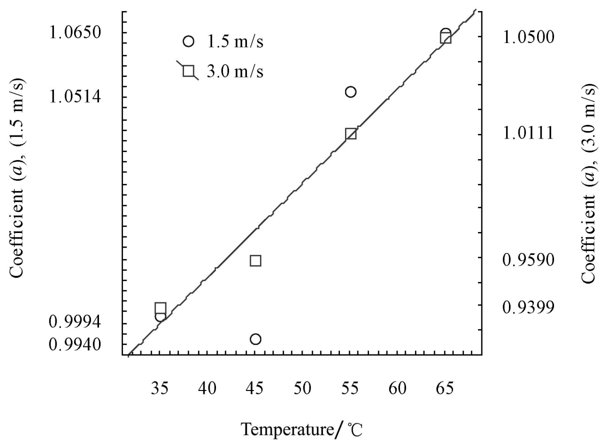


Figure 5 Coeff. (*a*) vs. drying conditions

4.3.3 Coefficient (*c*)

Coefficient (*c*) generally showed an inverse relation with the drying temperature. Figure 6 presents the plotting of the values of coefficient (*c*) with temperature at different air velocities. The linear fitting to the values resulted in the following equations:

$$c_{1.5} = 0.0191675-0.0011037T \quad (r^2 = 0.670) \quad (13)$$

$$c_{3.0} = 0.0287675-0.0009245T \quad (r^2 = 0.701) \quad (14)$$

Compared to (*k*) and (*a*), parameter (*c*) showed a moderate dependence on both drying-air temperature (r^2=0.778 and p=0.258) and air velocity (r^2=0.670 at 1.5 m/s and r^2 =0.701 at 3.0 m/s, with p=0.150). The three parameters, i.e. k, a, and *c* of the logarithmic model did not behave in the same manner, which agreed with the conclusion by Jayas et al. (1991) that it was not necessary that all the coefficients increase or decrease at the same time.

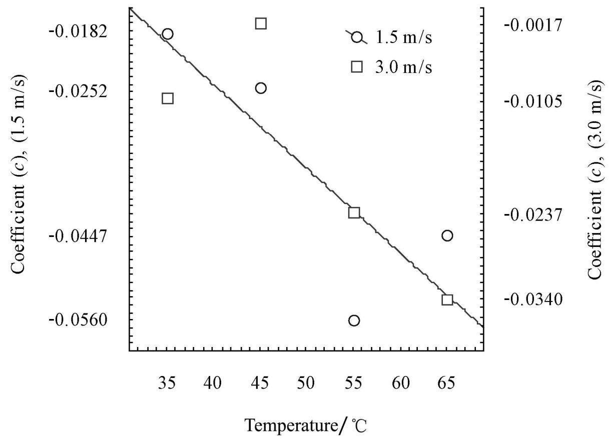
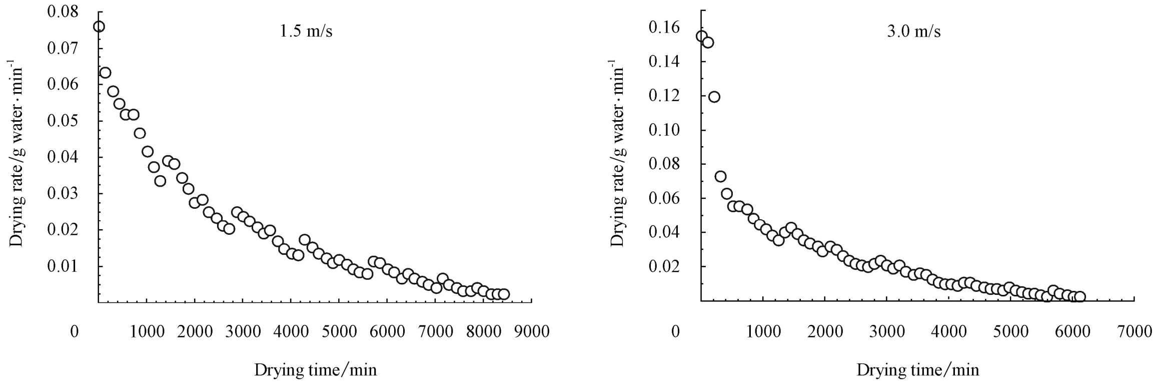


Figure 6 Coeff. (*c*) vs. drying conditions

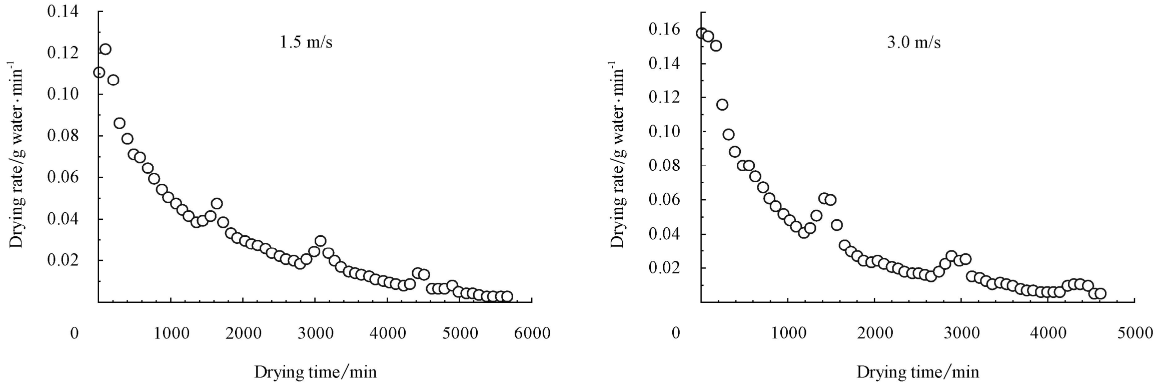
4.3.4 Drying rate

The drying rate (DR) of Roselle was highly influenced by drying air temperature. It increased with the increment of the drying-air temperature, to which similar results were observed by others (Saeed，Sopian and Zainol Abidin., 2008a; 2008b). The reason is that the increase of the heat supply rate to the product accelerates water migration inside the product at higher temperature (Belghit Kouhila and Boutaleb., 2000; Kouhila et al., 2002; Krokida Foundoukidis and Maroulis., 2004). In addition, several authors reported that drying rates increase with the increment of the temperature for drying of various products such as pumpkin (Akpinar Midilli and Bicer., 2003); okra (Doymaz, 2005); pumpkin slices (Doymaz, 2007); eggplant (Ertekin and Yaldiz, 2004) and garlic (Madamba Driscoll and Buckle., 1996). It is observed that, during the drying processes some crops have a tendency to form dry surface layers (Ekechukwua and Nortonb, 1999) which are impervious to subsequent moisture transfer if the drying is very rapid. Janjai and Tung (2005) reported that Roselle's calyxes have a natural wax coating on their surfaces. This wax prevents most of the migration of moisture from the inside into drying-air. After the surface is dried and the wax is broken, the moisture from inside can be easily released when the drying rate starts to increase. Furthermore, at the end of the drying, the drying rate is very slow because most of water to be evaporated is in the monolayer or multi-layer water form with a high binding energy. Figure 7 presents the drying rates of Roselle at different drying conditions. The drying rates at 35℃ and 45℃ showed a “zigzag-like” form. This might be attributed to the subsequent development and cracking of the hard layers. Besides, the fluctuation of the dryer’s inlet air properties coincides with the alternative dehumidification and regeneration processes of the silica gel columns.

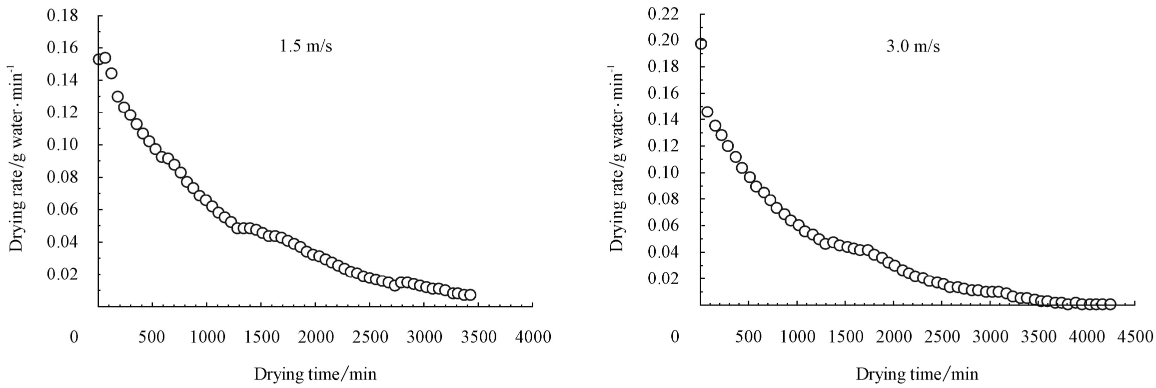
For drying at higher temperatures (55℃ and 65℃), the phenomenon occurred at shorter time intervals and the data points appear nearly as continuous lines. High temperature increases the heat content, as well as the saturation humidity of the drying air. Moreover, at higher temperatures drying rates increased because of increasing equilibrium concentration of the water vapour on the surface of the drying material (Togrul and Pehlivan, 2003). However, very high temperatures or drying air rates may cause some shrinkage and deterioration of the material’s skin. Moreover, researchers generally agreed that air velocity during thin-layer drying of grains has minor effect on the drying rate (Iguaz et al., 2003; Jayas et al., 1991).



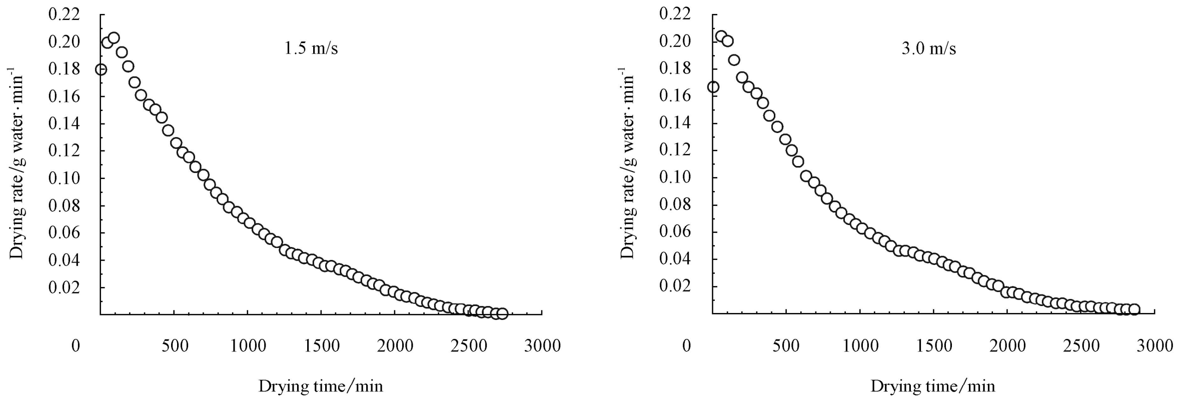
a. 35℃



b. 45℃



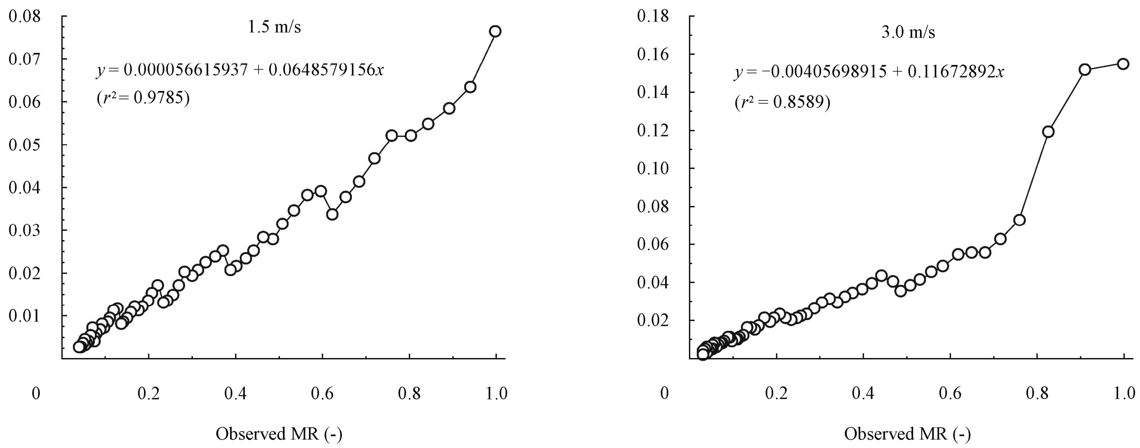
c. 55℃



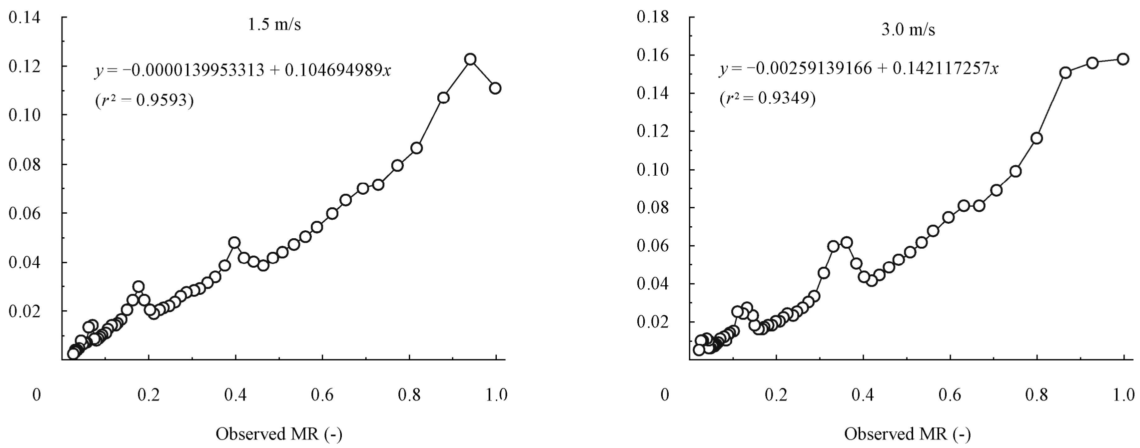
d. 65℃

Figure 7 Drying rate (DR) at 35℃, 45℃, 55℃ and 65℃

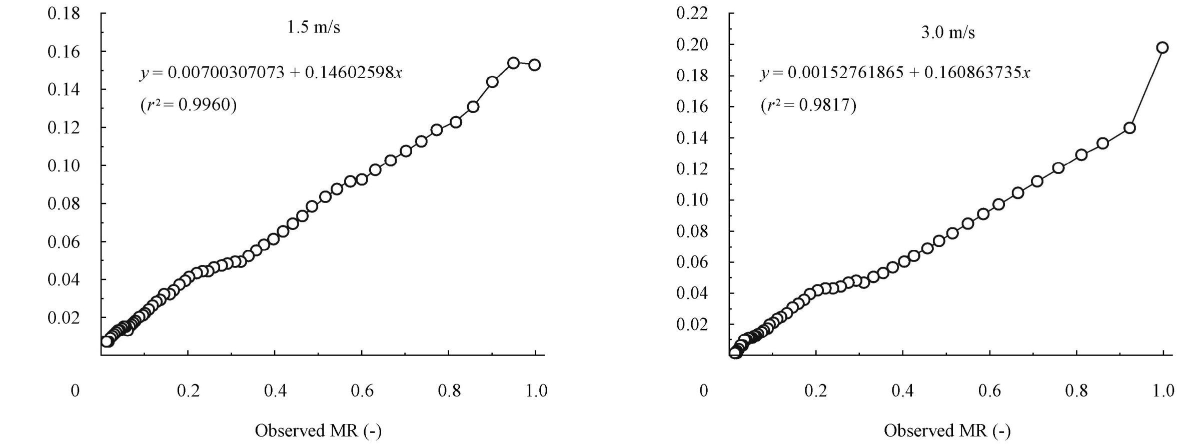
Figure 8 shows the plotting of the drying rate (DR) vs. MR at different drying conditions. Higher drying rates occurred at high moisture levels (Guiné et al., 2007). The rates, then, tend to approach approximately zero at the end of the process, since at this stage, the moisture content diminishes and the water removal becomes negligible. Higher temperatures of the drying-air produced higher drying rates and hence the moisture ratio is decreased (Belghit Kouhila and Boutaleb, 2000; Kouhila et al., 2002). On the other hand, the drying time decreased dramatically with the air temperature (Goyal et al., 2007; Saeed, Sopian and Zainol Abidin., 2006), as the capacity of air to remove moisture increases with its temperature (Sigge, Hansmann and Joubert, 1998).



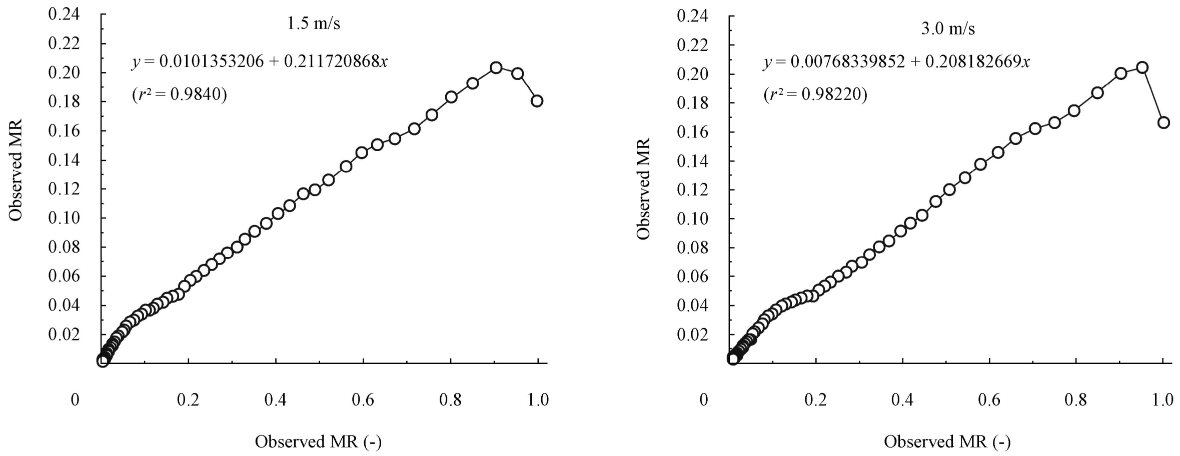
a. 35℃



b. 45℃



c. 55℃



d. 65℃

Figure 8 Drying rate vs. MR at 35℃, 45℃, 55℃ and 65℃

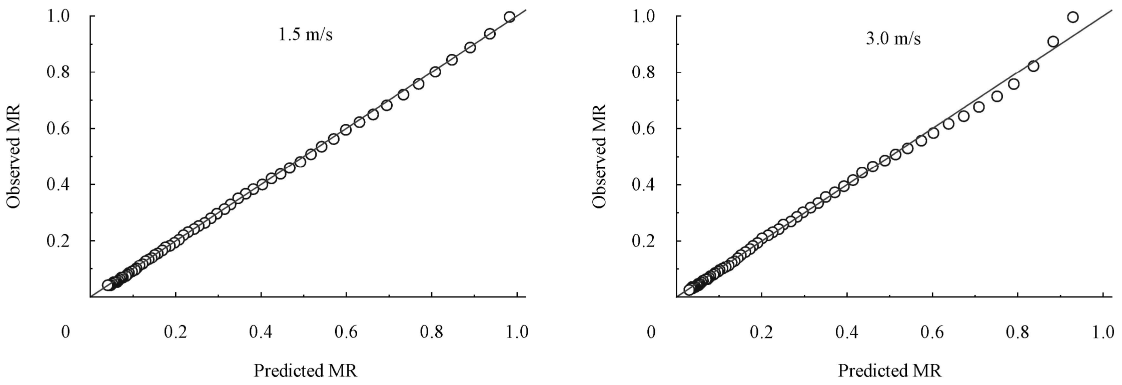
The drying rate increased with the increment of the temperature from 35℃ to 65℃, as the main factor influencing the drying kinetics is the drying-air temperature (Belghit., Kouhila and Boutaleb., 2000; Saeed, Sopian and Zainol Abidin, 2006; 2008a; Sigge Hansmann and Joubert, 1998). This is because that drying at high temperature led to high moisture diffusivity and provided a large water vapour pressure deficit, which is one of the driving forces for the drying process (Methakhup, Chiewchan and Devahastin, 2005; Prabhanjan, Ramaswamy and Raghavan, 1995). In addition, the soft heating of the product accelerates the water migration inside the product (Kouhila et al., 2002).

4.4 Validation of the model

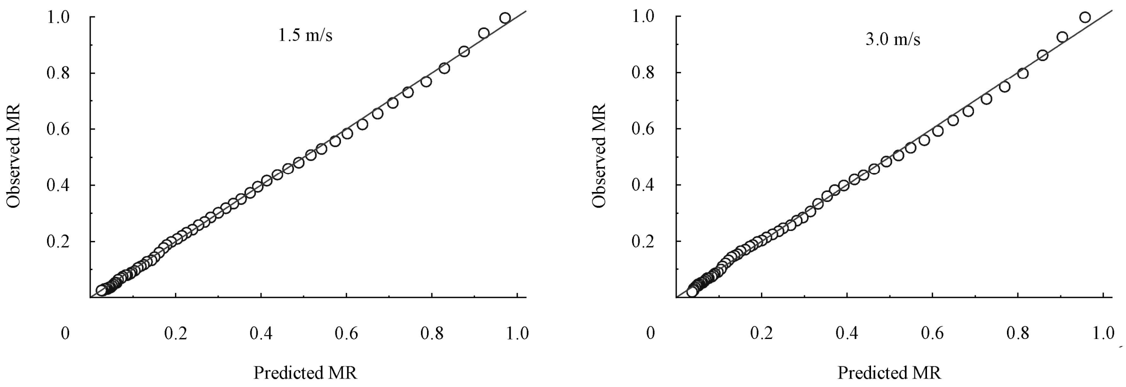
Two criteria were applied to validate the developed logarithmic drying model. The first one is the plotting of the predicted moisture ratio (MR_{pred}) against the observed moisture ratio (MR_{obser}) (Saeed, Sopian and Zainol Abidin., 2006; 2008b; Simal et al., 2005; Togrul and Pehlivan, 2003). Figure 9 shows the predicted moisture contents (by the logarithmic model) versus observed moisture contents at different drying conditions. The results showed smooth and a good scatter of the data-points around the fitted straight lines. This confirmed the validity of the logarithmic model in estimating the moisture content of the Roselle during the drying processes. Moreover, the values of the correlation coefficient (r^2) obtained from the plotting of the MR_{exp} and MR_{pred} at different drying conditions were given in Table 3, with an average of 0.999.

Table 3 Values of (r^2) from plotting of observed MR vs. predicted values

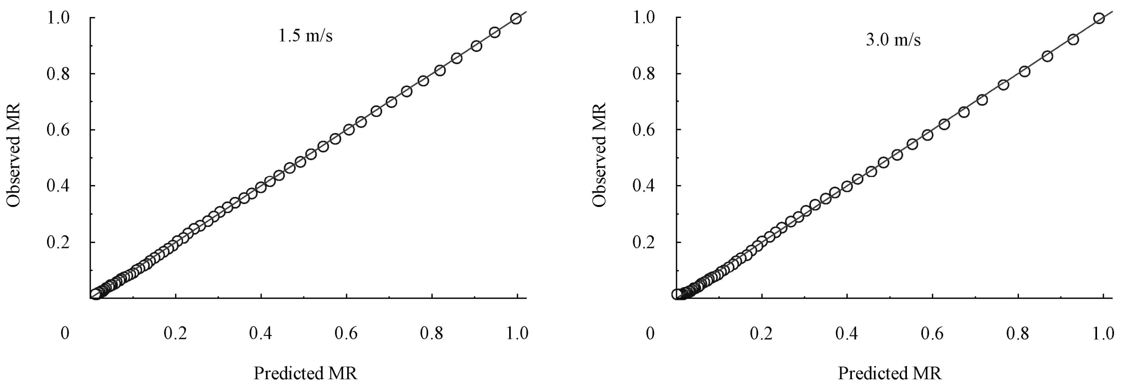
35℃		45℃		55℃		65℃	
1.5 m/s	3.0 m/s	1.5 m/s	3.0 m/s	1.5 m/s	3.0 m/s	1.5 m/s	3.0 m/s
0.9997	0.9968	0.9990	0.9979	0.9999	0.9994	0.9995	0.9997



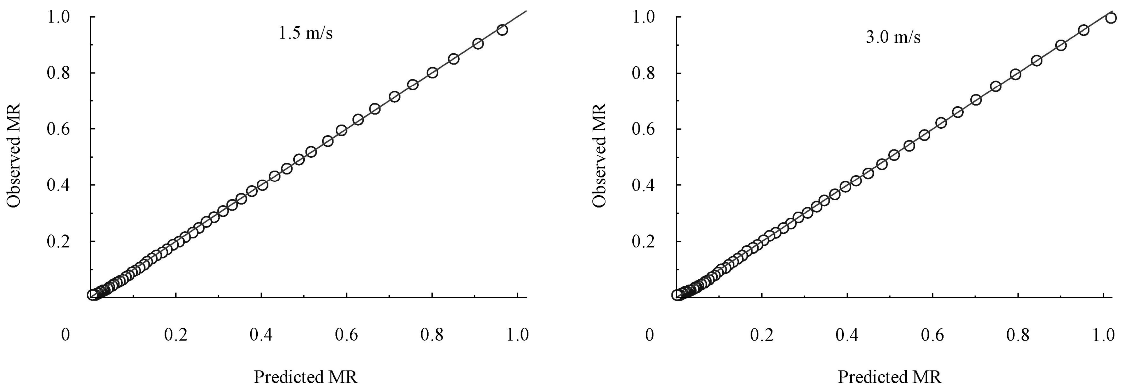
a. 35℃



b. 45℃



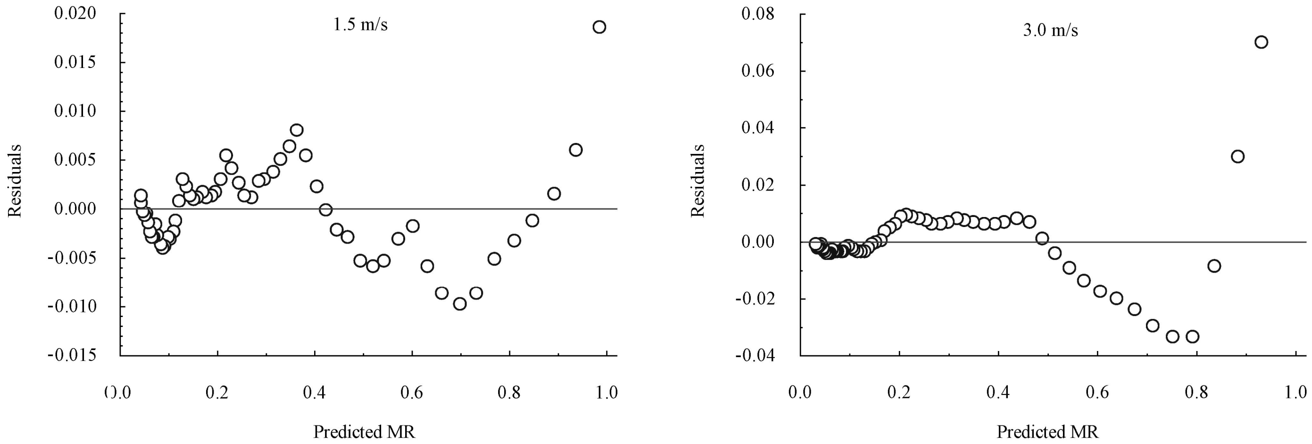
c. 55℃



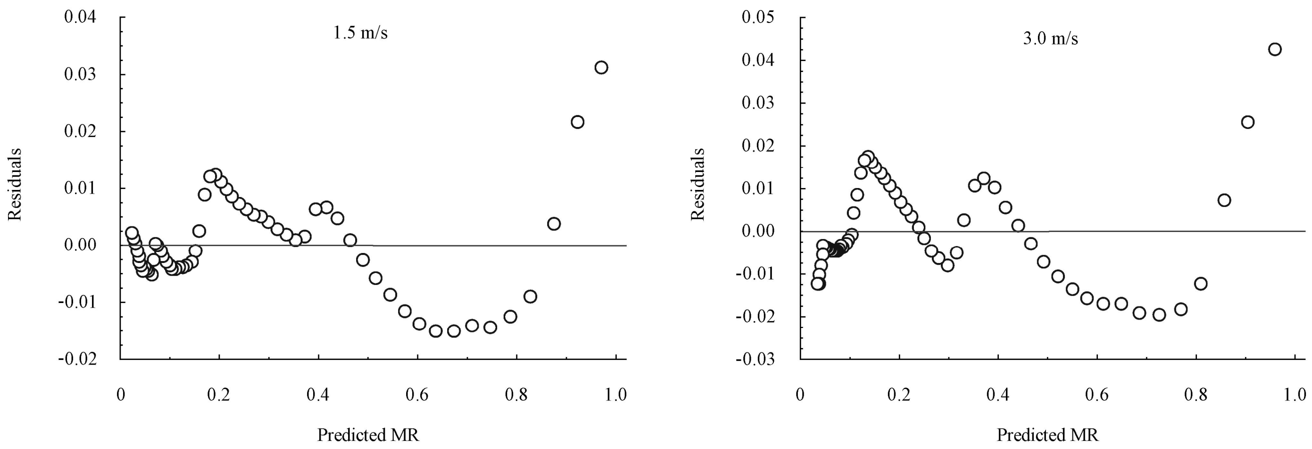
d. 65℃

Figure 9 MR_{exp} vs. MR_{pred} at 35℃, 45℃, 55℃ and 65℃

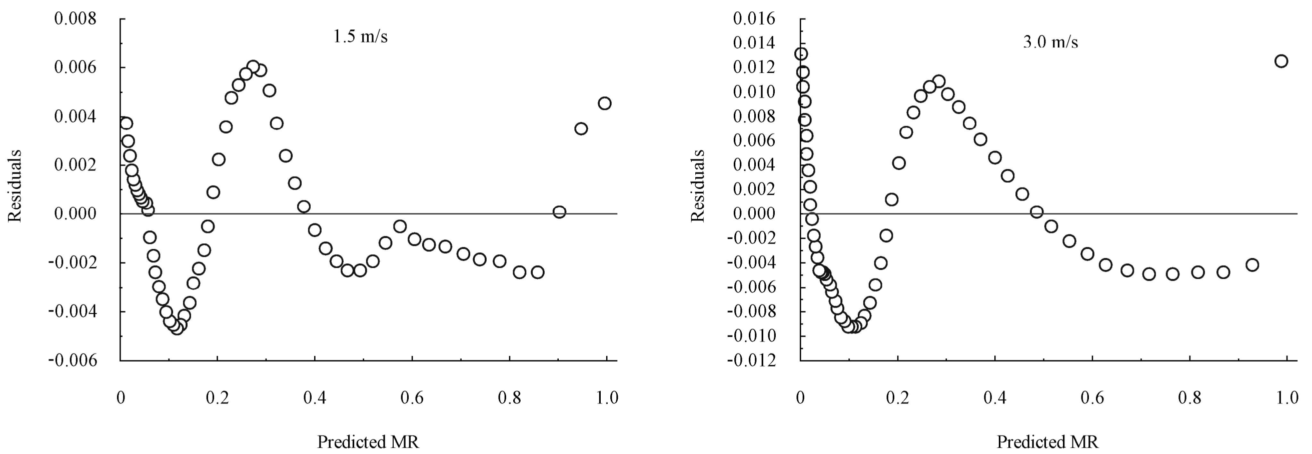
The second criterion used to validate the logarithmic model is to plot the residual versus the predicted values by the model (Keller, 2001; Spatz, 2001). Figure 10 shows the plotting of the residual and predicted values (MR_{pred}) resulted from fitting of the logarithmic model to the experimental data. The residual were randomly scattered around "zero-line" indicating that the model describes the data well. There was no systematically positive or negative pattern of the residual data for much of the data range, and the data points were not skewed. These signify the adequate suitability of the logarithmic model to describe the drying behaviour of the Roselle.



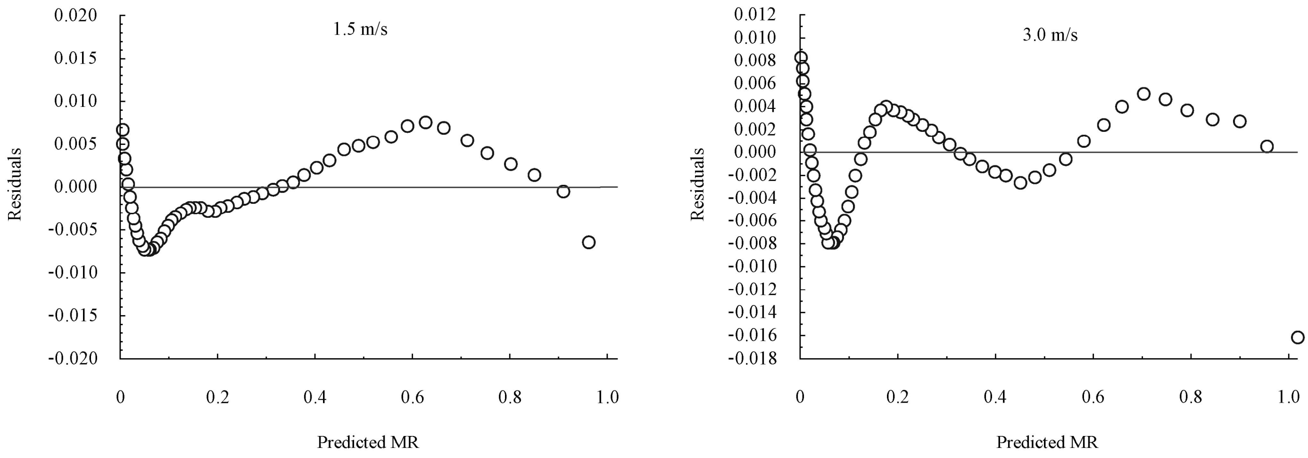
a. 35℃



b. 45℃



c. 55℃



d. 65℃

Figure 10 Residuals vs. MR_{pred} at 35℃, 45℃, 55℃ and 65℃

The moisture ratio (MR) can be expressed as a function of the drying constant and coefficients as follows:

$$MR\ (a,k,c,t) = \frac{M}{M_0} = a.\ \exp(-kt) + c \qquad (15)$$

Where, the parameters can be given as follows:

a = 0.849592375 + 0.003182815T (r^2 = 0.929)

k = -0.0005485 + 0.00002662T (r^2 = 0.966)

c = 0.0239675−0.0010141T (r^2 = 0.778)

The parameters can be used, satisfactorily, to estimate the moisture content of Roselle at any time during the drying process.

5 Conclusions

The objectives of part II of the work on solar drying of Roselle, were to study the effects of the drying conditions on the drying constant, drying coefficients, and drying rate; and to validate the developed logarithmic model. In part I, statistical analysis proved the superiority of the logarithmic model to the others. The drying air temperature highly influenced the drying rate constant (p=0.004). Higher values were obtained at higher temperatures. The linearity of (k) is obvious with the drying air temperature (r^2 = 0.965). Compared to the effect of drying temperature, air velocity had slightly influenced rate constant (p=0.697). The coefficient (a) showed a positive relation with drying temperature (p=0.093). Parameter (c) showed a moderate dependence on both drying-air temperature (r^2=0.778 and p=0.258) and air velocity (r^2=0.670 at 1.5 m/s and r^2=0.701 at 3.0 m/s, with p=0.150). The average values of the drying constant (k) and coefficients (a) and (c) obtained from logarithmic model were 0.000783, 1.008733 and -0.026738, respectively. The drying rate of Roselle was highly influenced by the drying air temperature. Higher temperatures resulted in higher drying rate. Air velocity had minor effect on the drying rate compared to that of the air temperature. Two criteria in the form of plotting were applied to validate the developed logarithmic model. Plotting of the experimental data against predicted values and the residual versus predicted values confirmed the sufficient suitability of the model in predicting the drying characteristics of the Roselle under the studied drying conditions.

Nomenclature

a	coefficient in drying models	k_0	constant in equation (4)
A	constant in equation (5)	k_1	coefficient in drying models
$a_{1.5}$	coefficient (a) at 1.5 m/s	$k_{1.5}$	coefficient (k) at 1.5 m.s^{-1}
$a_{3.0}$	coefficient (a) at 3.0 m/s	$k_{3.0}$	coefficient (k) at 3.0 m/s
b	coefficient in drying models	l	coefficient in drying models

c	coefficient in drying models	MC_{db}	moisture content dry base ($g_w \cdot g_{dm}^{-1}$)
B	constant in equation (5)	M_e	equilibrium moisture content
$c_{1.5}$	coefficient (c) at 1.5 m/s	M_o	initial moisture content ($g_w \cdot g_{dm}^{-1}$)
$c_{3.0}$	coefficient (c) at 3.0 m/s	MR	moisture ratio (-)
DR	drying rate ($g_w \cdot g_{dm}^{-1} min^{-1}$)	M_t	moisture content at time t ($g_w \cdot g_{dm}^{-1}$)
E	constant in equation (4)	M_{t+dt}	moisture content at ($t+dt$)
exp	exponent	n	coefficient in drying models
g	coefficient in drying models	R	constant in equation (4)
h	coefficient in drying models	r^2	correlation coefficient
k	drying constant (min^{-1})	t	drying time (min)
k_o	coefficient in drying models	T	temperature (°C)
	Subscripts		
1.5	air velocity (m/s)	exp	experimental
3.0	air velocity (m/s)	pred	predicted
d	dry matter (g)	obser.	observed
db	dry base (-)	w	water (g)

References

Akpinar, E., A. Midilli, and Y. Bicer. 2003. Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modeling. Energy Conversion Management, 44: 1689－1705.

Azzouz, S., A. Guizani, W. Jomaa, and A. Belghith. 2002. Moisture diffusivity and drying kinetic equation of convective drying of grapes. Journal of Food Engineering, 55:323－330.

Barbosa-Canovas, G. V. and H. Vega-Mercado. 1996. Dehydration of Foods. 1st. ed. Chapman and Hall, New York.

Belghit, A., M. Kouhila, and B. C. Boutaleb. 2000. Experimental study of drying kinetics by forced convection of aromatic plants. Energy Conversion Management, 44: 1303－1321.

Ceylan, I., M. Aktas, and H. Dogˇan, 2007. Mathematical modeling of drying characteristics of tropical fruits. Applied Thermal Engineering, 27: 1931－1936.

Doymaz, I. 2007. The kinetics of forced convective air-drying of pumpkin slices. Journal of Food Engineering, 79: 243－248.

Doymaz, I. 2005. Drying characteristics and kinetics of okra. Journal of Food Engineering, 69: 275－279.

Ekechukwua, O. V., and B. Nortonb. 1999. Review of solar-energy drying systems II: an overview of solar drying technology. Energy Conversion and Management, 40: 615－655.

Erenturka, S., M.S. Gulaboglua, and S. Gultekin. 2004. The thin-layer drying characteristics of rosehip. Biosystems Engineering, 89(2): 159－166.

Ertekin, C., and E. Yaldiz. 2004. Drying of eggplant and selection of a suitable thin layer drying model. Journal of Food Engineering, 63: 349－359.

Goyal, R. K., A. R. P. Kingsly, M. R. Manikantan, and S. M. Ilyas. 2007. Mathematical modeling of thin layer drying kinetics of plum in a tunnel dryer. Journal of Food Engineering, 79: 176－180.

Guiné, R. P. F., D. M. S. Ferreira, M. J. Barroca, and F. M. Goncalves. 2007. Study of the drying kinetics of solar-dried pears. Biosystems Engineering, 98: 422－429.

Gupta, P., J. Ahmed, U. S. Shihare, and G. S. V. Raghavan. 2002. Drying characteristics of red chili. Drying Technology, 20(10): 1975－1987.

Iguaz, A., M. B. San Martin, J. I. Mate, T. Fernandez, and P. Virseda. 2003. Modeling effective moisture diffusivity of rough rice (Lido cultivar) at low drying temperatures. Journal of Food Engineering, 59: 253－258.

Janjai, S., and P. Tung. 2005. Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices. Renewable Energy, 30: 2085－2095.

Jayas, D. S., S. Cenkowski, S. Pabis, and W. E. Muir. 1991. Review of thin-layer drying and wetting equations. Drying technology, 9(3): 551－588.

Keller, G. 2001. Applied statistics with Microsoft excel. Wadsworth group, Duxbury.

Kingsly, A. R. P. and D. B. Singh. 2007. Drying kinetics of pomegranate arils. Journal of Food Engineering, 79: 741－744.

Kouhila, M., N. Kechaou, M. Otmani, M. Fliyou, and S. Lahsasni. 2002. Experimental study of sorption isotherms and drying kinetics of Moroccan Eucalyptus Globulus. Drying Technology, 20(10): 2027－2039.

Krokida, M. K., E. Foundoukidis, and Z. Maroulis. 2004. Drying constant: literature data compilation for foodstuffs. Journal of Food Engineering, 61, 321－330.

Madamba, P. S, R. H. Driscoll, and K. A. Buckle. 1994. Shrinkage density and porosity of garlic during drying. Journal of Food Engineering, 23: 309－319.

Madamba, P. S., R. H. Driscoll, and K. A. Buckle. 1996. The thin layer drying characteristics of garlic slices. Journal of Food Engineering, 29: 75－97.

Methakhup, S., N. Chiewchan, and S. Devahastin. 2005. Effects of drying methods and conditions on drying kinetics and quality of Indian gooseberry flake. Swiss Society of Food Science and Technology, 38: 579－587.

Midilli, A., and H. Kucuk. 2003. Mathematical modeling of thin layer drying of pistachio by using solar energy. Energy Conversion and Management, 44: 1111－1122.

Özbek, B., and G. Dadali. 2007. Thin-layer drying characteristics and modeling of mint leaves undergoing microwave treatment. Journal of Food Engineering, 83: 541－549.

Panchariya, P. C., D. Popovic, and A. L. Sharma. 2002. Thin-layer modeling of black tea drying process. Journal of Food Engineering, 52: 349－357.

Pangavhane, D. R., R. L. Sawhney, and P. N. Sarsavadia. 1999. Effect of various dipping pre-treatment on drying kinetics of Thompson seedless grapes. Journal of Food Engineering, 39: 211－216.

Prabhanjan, D. G., H. S. Ramaswamy, and G. S. V. Raghavan. 1995. Microwave-assisted convective air-drying of thin layer carrots. Journal of food engineering, 25: 283－293.

Rapusas, R. S. and R. H. Driscoll. 1995. The thin-layer drying characteristics of white onion slices. Drying Technology, 13(8-9): 1905－1931.

Ruiz, R. P. 2005. Gravimetric measurements of water. Handbook of food analytical chemistry. Wrolstad, R.E. et al., ed. John Wiley and Sons, New Jersey.

Sacilik, K. 2007. Effect of drying methods on thin-layer drying characteristics of hull-less seed pumpkin (*Cucurbita pepo* L.). Journal of Food Engineering, 79: 23－30.

Saeed, I. E, K. Sopian, and Z. Zainol Abidin. 2006, Drying kinetics of Roselle (*Hibiscus sabdariffa* L.): Dried in constant temperature and humidity chamber. In the Proceeding, SPS 2006. Muchtar et al., ed. 29-30 Aug. Bangi, S.D.E., Malaysia, P143－148.

Saeed, I. E., K. Sopian, and Z. Zainol Abidin. 2008. “Thin-Layer drying of Roselle (I): mathematical modeling and drying experiments”. Agricultural Engineering International: the CIGR Ejournal. Manuscript FP 08 015. Vol. X. September, 2008a.

Saeed, I. E., K. Sopian, and Z. Zainol Abidin. 2008b. “Drying characteristics of Roselle: Study of the Two-term exponential model and drying parameters”. Agricultural Engineering International: the CIGR Ejournal. Manuscript FP 08 016. Vol. X. December, 2008b.

Sahin, A. Z., and I. Dincer. 2005. Prediction of drying times for irregular shaped multi-dimensional moist solids. Journal of Food Engineering, 71: 119－126.

Shivhare, U. S., A. Gupta, A. S. Bawa, and P. Gupta. 2000. Drying characteristics and product quality of okra. Drying Technology, 18(1-2): 409－419.

Sigge, G. O., C. F. Hansmann, and E. Joubert. 1998. Effect of temperature and relative humidity on the drying rates and drying times of green bell peppers (Capsicum annuum l.). Drying technology, 16: 1703－1714.

Simal, S., A. Femenia, M. C Garau, and C. Roselló. 2005. Use of exponential Page's and diffusional models to simulate the drying kinetics of kiwi fruit. Journal of Food Engineering, 66(3): 323－328.

Spatz, C. 2001. Basic statistics, Tales of distributions. 7th ed. Wadsworth/ Thomson.

Tarigan, E., G. Prateepchaikul, R. Yamsaengsung, A. Sirichote, and P. Tekasakul. 2007. Drying characteristics of unshelled kernels of candle nuts. Journal of Food Engineering, 79, 828－833.

Togrul, I. T., and D. Pehlivan. 2002. Mathematical modeling of solar drying of apricots in thin layers. Journal of Food Engineering, 55(1): 209－216.

Togrul, I. T., D. Pehlivan. 2003. Modeling of drying kinetics of single apricot. Journal of Food Engineering, 58(1): 23－32.

Wang, Z., J Sun, X. Liao, F. Chen, G. Zhao, J. Wu, and X. Hu. 2007. Mathematical modeling on hot air drying of thin layer apple pomace. Food Research International, 40: 39－46.

Xanthopoulos, G., N. Oikonomou, and G. Lambrinos. 2007. Applicability of a single-layer drying model to predict the drying rate of whole figs. Journal of Food Engineering, 81: 553－559.

Yaldiz, O., C. Ertekin, and H. I. Uzun. 2001. Mathematical modeling of thin layer solar drying of Sultana grapes. Energy, 26(5): 457－465.