Solar Drying of Roselle (*Hibiscus Sabdariffa* L.) Part II: Effects of Drying Conditions on the Drying Constant and Coefficients, and Validation of the Logarithmic Model

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ABSTRACT

In part (I), of this series of drying papers on solar drying of Roselle (karkade), statistical analyses on twelve thin-layer drying model, proved the superiority of logarithmic model. This part (II) investigated the effects of the drying conditions on the drying constant (k), coefficients, and drying rate. In addition, validation of the model as well was presented. The rate constant (k) was highly affected by the drying temperature. It was increased linearly with the temperature. Air velocity had, to lesser extent influenced (k). Coefficient (a) showed a positive relation with both drying-air temperature and velocity. In contrast to coefficient (a), parameter (c) was 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 criterions were applied to validate the developed model.

Keywords: Roselle, drying constant, coefficients, rate; logarithmic model, model validation

1. INTRODUCTION

Drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously (Sahin & Dincer, 2005). Drying is 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 & Vega-Mercado, 1996; O¨zbek & Dadali, 2007). The drying kinetics of food is a complex phenomenon and requires dependable models to predict the drying behaviour (Kingsly & Singh, 2007). Madamba *et al.*, (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 quantity for purposes of design, optimization, and any 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 four prevailing transport phenomena during drying (internal-external, heat-mass transfer), require a lot of time for their numerical solution and thus are not attractive for iterative calculations (Krokida *et al.*, 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, capable of predicting the water removal rates and describing the drying performance of each particular 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 & Kucuk, 2003), prediction of the drying time; for 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 & Pabis, Logarithmic, Simplified Fick's diffusion, Two-term, Two-term exponential, Verma *et al.*, and Diffusion approach were presented in part (I). In addition, the statistical measures of goodness of-fit were also given.

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

$$\% \, MC_{db} = \frac{W_w}{W_d} .100 \qquad (1)$$

2.3 Moisture ratio (MR) (O¨zbek & Dadali, 2007; Shivhare *et al.*, 2000; Saeed *et al.*, 2008b) is given by:

$$MR = \frac{M - M_e}{M_o - M_e} \qquad (2)$$

2.4 Drying rate (Ceylanl *et al.*, 2007; Doymaz, 2007; Saeed *et al.*, 2008b) is given by:

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (3)$$

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

$$MR = a. \exp(-c\,(t/L^2)) \qquad (4)$$

3. DRYING EXPERIMENTS

Thin-layer drying experiments with Roselle were carried out in a solar-assisted dehumidification drying-system for drying agricultural products. A flat-plate solar collector was used (five panels connected in parallel, 9.86m^2). In addition, auxiliary electric air-heaters are used. A cabinet-type drying chamber is used (100cm ×100cm ×240cm L, W, and H). Moreover, the distance between the shelves can be adjusted 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^{o}C to 400^{o}C). 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 Fuji Micro-jet recorder (type PHA, Fuji Electric Co., Ltd, Tokyo, Japan). 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 rates are measured by Aalborg WF-meters (Aalborg instruments and controls, NY, USA), 3.4-45l/min, with ±5% accuracy, and 100psi max working pressure. Two silica gel columns were used alternatively for the dehumidification and regeneration processes (25cm ×25cm ×125cm: L, W, and H), the silica gel height is about 85cm (42.5 kg silica gel/column). A digital balance (Shimadzu; model UX2200H, Capacity of 2200g, readability of 0.01g; from Shimadzu Co., Japan) was used to weigh Roselle samples. The data was recorded to personal computer at 5minutes. A convective oven (Venticell, MMM, Medcener, Germany) was used to determine the initial and final moisture content at 105°C (Ruiz, 2005). Five average temperatures (35, 45, 55, 60, and 65°C) and two average air velocities (1.5 and 3.0m/s) were considered. An approx. 10 kg of fresh Roselle's calyces (variety Arab) was 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 is 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 *et al.*, 2006; 2008a). The method was used to find the best-fit model to describe the solar-drying behavior of Roselle.

4. RESULTS AND DISCUSSIONS

As it was shown in part (I), the drying air temperature was the main factor affected the solar-drying kinetics of Roselle. The drying air velocity had a little effects on the drying processes compared to that of air temperature. Moreover, the results of statistical analysis showed the goodness of logarithmic model to describe the drying behaviour of Roselle. This 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.

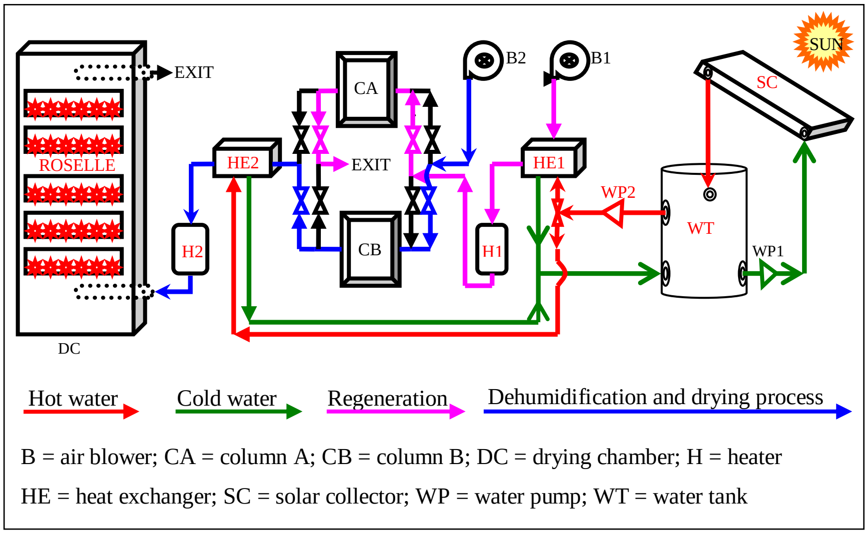

Figure 1. Regeneration (column A) and dehumidification (column B)

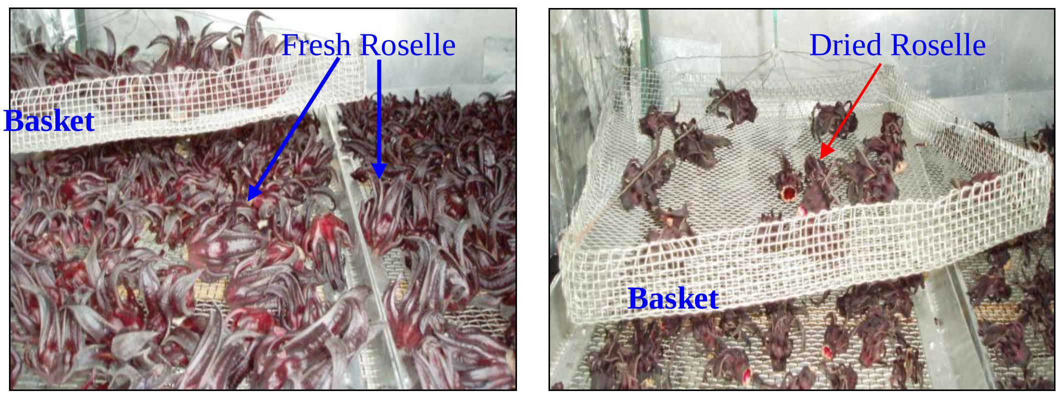

Figure 2. Fresh (left) and dried Roselle (right)

3.1 Observed and predicted moisture content

The Roselle's calyces (karkade) were dried from average initial moisture content of 9.88db to an average final moisture content of 0.19db. Figure 3 present 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 predict well the drying curves of Roselle, as the lines of the observed and predicted data were identical for the most of the drying time. The model was found satisfactorily described the drying behaviour of several agricultural products. For examples, drying of rosehip (Erenturka *et al.*, 2004); thin-layer drying kinetics of plum (Goyal *et al.*, 2007); solar drying of shelled and unshelled pistachios (Midilli & Kucuk, 2003); drying of hull-less seed pumpkin (Sacilik *et al.*, 2007); thin-layer solar drying of Sultana grapes (Yaldiz *et al.*, 2001).

3.2 Drying constants and coefficients

Table1 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.

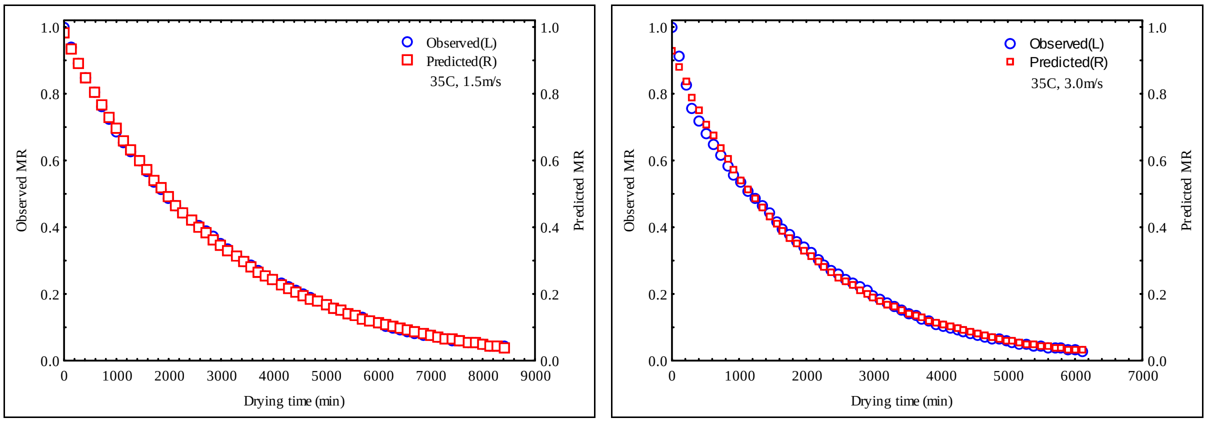

Figure 3a. MR $_{obser.}$ and MR$_{pred}$ vs. time at 35°C (left: 1.5m/s; right: 3.0m/s)

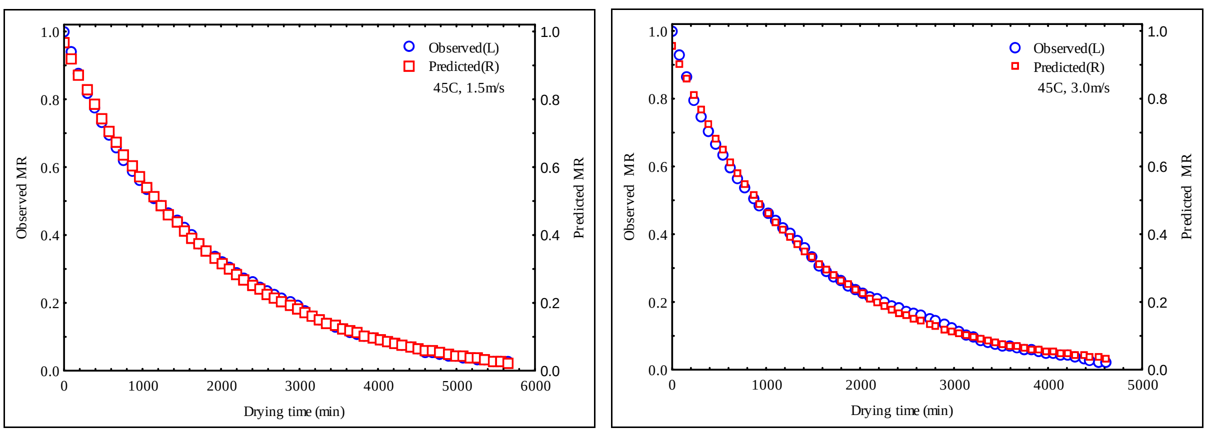

Figure 3b. MR $_{obser.}$ and MR$_{pred}$ vs. time at 45°C (left: 1.5m/s; right: 3.0m/s)

The values of (k), (a), and (c) resulted from fitting of logarithmic model, at different drying air conditions, were presented 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 agreed 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, some authors obtained higher values, as examples, solar drying

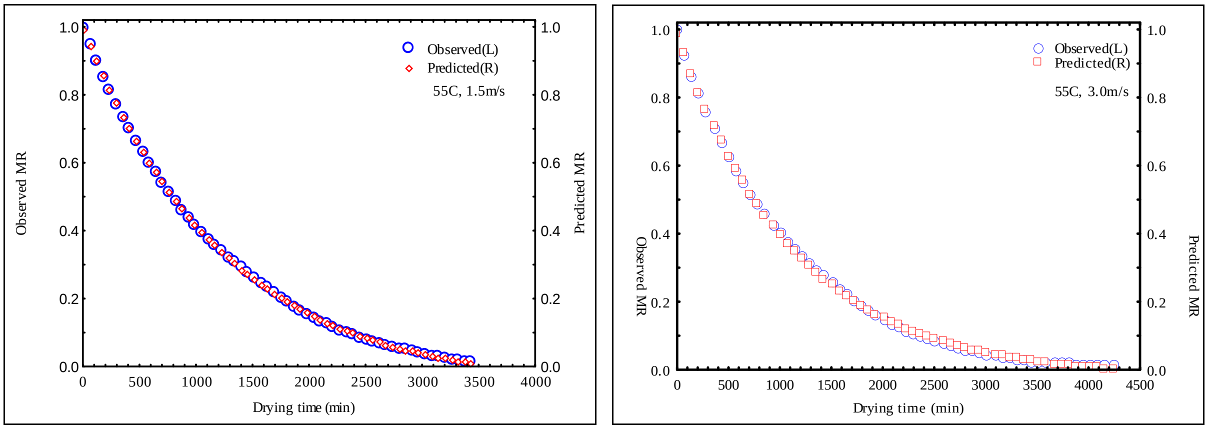

Figure 3c. MR $_{obser.}$ and MR$_{pred}$ vs. time at 55°C (left: 1.5m/s; right: 3.0m/s)

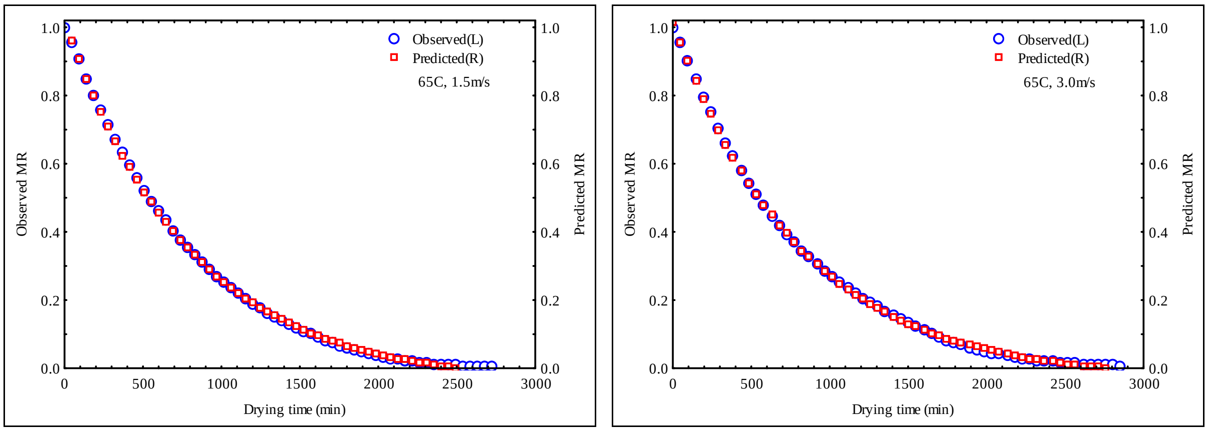

Figure 3d. MR $_{obser.}$ and MR$_{pred}$ vs. time at 65°C (left: 1.5m/s; right: 3.0m/s)

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 & Pehlivan, 2002); drying of single apricot: k = 0.0035, a = 1.0984, c = -0.0926 (Togrul & 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).

3.3 Effects of drying conditions on the drying constant and coefficients

3.3.1 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 *et al.*, 2004). The drying-air temperature was greatly influenced (p = 0.004) the drying rate constant.

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 & 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

Similar result was reported by others (Tarigan *et al.*, 2007). As the drying temperature is raised from 35°C to 65°C, the values of the drying constant were increased from 4.27 x 10^{-4} to 1.24 x 10^{-3}. On the other hand, drying air velocity has less influence on the drying constant. Similar result was found by Pangavhane *et al.*, (1999); Rapusas & Driscoll, (1995).

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

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

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 *et al.*, 2002; Simal *et al.*, 2005; Togrul & Pehlivan, 2003). The results of correlation of (k) with the temperature were given as follows:

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

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

Furthermore, the two set of the data points representing the values of (k) at 1.5m/s and 3.0m/s air velocities were coincides 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 3.0m/s resulted in a little tad high values of (k) than that of 1.5m/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:

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

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

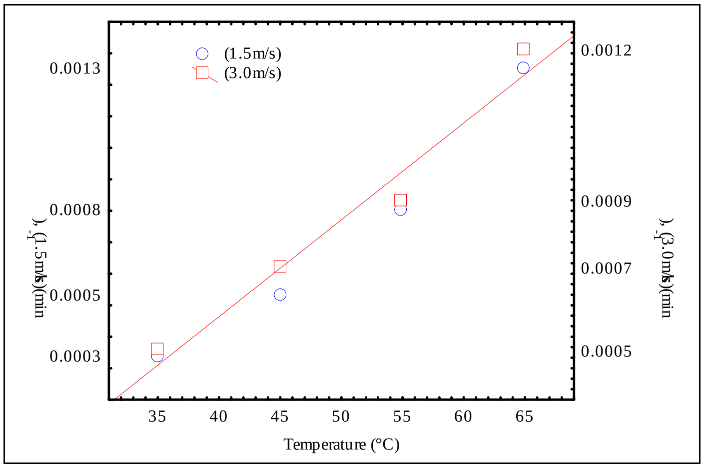

Figure 4a. Drying constant (k) vs. temperature (°C)

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:

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

$$k = (0.00000000751)\exp(-(-.03551)/T) \qquad (R^2 = 0.997) \qquad (10)$$

The values of R^2 from equations (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).

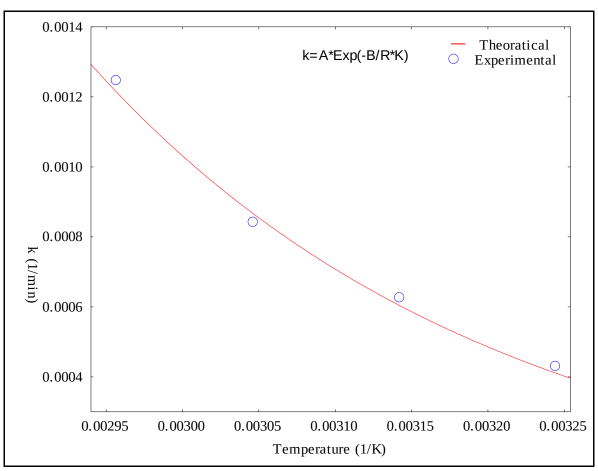

Figure 4b. k vs. temperature (K): eq. (4)

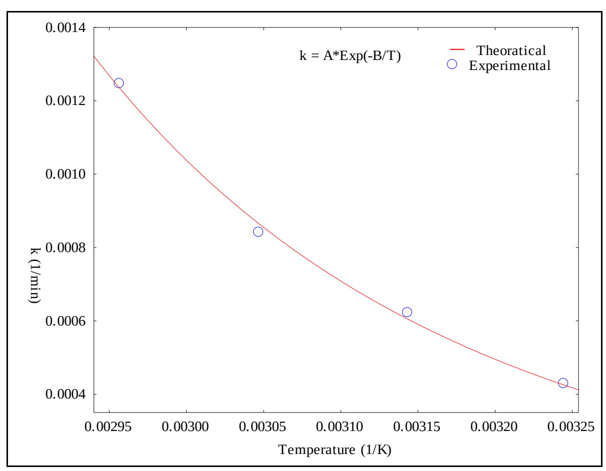

Figure 4c. k vs. temperature (K): eq. (5)

3.3.2 Coefficient (a)

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

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

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

3.3.3 Coefficient (c)

Coefficient (c) was 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:

$$c_{1.5} = 0.0191675 - 0.0011037T \qquad (r^2 = 0.670) \qquad (10)$$

$$c_{3.0} = 0.0287675 - 0.0009245T \qquad (r^2 = 0.701) \qquad (11)$$

Compared to (k) and (a), parameter (c) showed a moderate dependent on both drying-air temperature (r^2 =0.778 and p =0.258) and air velocity (r^2 =0.670 at 1.5m/s and r^2 =0.701 at 3.0m/s, with p=0.150). The three parameters, i.e. k, a, and c of the logarithmic model were not behaved in the same manner; as (Jayas *et al.*, 1991) also concluded that it is not necessary all the coefficient increase or decrease at the same time.

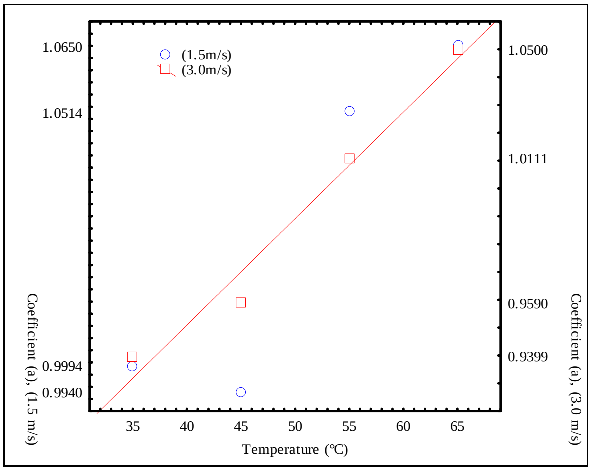

Figure 5. Coeff. (a) vs. drying conditions

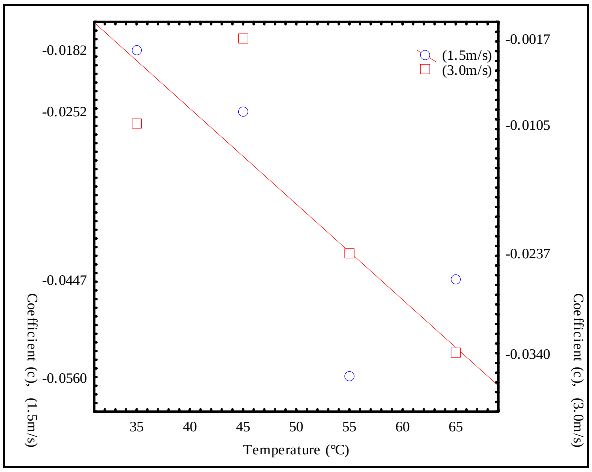

Figure 6. Coeff. (c) vs. drying conditions

3.3.4 Drying rate

The drying rate (DR) of Roselle was highly influenced by drying air temperature. It was increased with the increment of the drying-air temperature, similar result was observed by others (Saeed *et al.*, 2008a; 2008b). This is due to the increase of the heat supply rate to the product, hence, acceleration of water migration inside the product at higher temperature (Belghit *et al.*, 2000; Kouhila *et al.*, 2002; Krokida *et al.*, 2004). In addition, several authors reported that drying rates increases with the increment of the temperature for drying of various products; such as drying of pumpkin (Akpinar *et al.*, 2003); okra (Doymaz, 2005); pumpkin slices (Doymaz, 2007); eggplant (Ertekin & Yaldiz, 2004) and garlic (Madamba *et al.*, 1996). It is observed that, during the drying processes some crops have a tendency to form dry surface layers (Ekechukwua & Nortonb, 1999) which are impervious to subsequent moisture transfer if the drying is very rapid. (Janjai & Tung, 2005) reported that Roselle's calyxes have a natural wax coated on their surfaces. This wax prevents most of the migration of moisture from the inside into drying-air. After the surface is dried the wax is broken, and the moisture from inside can be easily released, thus increasing the drying rate. 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 with a high binding energy. Figures 7 present the drying rates of Roselle at different drying conditions. The drying rates at temperature 35°C and 45°C 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 that coincides with the alternative dehumidification and regeneration processes of the silica gel columns.

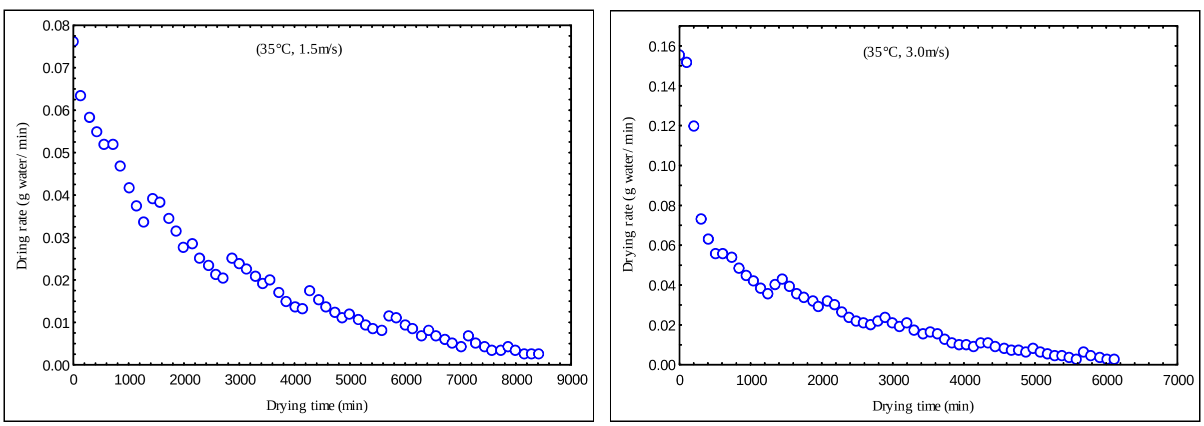

Figure 7a. Drying rate (DR) at 35°C (left: 1.5m/s; right: 3.0m/s)

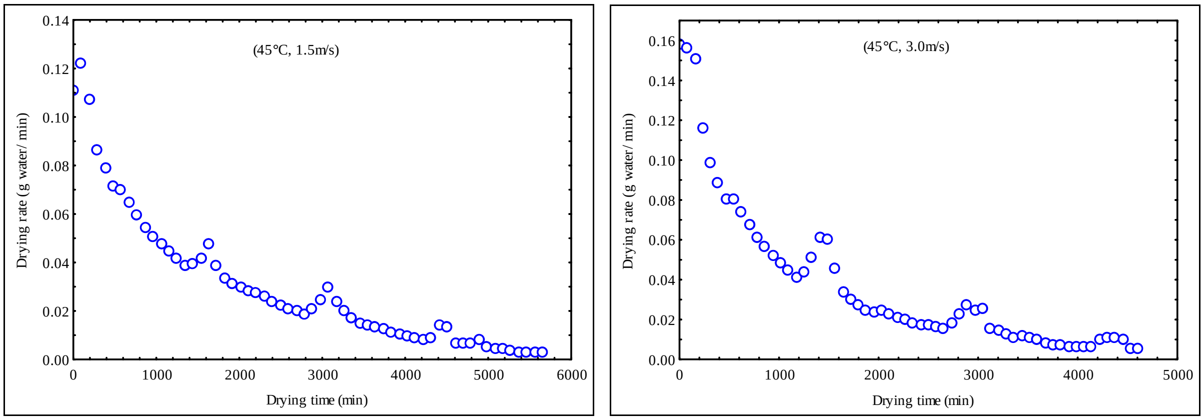

Figure 7b. Drying rate at 45°C (left: 1.5m/s; right: 3.0m/s)

For drying at higher temperatures (55°C and 65°C), 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 & 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 a little affect on the drying rate (Iguaz *et al*., 2003; Jayas *et al*., 1991).

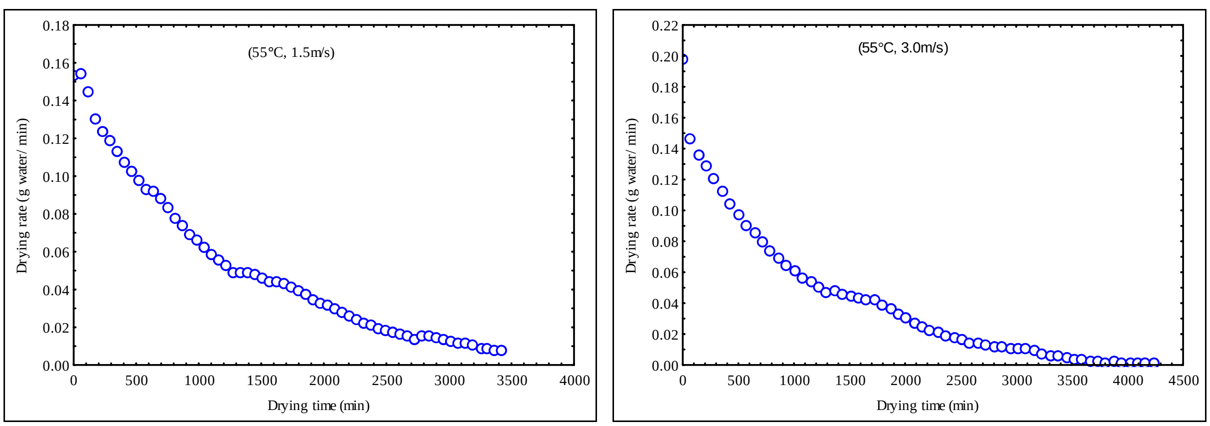

Figure 7c. Drying rate at 55°C (left: 1.5m/s; right: 3.0m/s)

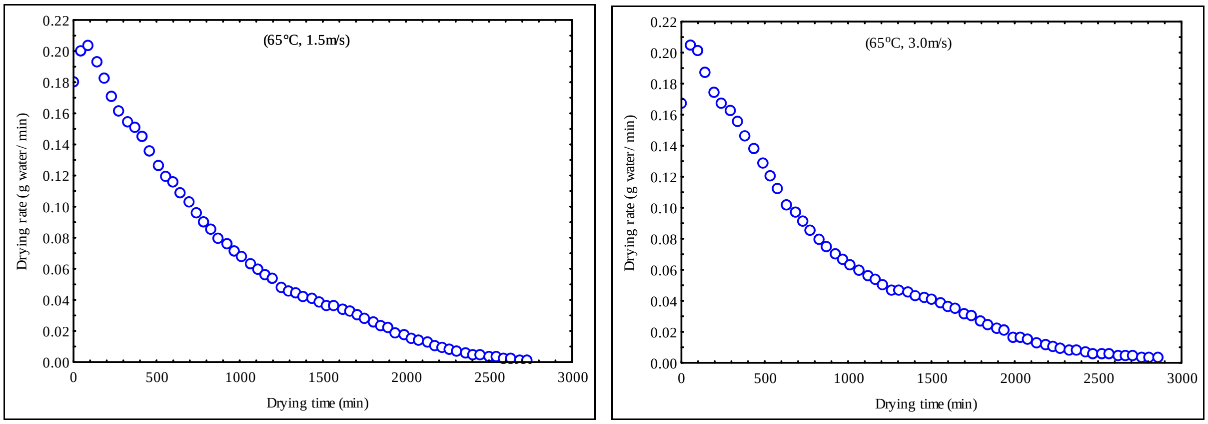

Figure 7d. Drying rate at 65°C (left: 1.5m/s; right: 3.0m/s)

Figures 8 show the plotting of the drying rate (DR) vs. MR at different drying conditions. Higher drying rates were occurred at high moisture levels (Guine´ *et al.*, 2007). The rates, then, tend to towards 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 *et al.*, 2000; Kouhila *et al.*, 2002). On the other hand, the drying time decreased dramatically with the air temperature (Goyal *et al.*, 2007; Saeed *et al.*, 2006), as the capacity of air to remove moisture increases with its temperature (Sigge *et al.*, 1998).

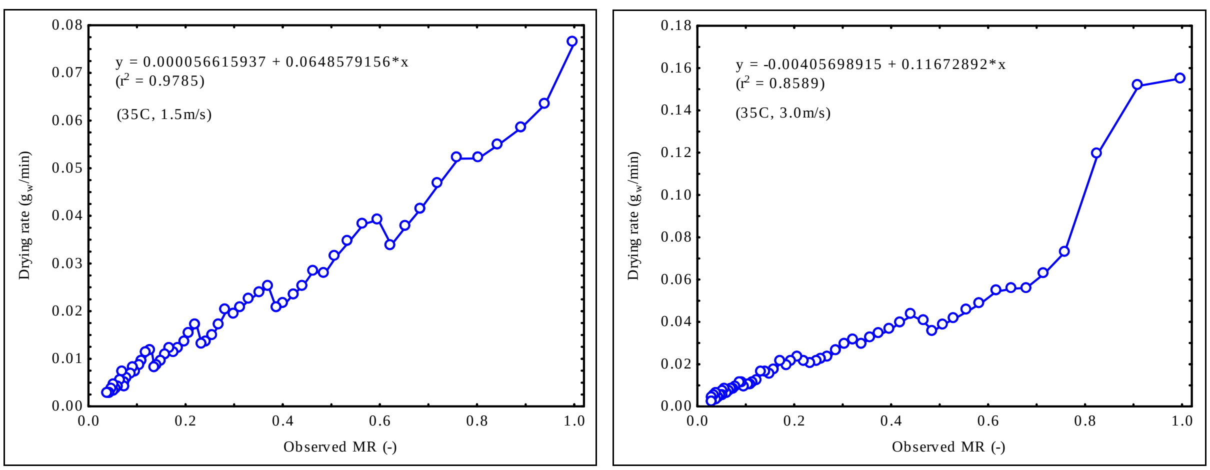

Figure 8a. Drying rate vs. MR at 35°C (left: 1.5m/s; right: 3.0m/s)

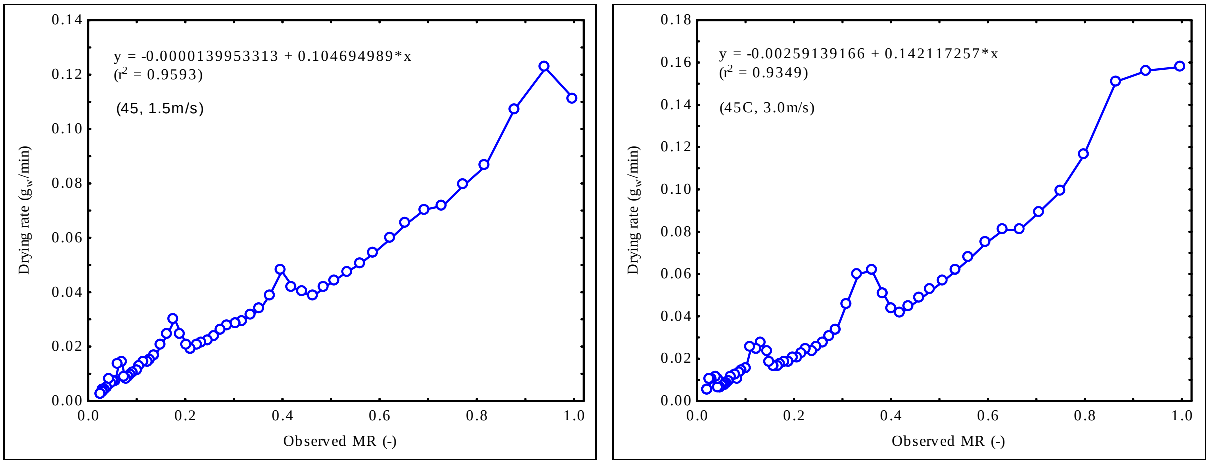

Figure 8b. Drying rate vs. MR at 45°C (left: 1.5m/s; right: 3.0m/s)

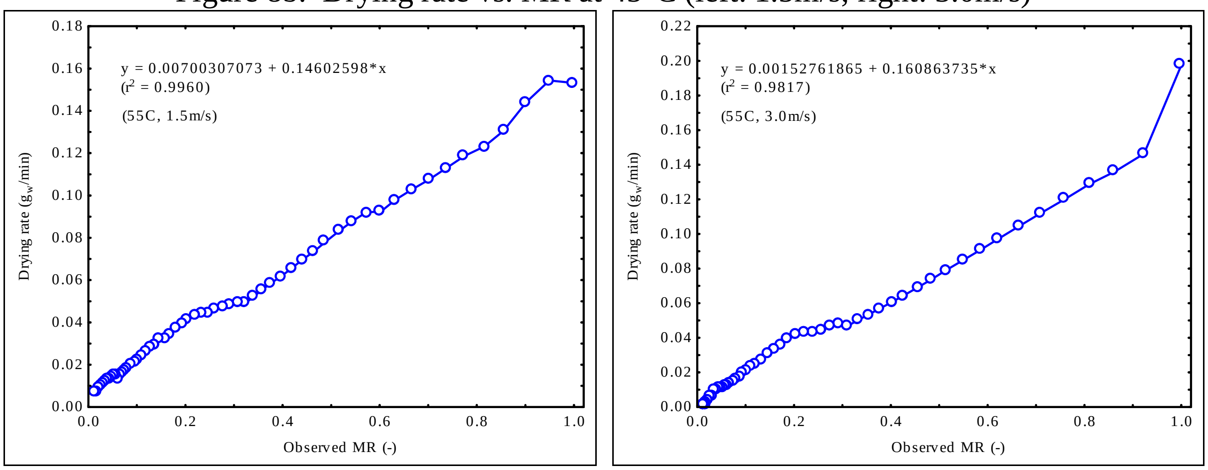

Figure 8c. Drying rate vs. MR at 55°C (left: 1.5m/s; right: 3.0m/s)

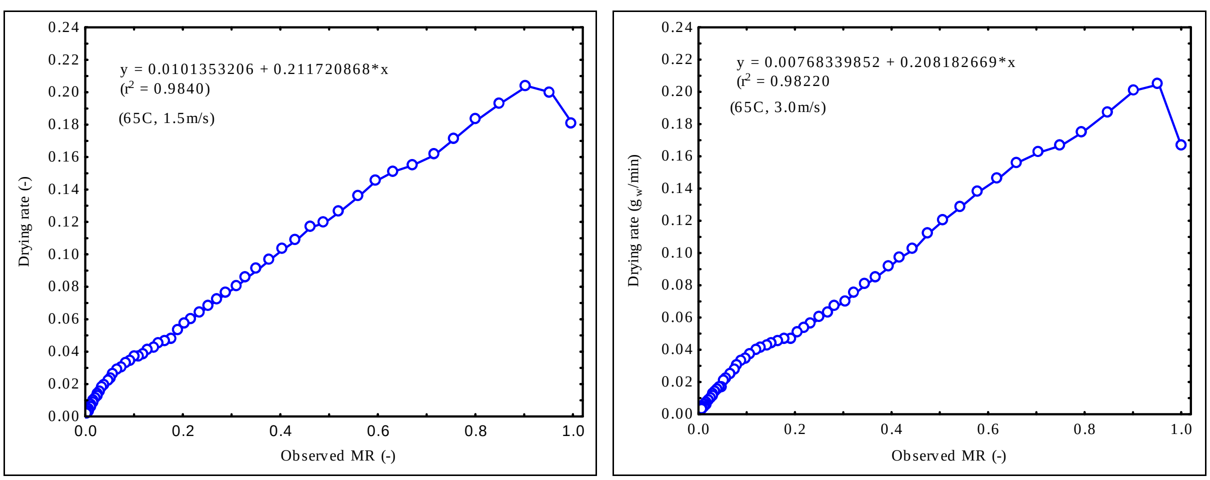

Figure 8d. Drying rate vs. MR at 65°C (left: 1.5m/s; right: 3.0m/s)

The drying rate was increased with the increment of the temperature from 35°C to 65°C, as the main factor influencing the drying kinetics is the drying-air temperature (Belghit *et al.*, 2000; Saeed *et al.*, 2006; 2008a; Sigge *et al.*, 1998). This is because, 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 *et al.*, 2005; Prabhanjan *et al.*, 1995). In addition, the soft heating of the product accelerates the water migration inside the product (Kouhila *et al.*, 2002).

3.4 Validation of the model

Two criterions 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 *et al.*, 2006; 2008b; Simal *et al.*, 2005; Togrul & Pehlivan, 2003). Figures 9 show 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 goodness of the logarithmic model to estimate 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°C		45°C		55°C		65°C	
1.5m/s	3.0m/s	1.5m/s	3.0m/s	1.5m/s	3.0m/s	1.5m/s	3.0m/s
0.9997	0.9968	0.9990	0.9979	0.9999	0.9994	0.9995	0.9997

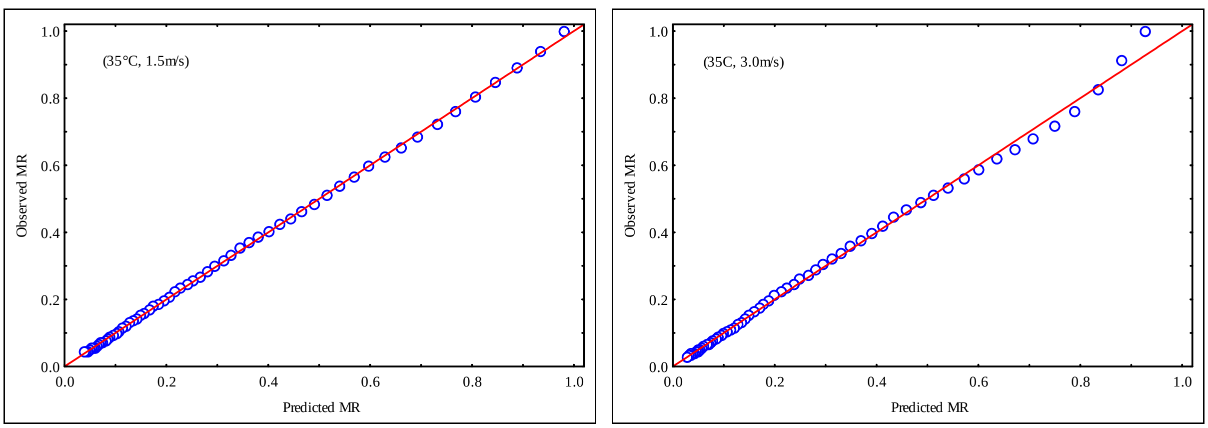

Figure 9a. MR_{exp} vs. MR_{pred} at 35°C (left: 1.5m/s; right: 3.0m/s)

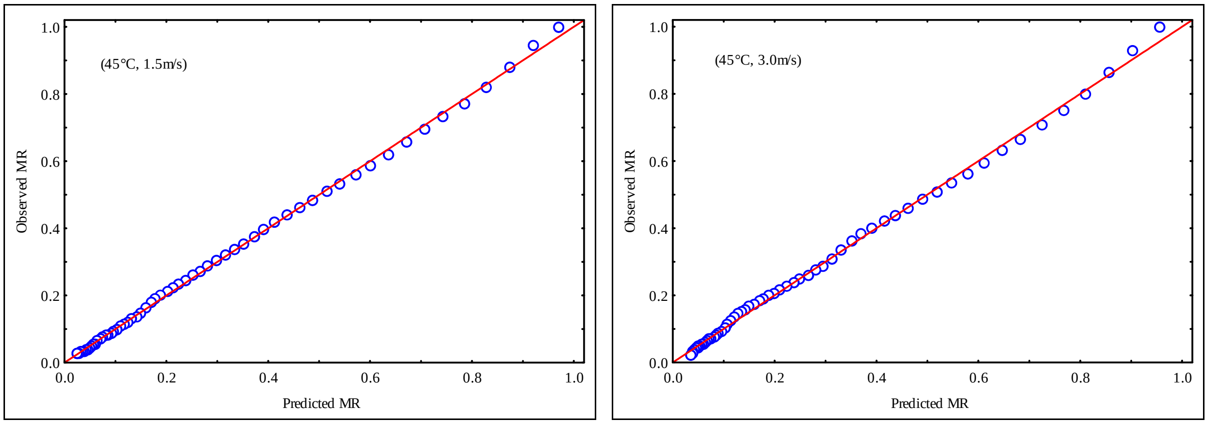

Figure 9b. MR_{exp} vs. MR_{pred} at 45°C (left: 1.5m/s; right: 3.0m/s)

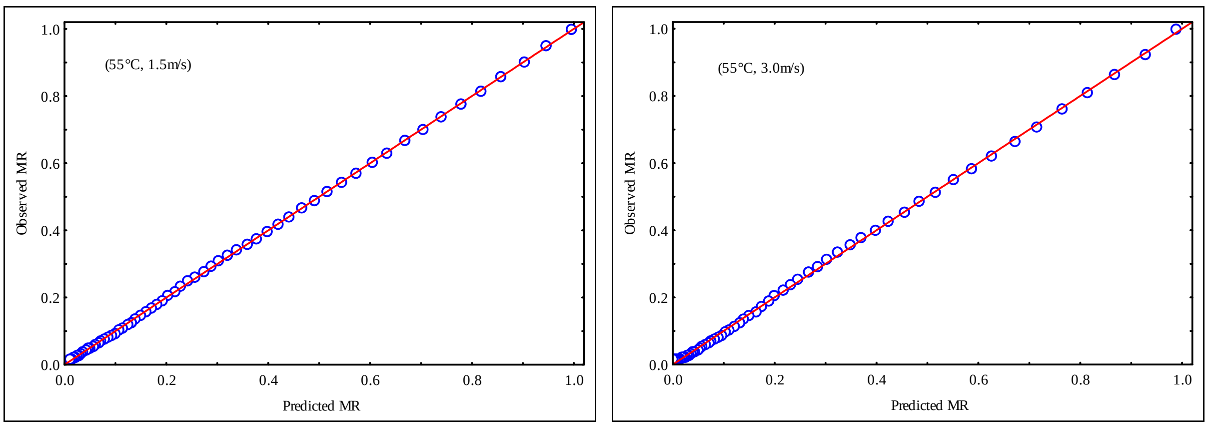

Figure 9c. MR_{exp} vs. MR_{pred} at 55°C (left: 1.5m/s; right: 3.0m/s)

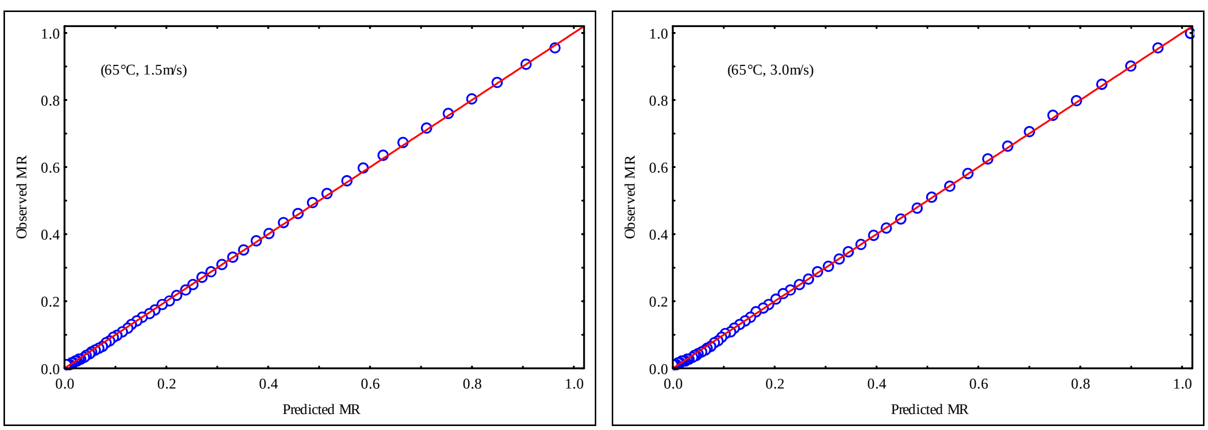

Figure 9d. MR_{exp} vs. MR_{pred} at 65°C (left: 1.5m/s; right: 3.0m/s)

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 suitability of the logarithmic model to describe the drying behaviour of the Roselle adequately.

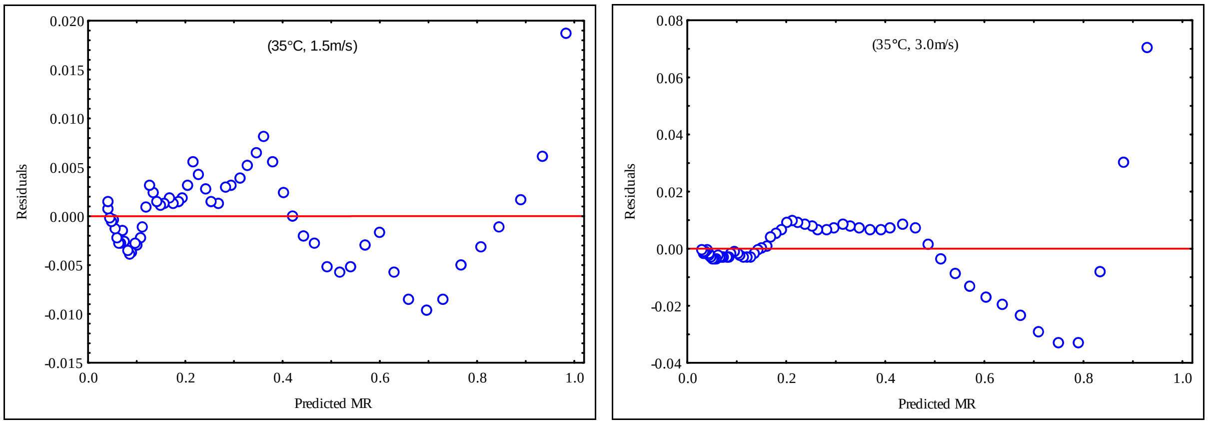

Figure 10a. Residuals vs. MR_{pred} at 35°C (left: 1.5m/s; right: 3.0m/s)

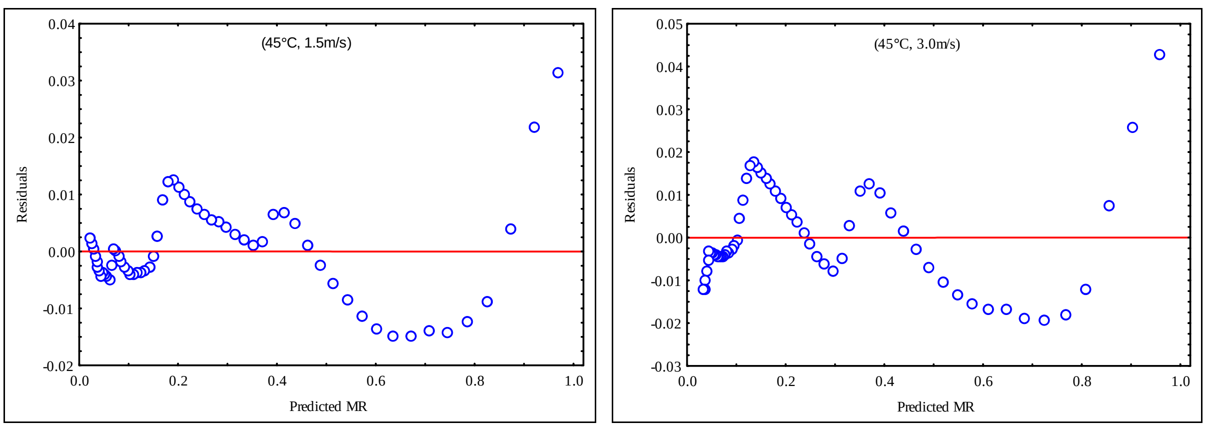

Figure 10b. Residuals vs. MR_{pred} at 45°C (left: 1.5m/s; right: 3.0m/s)

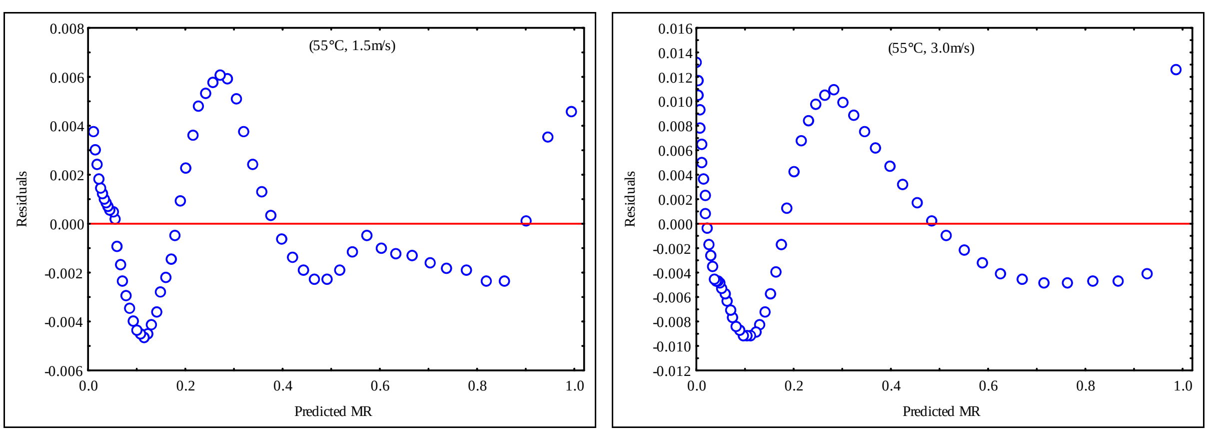

Figure 10c. Residuals vs. MR_{pred} at 55°C (left: 1.5m/s; right: 3.0m/s)

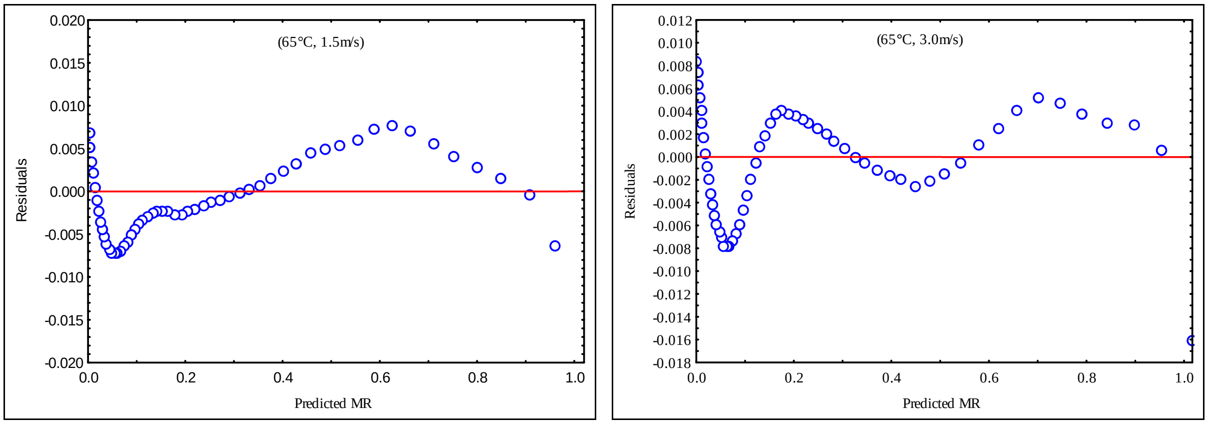

Figure 10d. Residuals vs. MR_{pred} at 65°C (left: 1.5m/s; right: 3.0m/s)

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

$$MR\,(a, k, c, t) = \frac{M}{M_0} = a\,.\exp(-kt) + c \tag{12}$$

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 this 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 was 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 dependent on both drying-air temperature (r^2 =0.778 and p =0.258) and air velocity (r^2 =0.670 at 1.5m/s and r^2 =0.701 at 3.0m/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 a little effect on the drying rate compared to that of the air temperature. Two criterions were applied to validate the developed logarithmic model. Plotting of the experimental against predicted values, and the residual versus predicted values. The results confirmed the suitability of the model to predict the drying characteristics of the Roselle, satisfactorily, under the studied drying conditions.

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7. NOMENCLATURE

a	coefficient in drying models	k_o	constant in equation (4)
A	constant in equation (5)	k_1	coefficient in drying models
$a_{1.5}$	coefficient (a) at 1.5m.s^{-1}	$k_{1.5}$	coefficient (k) at 1.5 m.s^{-1}
$a_{3.0}$	coefficient (a) at 3.0m.s^{-1}	$k_{3.0}$	coefficient (k) at 3.0 m.s^{-1}
b	coefficient in drying models	l	coefficient in drying models
c	coefficient in drying models	MC_{db}	moisture content dry base ($g_w.g_{dm}^{-1}$)
B	constant in equation (5)	M_e	equilibrium moisture content
$c_{1.5}$	coefficient (c) at 1.5m.s^{-1}	M_o	initial moisture content ($g_w.g_{dm}^{-1}$)
$c_{3.0}$	coefficient (c) at 3.0m.s^{-1}	MR	moisture ratio (-)
DR	drying rate ($g_w.g_{dm}^{-1}min^{-1}$)	M_t	moisture content at time t ($g_w.g_{dm}^{-1}$)
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^{-1})	exp	experimental
3.0	air velocity (m.s^{-1})	pred	predicted
d	dry matter (g)	obser.	observed
db	dry base (-)	w	water (g)