Drying Characteristics of Roselle: Study of the Two-term Exponential Model and Drying Parameters

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ABSTRACT

Thin-layer drying experiments with Roselle (*Hibiscus sabdariffa* .L) were carried out in a constant temperature and humidity chamber. Four temperatures (35, 45, 55, and 65°C) and five relative humidities (30, 35, 40, 45, and 50%RH) were tested. Statistical analysis on twelve thin-layer drying model proved the superiority of two-term exponential model. The objectives of this work were to evaluate and validate the two-term exponential model; besides, examine the effects of the drying conditions on the drying rate and constant. Validation of the developed model was done using two criterions, plotting of the predicted against experimental moisture contents and the residual versus predicted moisture content. The average values of the drying constant (k) and coefficient (a) were 0.009167 and 0.776132, respectively.

Keywords: Roselle; two-term exponential model; model validation; drying rate and drying parameters

1. INTRODUCTION

Air-drying is the most frequently used dehydration operation in the food industry, where the temperature of this operation is limited by the heat sensitivity of the material and expected quality of the final product (Lewicki, 2006). The wide variety of dehydrated foods, which today are available to the consumers and the interesting concern for meeting quality specifications (nutritional factors, colour, shape and texture) and energy conservation, emphasize the need for a thorough understanding of the drying process (Górnicki *et al.*, 2007). Due to the complexity of food, drying can occur simultaneously by different mechanisms. Consequently, modelling the drying process, and predicting the drying behaviour under different conditions is necessary to have a better understanding of the mechanisms of drying at play. In the falling rate period, the concentration gradient in food matrix controls the drying rate and is temperature dependent (Nguyen & Price, 2007).

Mathematical modelling of thin layer drying is important for optimum management of operating parameters and prediction of performance of the drying system (Jain *et al.*, 2004), and understanding of the drying process (Górnicki *et al.*, 2007). It is essential to set out accurate models to simulate the drying curves under different drying conditions (Simal *et al.*, 2005). The theoretical drying models suggest that the moisture transport is controlled mainly by internal resistance mechanisms, while the others (semi-theoretical and empirical models) consider only external resistance (Babalis *et al.*, 2006). Furthermore, few numbers of parameters in the drying model is preferable to find meaningful relations between the parameters values and the drying conditions (Chen, 2002). The description and prediction of the drying kinetics of a given material is still a weakness in the modelling of drying processes. There is a great need for stable and reliable models to quantify and predict drying rates and drying times with a satisfying accuracy (Coumans, 2000).

Drying kinetics is greatly affected by air temperature and material characteristic dimension (Kiranoudis *et al.*, 1997; Krokida *et al.*, 2003). The drying rate constant can be determined without reference to the shape and to the changing dimension of the drying food-material (Rapusas & Driscoll, 1995; Simal *et al.*, 2005). It describes the mechanisms of heat and mass transport phenomena and investigates the influence that certain process variables exert on moisture removal processes. It is measured through experimental studies of moisture content removal versus time at various drying conditions (Krokida *et al.*, 2004). The factors that govern the transfer mechanisms determine the drying rate. These factors are vapour pressure of the material and drying air, air velocity and temperature, water diffusion velocity in the material, thickness, and surface exposed for drying (El-Aouar *et al.*, 2003). In addition, each product has its own drying kinetics (Belghit *et al.*, 2000).

The curves representing the variations of the mean water content as a function of time, or representing the drying rate as a function of mean water content are commonly called drying curves (Jannot, 2004). Validation of the established drying models, can be made by comparing the computed and measured moisture contents (Midilli *et al.*, 2002; Saeed *et al.*, 2006; Simal, 2005; Togrul & Pehlivan, 2002, 2003; Yaldiz & Ertekyn, 2001), and/or plotting of the residuals versus the predicted values by the model (Keller, 2001; Peck *et al.*, 2001; Spatz, 2001; Vardeman & Jobe, 2001). The objectives of this part of the work on thin-layer drying of Roselle (*Hibiscus sabdariffa* L.) were to evaluate and validate the developed drying model for thin-layer drying of Roselle variety Arab; as well, examine the effects of the drying conditions on the drying rates and constants.

2. MATHEMATICAL MODELING

2.1 Moisture Content

The amount of moisture content (MC) in a product is designated on the basis of the weight of water (i.e. dry or wet basis). On dry basis (%), it can be calculated as follows (Ceylan *et al.*, 2007; Haque & Langrish, 2005; Saeed *et al.*, 2006; Upadhyay *et al.,* 2008):

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

2.2 Moisture Ratio (MR)

Moisture ratio is the ratio of the moisture content at any given time to the initial moisture content (both relative to the equilibrium moisture content). It can be calculated as (O¨zbek & Dadali, 2007; Shivhare *et al.*, 2000; Thakor *et al.*, 1999):

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

2.3 Drying Rate (DR)

The drying rate can be given as (Ceylan *et al.*, 2007; Doymaz, 2007; O¨zbek & Dadali, 2007):

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

2.4 Two-term exponential: (Midilli & Kucuk, 2003; Sacilik *et al.*, 2006; Tarigan *et al.,* 2007)

$$MR = a \, . \exp(-k\,t) + (1 - a) \exp(-k\,a\,t) \quad (4)$$

2.5 Goodness-of Fit Statistics

Thin-layer drying models were evaluated and compared by using statistical measures. Consequently, the quality of the fitted models was evaluated. Some of these measures can be described as follows:

a. Coefficient of determination (R^2)

This is equivalent to the ratio of the regression sum of squares (SSR) to the total sum of squares (SST), which explains the proportion of variance accounted for in the dependent variable by the model. It evaluates how well the model fits the data. It is used by various authors to evaluate the drying models (Doymaz, 2007; Panchariya *et al.*, 2001; Saeed *et al.*, 2006; Singh *et al.*, 2006). The SSR and the SST can be calculated from the following formulae:
Regression sum of squares:

$$SSR = \sum_{i}^{N} \left(\hat{Y}_i - \overline{Y} \right)^2 \quad (5)$$

The total sum of squares

$$SST = \sum_{i=1}^{N} \left(Y_i - \overline{Y} \right)^2 \quad (6)$$

Consequently, the coefficient of determination (R^2) can be calculated as:

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \quad (7)$$

b. The standard error of estimate (SEE)

It represents the fitting ability of a model in relation to the number of data points (Sun, 1999), and measures the dispersion of the observed values about the regression line (Basunia & Abe, 1999; Basunia & Abe, 2001a; Mwithiga & Olwal, 2005)

$$SEE = \sqrt{\frac{\sum_{i=1}^{N} \left(MR_{exp,\ i} - MR_{cal,\ i} \right)^2}{N - np}} \quad (8)$$

c. Root mean square error (RMSE)

It is signifying the noise in the data (Demir *et al.*, 2004; Doymaz, 2005; Wang *et al.*, 2007):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N}} \qquad (9)$$

d. Mean sum of squares of errors (MSE) or (χ^2)

It is the mean square of the deviations between the experimental and calculated moisture levels (Iguaz *et al.*, 2003; Lopez *et al.*, 2000; Panchariya *et al.*, 2002). Several authors (Kingsly & Singh, 2007; Ertekin & Yaldiz, 2004; Sarsavadia *et al.*, 1999) used the term-reduced chi-square (χ^2) instead:

$$MSE = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N - n_p} \qquad (10)$$

3. DRYING EXPERIMENTS

Thin-layer drying experiments with Roselle were carried out in a Constant Temperature and Humidity Chamber (Model TH-1-180-L. JEIO TECH Co., Ltd, KOREA). Four drying-air temperatures (35°C, 45°C, 55°C, and 65°C) and five relative humidities (30%, 35%, 40%, 45%, and 50%RH) were tested. Fresh calyces of Roselle (variety Arab) were used. The seed's capsules were removed before commencing the drying experiments, and the calyces were used as whole (uncut). Analytical semi-microbalance (Model GR-200; sensitivity 0.1mg, from A and D Co., ltd, Japan), was used to weight the Roselle's samples.

The data were recorded by a personal computer at 5 minutes intervals, using data acquisition software (RsCOM Version 2.40). A convective oven (Venticell, MMM, Medcener, Germany) was used to determine the initial and the final moisture content at 105°C (Ruiz, 2005); in addition, dynamic equilibrium moisture contents were calculated (Basunia & Abe, 1999; Falade & Abbo, 2007; Hossain & Bala, 2002). Photographs of the drying system, fresh Roselle (with seed's capsules removing tool) and dried Roselle were shown in the Appendix. The moisture contents were expressed on dry basis, which is more convenient for modelling (Saeed *et al.* 2006; Togrul & Pehlivan, 2003). Moreover, the weight was converted to a more useful form, i.e., the dimensionless moisture ratio (MR) expression (Falade & Abbo, 2007; Fumagalli & Freire, 2007; Waewsak *et al.*, 2006; Xanthopoulos *et al.*, 2007) as the initial moisture contents of the products varies from one sample to another. Consequently, the comparison between different drying experiments can be done. The data obtained from the drying experiments was analyzed using statistical software package. Twelve thin-layer drying models were fitted to the observed data, and comparison was carried out using goodness-of fit statistical parameters.

4. RESULTS AND DISCUSSION

Drying-air temperature was found to be the main factor affecting the drying kinetics of Roselle. Raising the temperature dramatically reduced the drying time. On the other hand, the drying-air humidity was to lesser extend influenced the drying processes. In drying at low temperature (35^{o}C), the processes were a little bit slowed down as the relative humidity is increased, while at higher temperature (65^{o}C), this effect become negligible.

Moreover, statistical analysis was carried out and comparison between drying models was made to select the best-fit model for the drying curves. Among twelve investigated drying models, the two-term exponential model was found to be superior to the others. This work studies the effects of the drying conditions on the drying parameters, and evaluates and validates the two-term exponential model. The validation was conducted using two criterions, i.e., plotting of the experimental against predicted moisture contents, and the residual versus predicted moisture content.

4.1 Observed and Predicted Moisture Contents

Moisture contents were expressed as a dimensionless moisture ratio (MR). The experimental moisture ratio and predicted moisture ratio by the two-term exponential model were plotted as a function of time (Figures 1 through 4). To have a clear visual judgment; they were shown individually. It is obviously that the model predicts well the drying curves of Roselle, as the data points of the predicted and observed moisture were identical for most of the time.

Furthermore, the values of the statistical measures, i.e., R^2, SEE, RMSE, and MSE, are shown in Tables 1 and 2. At the start of the drying processes the moisture contents of Roselle decreased rapidly; and this effect is increased with the drying temperature. Then, the process tends to slow down until the end of the drying, as moisture contents of Roselle diminishes.

Table1. Statistical measures (two-term exponential model): 35°C and 45°C

RH	35°C				45°C			
%	R^2	SEE	RMSE	MSE	R^2	SEE	RMSE	MSE
30	0.99946	0.00969	0.00953	0.00009	0.99929	0.01192	0.01172	0.00014
35	0.99977	0.00726	0.00714	0.00005	0.99907	0.01233	0.01212	0.00015
40	0.99949	0.01127	0.01108	0.00013	0.99861	0.01535	0.01510	0.00024
45	0.99973	0.00832	0.00818	0.00007	0.99930	0.01103	0.01084	0.00012
50	0.99969	0.00839	0.00825	0.00007	0.99975	0.00650	0.00639	0.00004

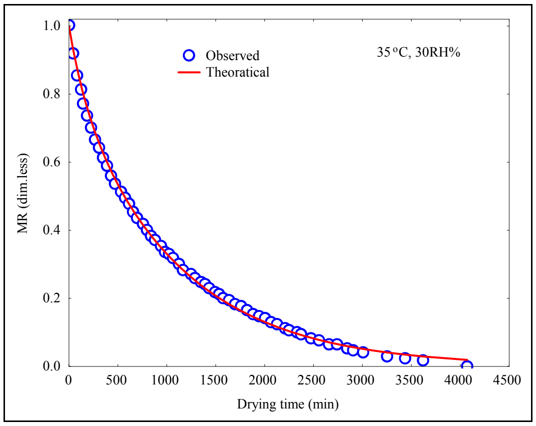

Figure 1a. MR vs. time (35°C, 30%RH).

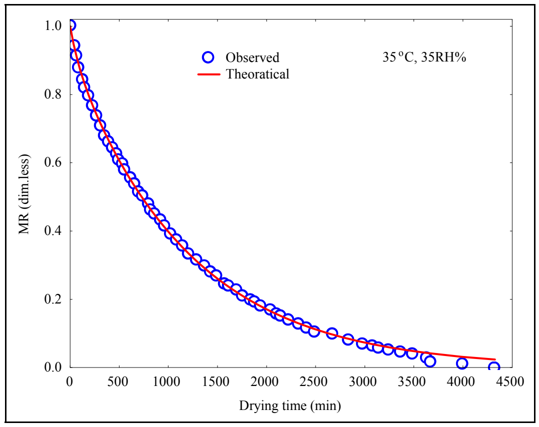

Figure 1b. MR vs. time (35°C, 35%RH).

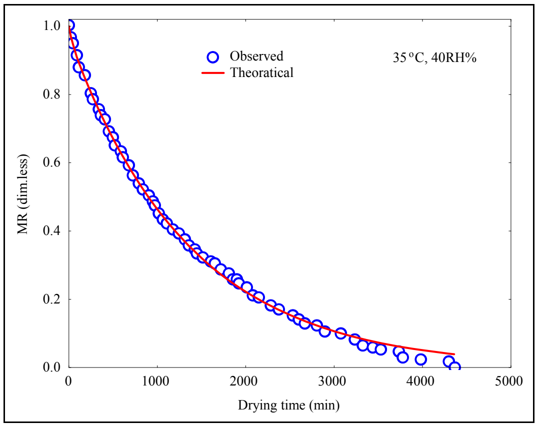

Figure 1c. MR vs. time (35°C, 40%RH).

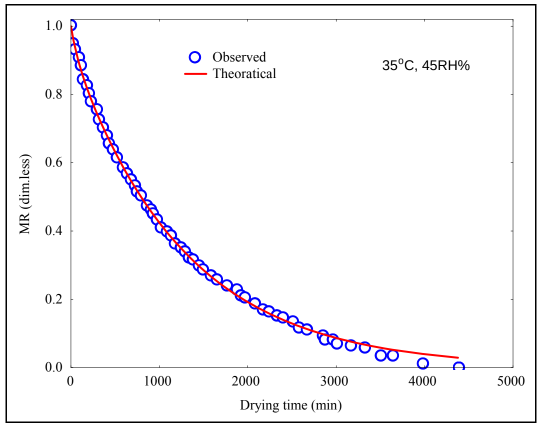

Figure 1d. MR vs. time (35°C, 45%RH).

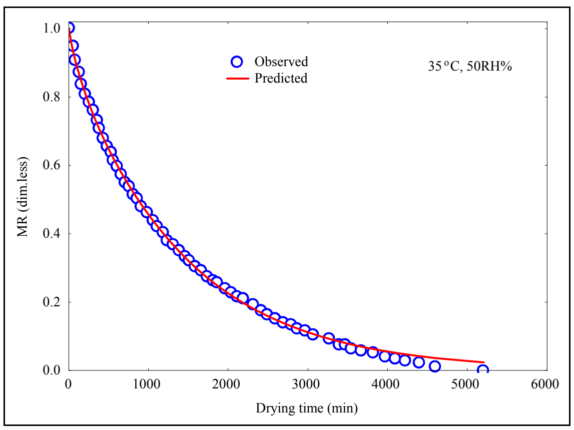

Figure 1e. MR vs. time (35°C, 50%RH).

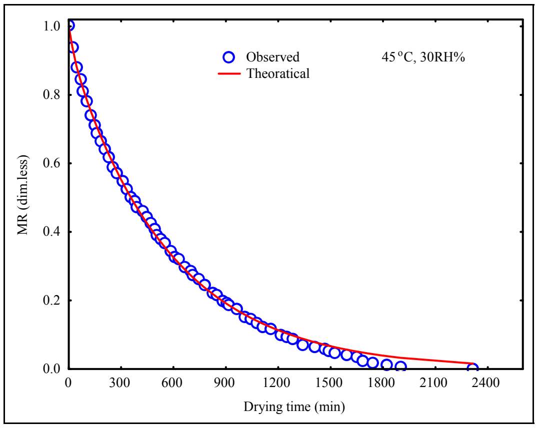

Figure 2a. MR vs. time (45°C, 30%RH).

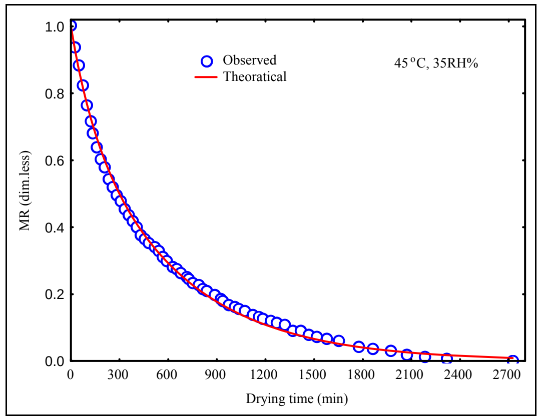

Figure 2b. MR vs. time (45°C, 35%RH).

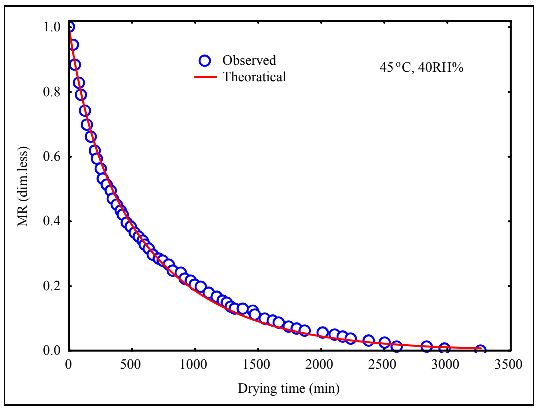

Figure 2c. MR vs. time (45°C, 40%RH).

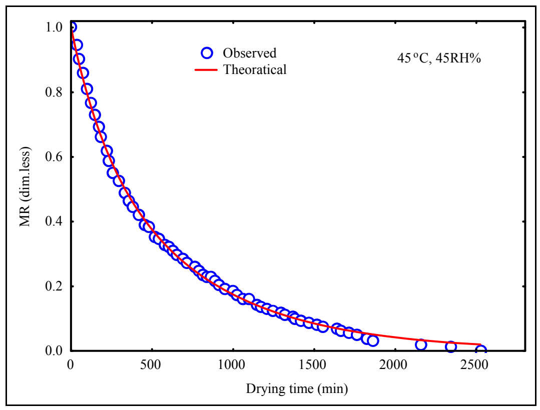

Figure 2d. MR vs. time (45°C, 45%RH).

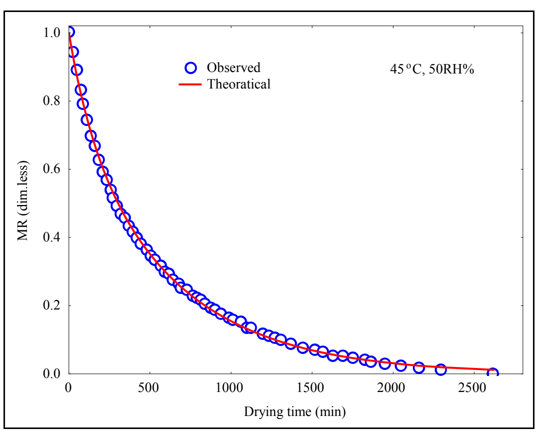

Figure 2e. MR vs. time (45°C, 50%RH).

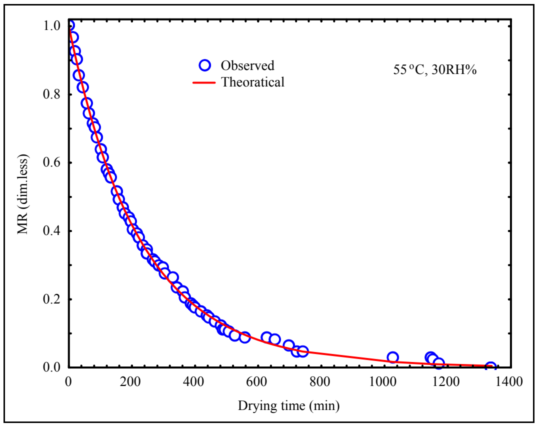

Figure 3a. MR vs. time (55°C, 30%RH).

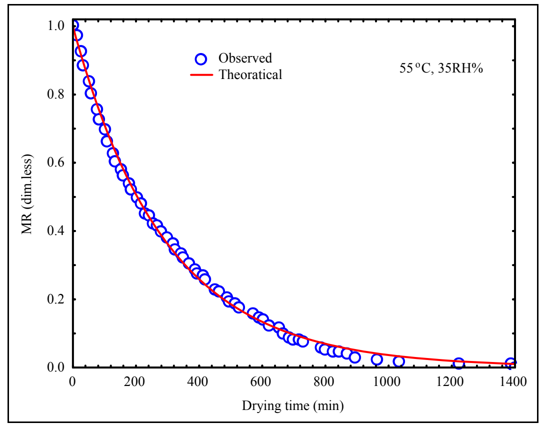

Figure 3b. MR vs. time (55°C, 35%RH).

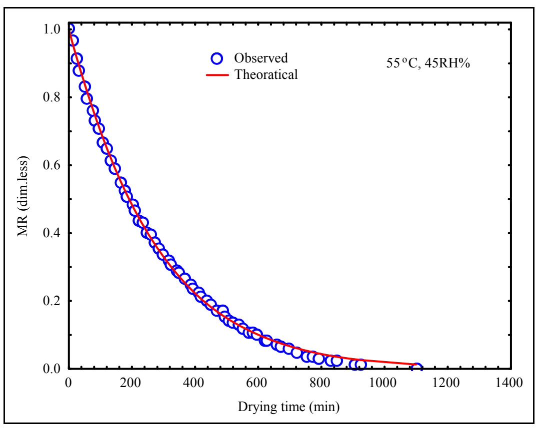

Figure 3c. MR vs. time (55°C, 45%RH).

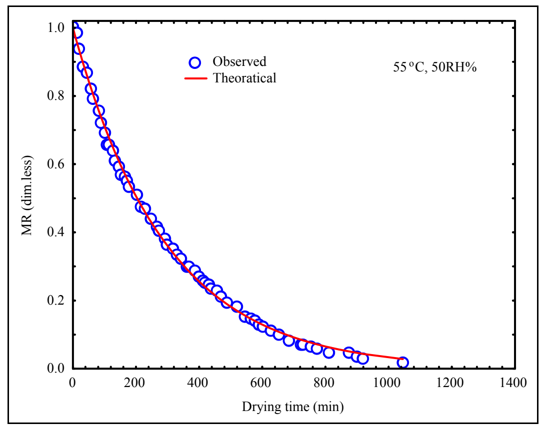

Figure 3d. MR vs. time (55°C, 50%RH).

Table 2. Statistical measures (two-term exponential model): 55°C and 65°C

RH	55°C				65°C			
%	R^2	SEE	RMSE	MSE	R^2	SEE	RMSE	MSE
30	0.99969	0.00820	0.00806	0.00007	0.99934	0.01195	0.01174	0.00014
35	0.99905	0.01385	0.01362	0.00019	0.99921	0.01299	0.01277	0.00017
40	0.99969	0.00783	0.00770	0.00006	0.99967	0.00784	0.00771	0.00006
45	0.99965	0.00832	0.00818	0.00007	0.99856	0.01756	0.01726	0.00031
50	0.99934	0.01230	0.01210	0.00015	0.99948	0.01059	0.01042	0.00011

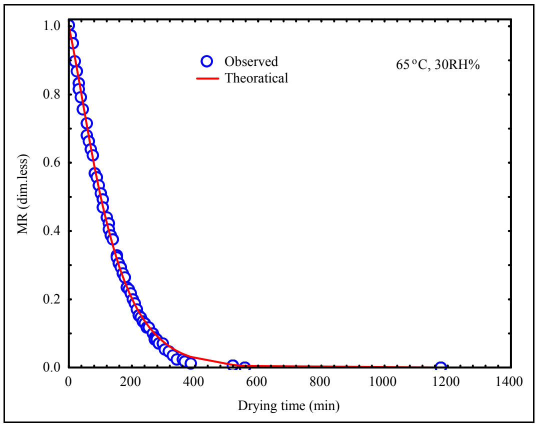

Figure 4a. MR vs. time (65°C, 30%RH).

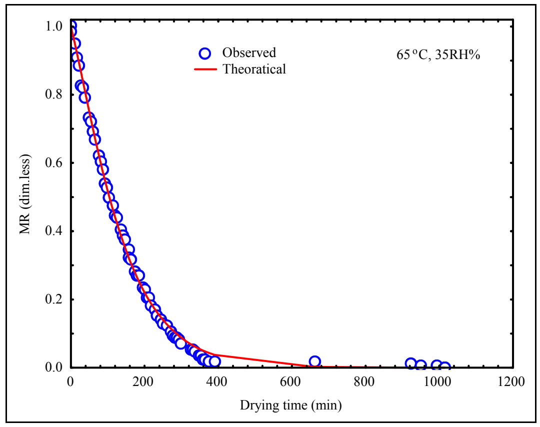

Figure 4b. MR vs. time (65°C, 35%RH).

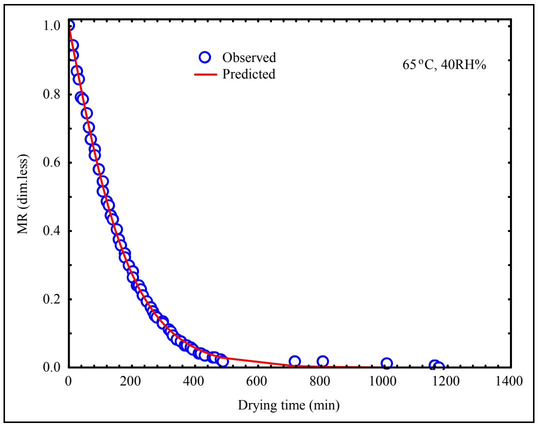

Figure 4c. MR vs. time (65°C, 40%RH).

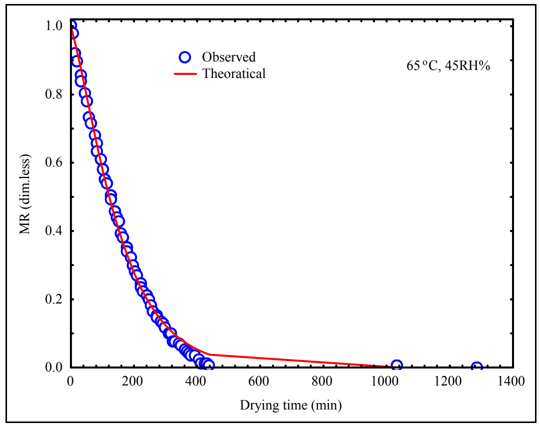

Figure 4d. MR vs. time (65°C, 45%RH).

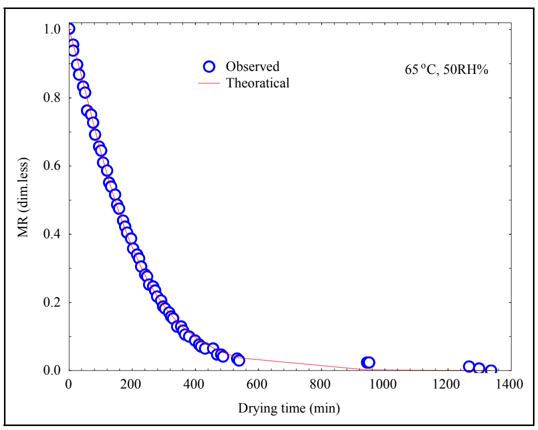

Figure 4e. MR vs. time (65°C, 50%RH).

4.2 Drying Constants (k)

The drying constant (k) data in the literature are scarce, which is 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 the drying rate constant, as it reported by several workers (Saeed *et al.*, 2006; Tarigan, 2007).

However, in drying of Roselle, the drying constant was not significantly affected by the drying temperature (p = 0.239), as shown in Tables 3 and 4. The values of (k) resulted from fitting of two-term exponential model, at different drying-air conditions, were shown in Table 3. The values were not followed a clear pattern with the drying temperatures.

Table 3. Drying constant (k): two term exponential

Temp.	Relative Humidity (%)				
°C	30	35	40	45	50
35	0.00557	0.01138	0.02353	0.01294	0.00890
45	0.02849	0.00739	0.00631	0.00478	0.00689
55	0.00518	0.00371	0.00635	0.00426	0.00341
65	0.01040	0.00978	0.00828	0.00870	0.00707

The drying constant increases, in general, with increasing the drying temperature. The effects of temperature depend strongly on the nature of the food material (Gupta *et al.*, 2002; Krokida *et al.*, 2004). On the other hand, drying-air relative humidity has, to lesser extent influenced the drying constant (p = 0.701), as shown in Table 5. Similar result was found by others (Saeed *et al.*, 2006).

Table 4. One-way ANOVA: Drying constant versus Temperature

```
Source  DF         SS         MS     F      P
Temp     3  0.0001730  0.0000577  1.56  0.239
Error   16  0.0005930  0.0000371
Total   19  0.0007659

S = 0.006088   R-Sq = 22.58%   R-Sq(adj) = 8.07%

                              Individual 95% CIs For Mean Based on Pooled StDev

Level  N      Mean     StDev  --+---------+---------+---------+-------
35     5  0.012467  0.006784                 (-----------*----------)
45     5  0.010773  0.009954              (-----------*----------)
55     5  0.004582  0.001199  (----------*-----------)
65     5  0.008847  0.001300          (-----------*----------)
                              --+---------+---------+---------+-------
                              0.0000    0.0050    0.0100    0.0150
Pooled StDev = 0.006088
```

Table 5. One-way ANOVA: Drying constant versus RH

```
Source  DF         SS         MS     F      P
RH       4  0.0000981  0.0000245  0.55  0.701
Error   15  0.0006678  0.0000445
Total   19  0.0007659

S = 0.006673   R-Sq = 12.81%   R-Sq(adj) = 0.00%


                               Individual 95% CIs For Mean Based on Pooled StDev

Level  N      Mean     StDev   -+---------+---------+---------+--------
30     4  0.012410  0.010981            (-----------*-----------)
35     4  0.008066  0.003338      (----------*-----------)
40     4  0.011120  0.008327           (-----------*----------)
45     4  0.007673  0.004035     (-----------*-----------)
50     4  0.006569  0.002296   (-----------*-----------)
                               -+---------+---------+---------+--------
                              0.0000    0.0060    0.0120    0.0180
Pooled StDev = 0.006673
```

The average value of the drying constant k obtained from the two-term exponential model was 0.009167. Furthermore, the values of k were within the range found in the literature for various agriculture produces. As examples, drying of potato slices (k = 0.144633) (Akpinar *et al.*, 2003a); Sun drying of figs (k = 0.186061) (Doymaz, 2005); drying of prickly pear fruit (k = 0.0097), (Lahsasni *et al.*, 2004b); laboratory drying of mushroom (k = 0.7001); and Pollen (k = 5.1933), solar drying of unshelled pistachio (k = 0.2296), natural solar drying shelled pistachios: k = 0.7412, and unshelled pistachios k = 0.6170 (Midilli *et al.*, 2002); convective drying of shelled pistachios (k = 0.1560), and unshelled: (k = 0.7590) (Midilli & Kucuk, 2003); natural solar drying of shelled pistachios (k = 0.7412), and unshelled (k = 0.6170) (Midilli & Kucuk, 2003); drying kinetics of single apricot (k = 2.1135) (Togrul & Pehlivan, 2003); solar drying of sultana grapes (k = 0.226307) (Yaldiz *et al.*, 2001).

4.3 Drying Parameters (a)

The values of the drying parameter (a) resulted from fitting of two-term exponential model, at different drying conditions, were shown in Table 6. The drying parameter (a) was significantly effected by the drying temperature (p = 0.000), as shown in Table 7.

Table 6. Drying parameter (a): two term exponential

Temp.	Relative Humidity (%)				
^{o}C	30	35	40	45	50
35	0.16627	0.07418	0.03125	0.06127	0.07888
45	0.06190	0.22234	0.22643	0.29516	0.23269
55	0.62615	0.72207	1.60136	1.43384	0.98888
65	1.77252	1.73487	1.66110	1.78543	1.74605

The parameter (a) was found to increase linearly with the drying temperature at constant relative humidity (Table 6). In addition, there was an increase in the average values of coefficient (a) with the relative humidity, at constant temperature. However, the relationship was not strong as that of the temperature (p = 0.989), as presented in Table 8. Westerman *et al.*, (1973) showed that a decrease in relative humidity from 54 to 11 % decreased the drying constant of corn from 0.884 to 0.523 at 71°C. The drying parameters (k) and (a) of the two-term exponential model were not behaved in the similar manner; as Jayas *et al.*, (1991) also concluded that it is not necessary all the coefficient increase or decrease at the same time.

Table 7. One-way ANOVA: drying parameter (a) versus Temperature

```
Source  DF      SS      MS      F      P
Temp     3  9.1122  3.0374  61.60  0.000
Error   16  0.7889  0.0493
Total   19  9.9012

S = 0.2221   R-Sq = 92.03%   R-Sq(adj) = 90.54%


                          Individual 95% CIs For Mean Based on Pooled StDev

Level  N    Mean   StDev  --+---------+---------+---------+-------
35     5  0.0824  0.0504  (--*---)
45     5  0.2077  0.0867    (--*---)
55     5  1.0745  0.4299                  (---*--)
65     5  1.7400  0.0485                             (---*---)
                          --+---------+---------+---------+-------
                          0.00      0.60      1.20      1.80
Pooled StDev = 0.2221
```

Table 8. One-way ANOVA: drying parameter (a) versus RH

```
Source  DF     SS     MS     F      P
RH       4  0.187  0.047  0.07  0.989
Error   15  9.714  0.648
Total   19  9.901

S = 0.8047   R-Sq = 1.89%   R-Sq(adj) = 0.00%


                          Individual 95% CIs For Mean Based on Pooled StDev

Level  N    Mean   StDev  ----+---------+---------+---------+-----
30     4  0.6567  0.7832  (----------------*----------------)
35     4  0.6884  0.7507   (----------------*----------------)
40     4  0.8800  0.8714      (----------------*----------------)
45     4  0.8939  0.8442       (----------------*----------------)
50     4  0.7616  0.7674    (----------------*----------------)
                          ----+---------+---------+---------+-----
                            0.00      0.50      1.00      1.50
Pooled StDev = 0.8047
```

The average values of the drying coefficients (a) obtained from the model was 0.776132. Moreover, the values of (a) were within the range found in the literature for various agriculture produces. As examples, drying of potato slices (a = 0.0667) (Akpinar *et al.*, 2003a); Sun drying of figs (0.140044) (Doymaz, 2005); drying of prickly pear fruit (a = 1.6283), (Lahsasni *et al.*, 2004b); laboratory drying of mushroom (a = 1.0001); and Pollen (a = 0.1981), solar drying of unshelled pistachio (a = 0.0627), natural solar drying shelled pistachios: a = 0.0434, and unshelled pistachios a = 0.0597 (Midilli *et al.*, 2002); convective drying of shelled pistachios (a = 0.0589), and unshelled: (a = 0.0627) (Midilli & Kucuk, 2003); natural solar drying of shelled pistachios (a = 0.0434), and unshelled (a = 0.0597) (Midilli & Kucuk, 2003); drying kinetics of single apricot (a = 0.0019) (Togrul & Pehlivan, 2003); solar drying of sultana grapes (a = 0.159830) (Yaldiz *et al.*, 2001).

4.4 Drying Rate (DR)

Figures 5 through 8 show the plotting of the drying rate (DR) vs. moisture ratio (MR) at different drying conditions. Higher drying rates were occurred at higher moisture levels. This observation is also reported by other researchers (Guine´ *et al.*, 2007). The rates were then tend to towards approximately zero at the end of the process, since at this stage, the moisture content of Roselle diminishes and the water removal becomes negligible.

Higher drying-air temperatures produced higher drying rates, at the same water content, and hence faster decrease in the moisture content of Roselle is observed, as it was reported in the literature (Akendo *et al.* 2008; Belghit *et al.*, 2000; Kouhila *et al.*, 2002; Lahsansi *et al.*, 2004b). Moreover, it is also evident that the drying time of Roselle was decreased considerably with increasing drying-air temperature, as similar behaviour was observed by many authors (Goyal *et al.*, 2007; Mwithiga & Olwal, 2005; Saeed *et al.*, 2006; Upadhyay *et al.*, 2008). This is because the capacity of the air to remove moisture increases with its temperature (Sigge *et al.*, 1998).

In contrast to air temperature, an increase in the air-relative humidity, at constant temperature, decreases the drying rate of Roselle; a similar result was observed others (Digvir *et al.*, 1991; Doymaz & Pala, 2002). Although, this effect was much lower than that of the air-temperature, as it reported by Saeed *et al.*, 2006.

According to Janjai & Tung, (2005) Roselle's calyxes have a natural wax-coat on their surfaces, which prevents most of the migration of moisture from the inside into the drying-air. After the surface is dried the wax is broken, and some of the moisture from inside can be released. Furthermore, at the end of the drying, the drying rate is very slow because of low water content gradient and most of water to be evaporated is in the monolayer or multi-layer water with a high binding energy. In the main, at the start of the drying process, the rate of water migration to the surface is lower than that of evaporation, causing a continuously drier surface. It is obviously that the drying rate was increased as the temperature is increased from 35^{o}C to 65^{o}C. The average drying rates at different drying conditions and MR intervals (1, 1-0.5, 0.5-0.1, 0.1-0.05, and 0.05-0.02), were shown in Table 9. These MR intervals are corresponding to 0%, 0-50%, 50-90%, 90-95%, 95-98% of the drying process. The results of correlations of the drying rates and MR are given in Table 10.

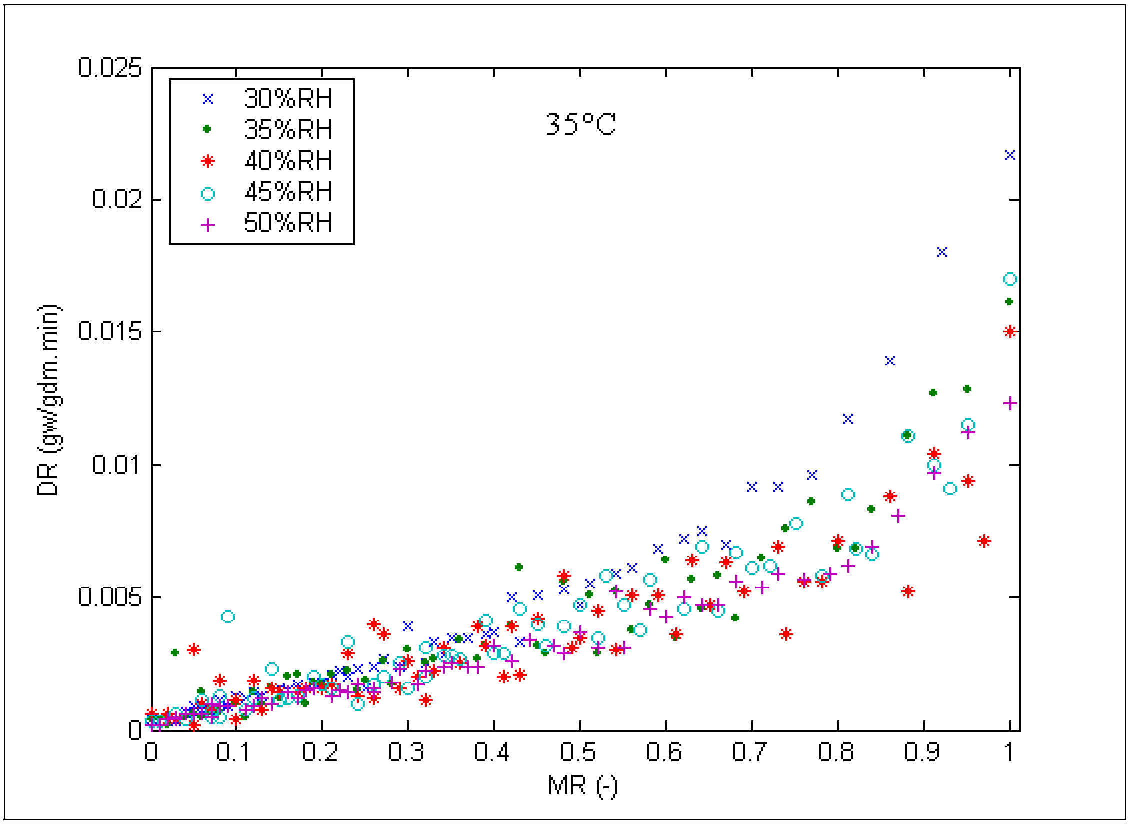

Figure 5. DR vs. MR at 35°C (30-50%RH).

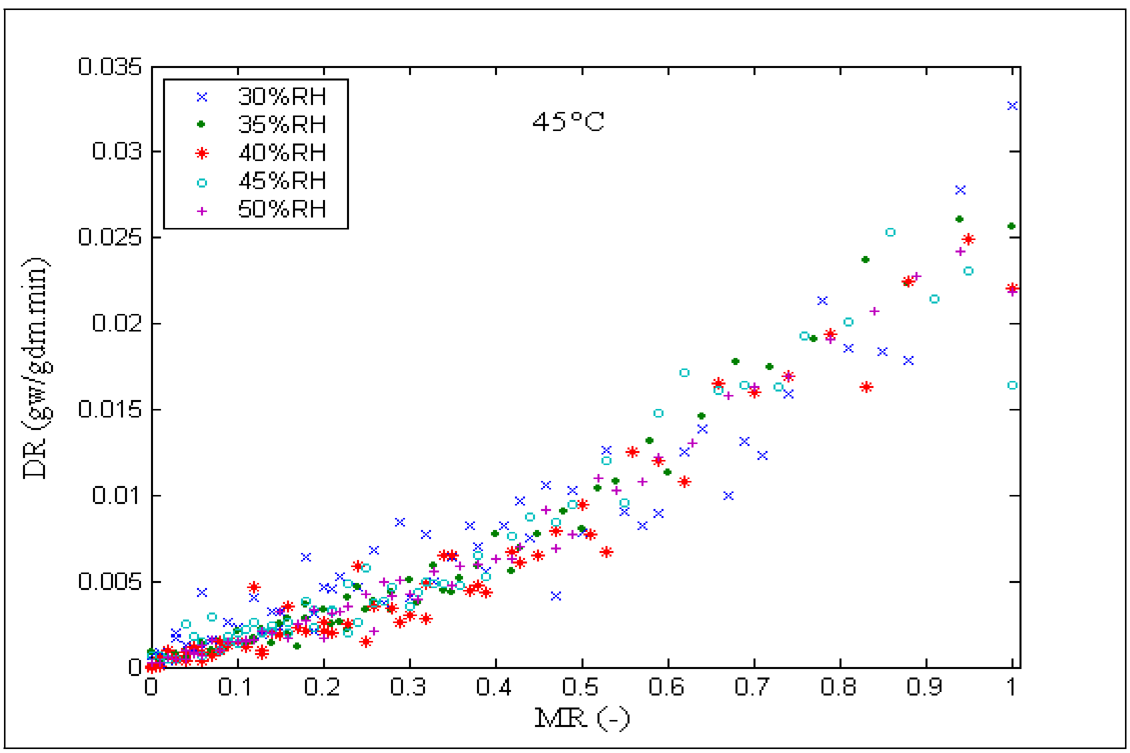

Figure 6. DR vs. MR at 45°C (30-50%RH).

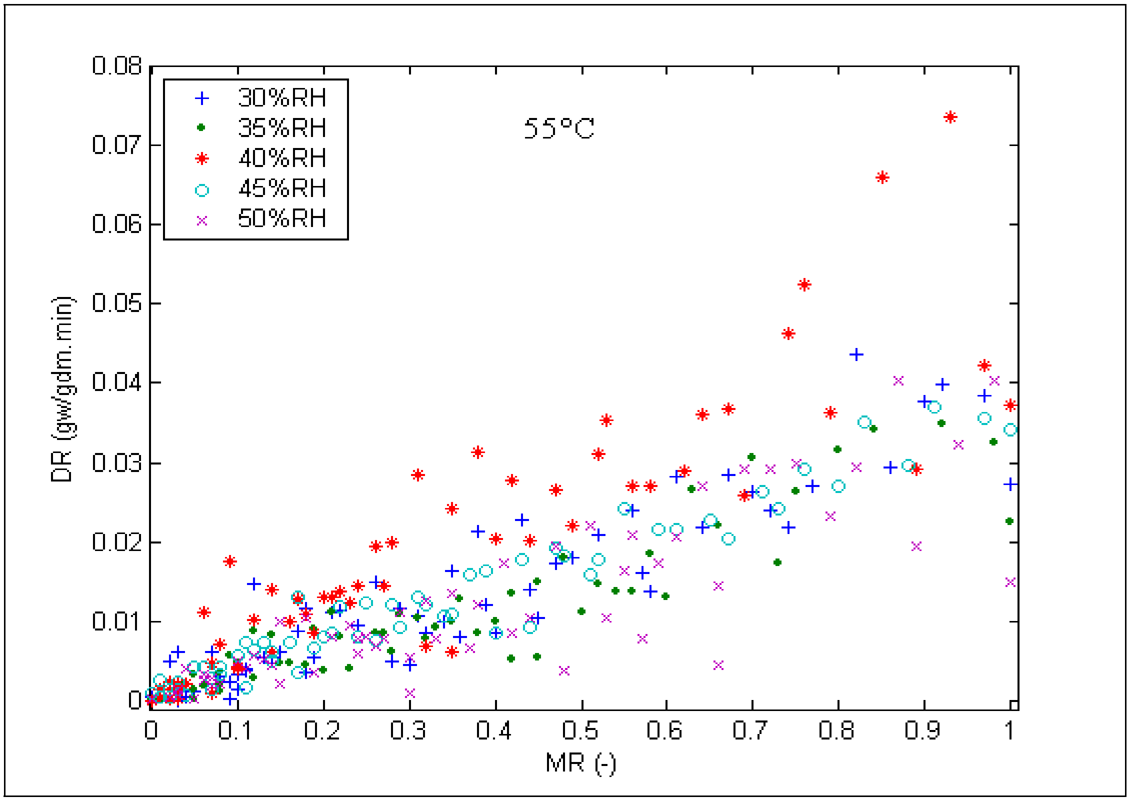

Figure 7. DR vs. MR at 55°C (30-50%RH).

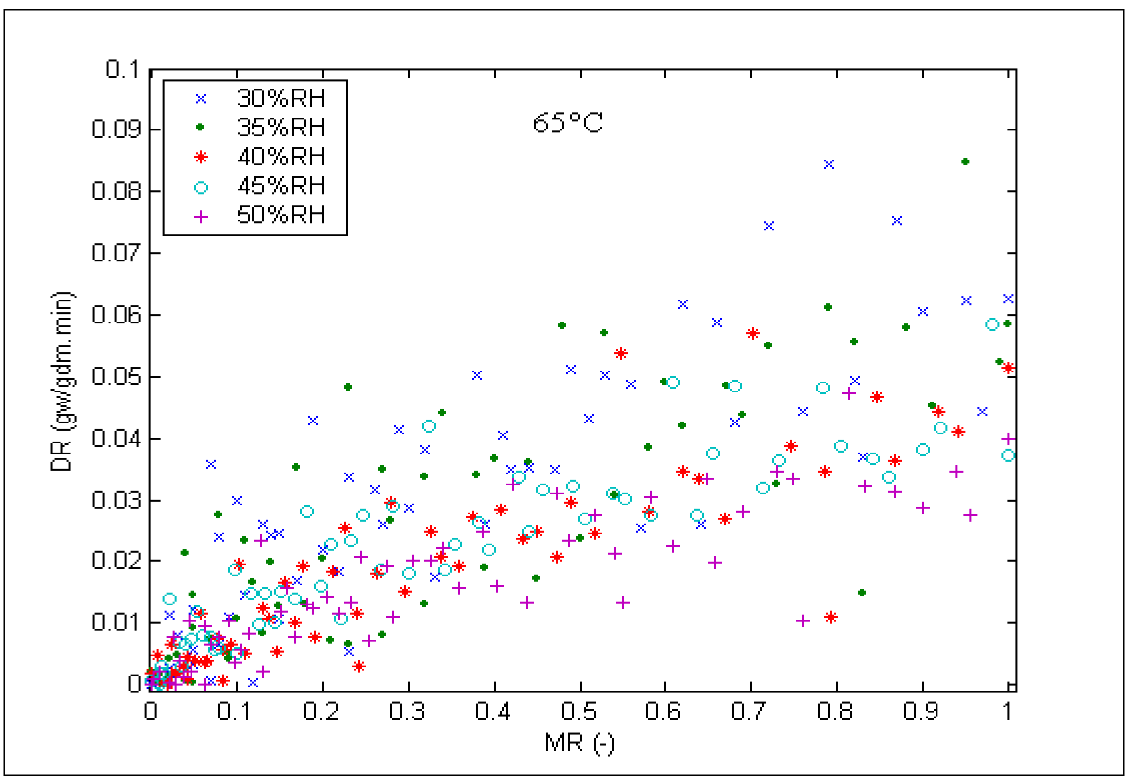

Figure 8. DR vs. MR at 65°C (30-50%RH).

Table 9. Average drying rates at different drying conditions and MR intervals

RH	MR (-)					MR(-)				
%	1.0	1-0.5	0.5-0.1	0.1-.05	0.05-.02	1.0	1.0-0.5	0.5-0.1	0.1-.05	0.05-.02
	35°C					45°C				
30	0.0217	0.0096	0.0025	0.0009	0.0005	0.0327	0.0154	0.0055	0.0020	0.0013
35	0.0161	0.0071	0.0025	0.0008	0.0012	0.0256	0.0169	0.0038	0.0012	0.0008
40	0.0150	0.0063	0.0024	0.0010	0.0013	0.0221	0.0157	0.0038	0.0010	0.0008
45	0.0170	0.0072	0.0023	0.0014	0.0004	0.0164	0.0175	0.0041	0.0015	0.0005
50	0.0123	0.0061	0.0019	0.0008	0.0005	0.0218	0.0165	0.0041	0.0012	0.0005
	55°C					65°C				
30	0.0273	0.0276	0.0103	0.0025	0.0030	0.0625	0.0529	0.0279	0.0139	0.0073
35	0.0226	0.0231	0.0084	0.0028	0.0016	0.0586	0.0473	0.0249	0.0099	0.0080
40	0.0373	0.0394	0.0155	0.0083	0.0017	0.0513	0.0375	0.0179	0.0054	0.0031
45	0.0342	0.0264	0.0102	0.0037	0.0019	0.0371	0.0377	0.0213	0.0096	0.0076
50	0.0149	0.0225	0.0082	0.0030	0.0014	0.0400	0.0287	0.0160	0.0063	0.0037

Table 10. Correlations: Drying rate and MR

	MR				
	1.0	1.0 - 0.5	0.5 - 0.10	0.10 - 0.05	0.05 - 0.02
Correlation coeff. (r^2)	0.945	0.992	0.946	0.926	0.865
p - values	0.055	0.008	0.054	0.074	0.135

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, 2005; Prabhanjan, 1995). In addition, the soft heating of the product accelerates the water migration inside the product (Kouhila *et al.*, 2002).

Moreover, the drying is observed in the falling rate period only for the range of the temperatures applied (Efremov, 2002; Togrul & Pehlivan, 2003). Drying during the falling rate period is so governed by water diffusion in the solid. This is a complex mechanism involving water in both liquid and vapour states, which is very often characterized by a so-called effective diffusivity (Lahsasni *et al.*, 2004b).

The moisture ratio can be given as a function the drying constant and coefficients of the model (Jain & Pathare, 2004; Sacilik 2007; Wang, 2007) as follows:

$$MR(a,k,t) = \frac{M - M_e}{M_o - M_e} = a \,.\, \exp(-kt) + (1-a)\exp(-kat)$$

The constant and coefficients were correlated with the drying-air temperature and RH as follows:

$$a = -2.143684 + 0.058396\ T \qquad (r^2 = 0.9356)$$

$$k = 0.018828 - 0.000242\ RH \qquad (r^2 = 0.5945)$$

Where, MR, t, T, and RH are dimensionless moisture ratio, drying time (minutes), temperature (^oC), and relative humidity (%), respectively. These expressions can be used to estimate the moisture content of Roselle, with a good accuracy, in the range of the tested drying conditions.

4.5 Validation of the Two-term Exponential Model

To validate the two-term exponential model, the predicted MR were plotted against the observed values (Midilli *et al.*, 2002; Saeed *et al.*, 2006; Simal, 2005; Togrul & Pehlivan, 2002, 2003; Yaldiz & Ertekyn, 2001). Figures 9a to 9d show the plotting of the predicted moisture content (MR_{pred}) versus observed moisture content (MR_{exp}) of the two-term exponential model, at different drying conditions.

The plots show smooth and good scatter of the data-points around the fitted straight-line. This indicated that the differences between the predicted and observed values are very low, and the model has very high performance for describing the characteristics of drying curves (Waewsak *et al.*, 2006), which confirms the goodness of the model to estimate the moisture content of the Roselle. Moreover, the values of the correlation coefficient (r^2) obtained from plotting of the predicted and observed MR values, at different conditions, were given in Table 11. The hypothesis of linearity (y = Ax + B) and that A = 1 and B = 0 were tested, and the results are presented in Table 12.

Table 11. Values of r^2 obtained from plotting of MR_{pred} vs. MR_{exp}

Temp.	Relative Humidity (%)				
^oC	30	35	40	45	50
35	0.9990	0.9994	0.9986	0.9992	0.9992
45	0.9984	0.9983	0.9978	0.9985	0.9994
55	0.9992	0.9977	0.9993	0.9992	0.9982
65	0.9986	0.9983	0.9993	0.9970	0.9988

Table 12. Testing of the hypothesis: y = Ax + B; A=1 and B=0

T (^oC)	Formula	A	B	r^2
35	$MR_{pred} = 1.00 * MR_{exp} - 0.004$	1.00	-0.004	0.999
45	$MR_{pred} = 0.99 * MR_{exp} + 0.007$	0.99	0.007	0.999
55	$MR_{pred} = 1.00 * MR_{exp} + 0.002$	1.00	0.002	0.999
65	$MR_{pred} = 0.99 * MR_{exp} + 0.006$	0.99	0.006	0.998

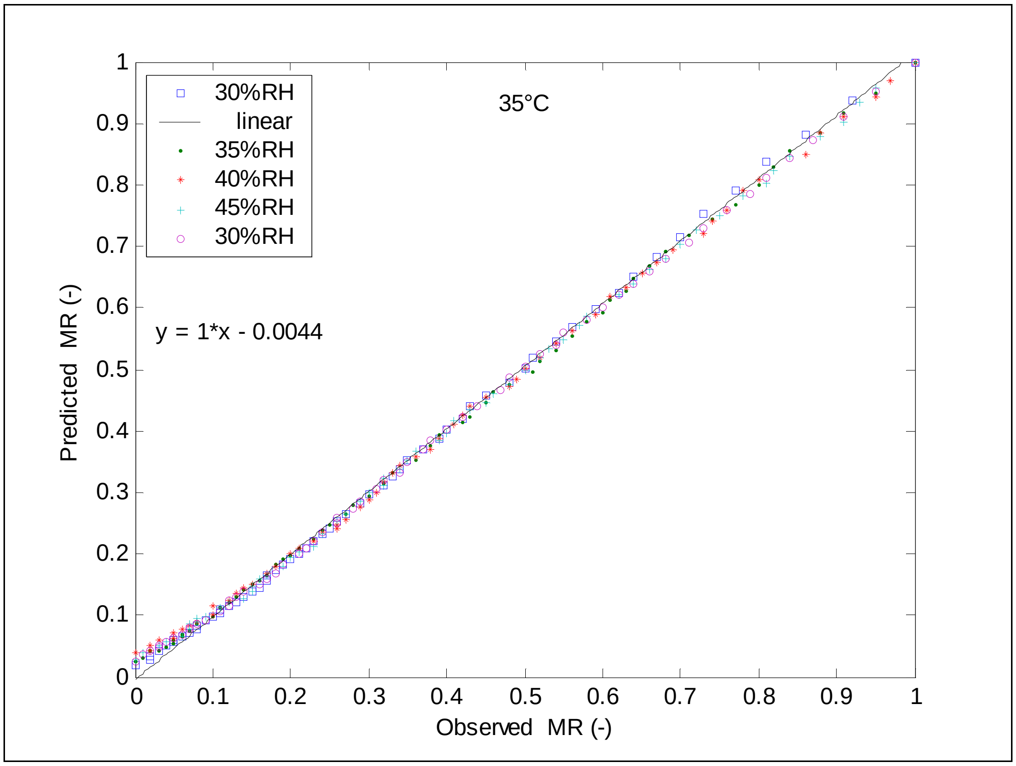

Figure 9a MR_{pred}. vs. MR_{obser} (35°C; 30, 35, 40, 45, and 50%RH).

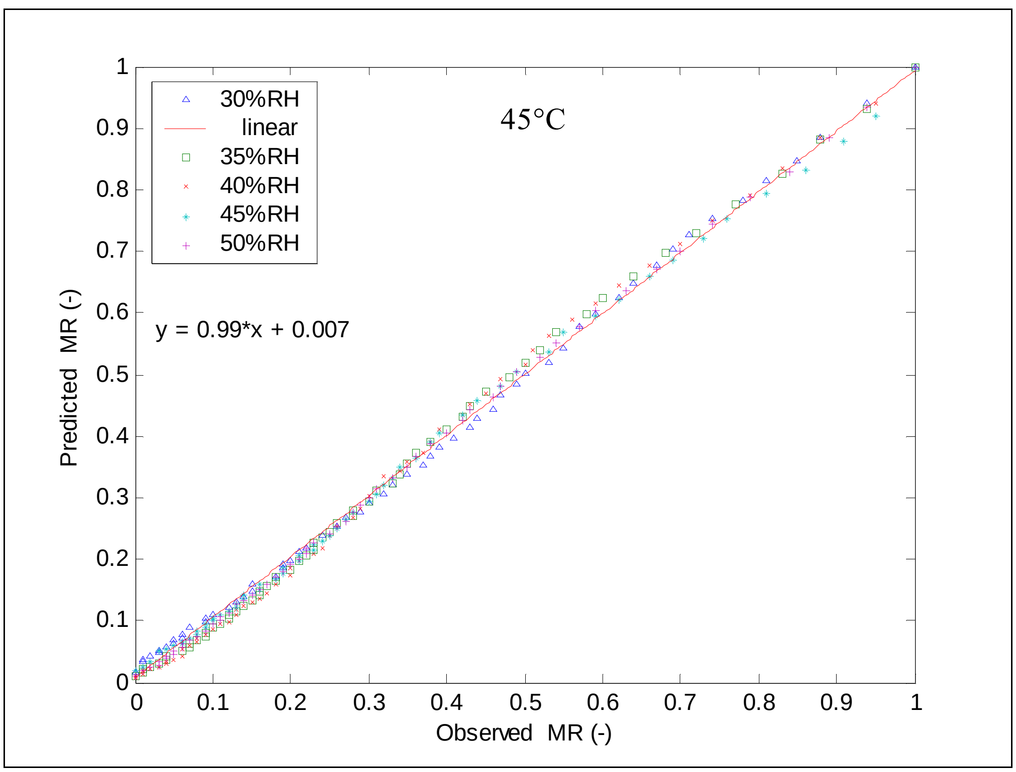

Figure 9b. MR_{pred} vs. MR_{obser} (45°C; 30, 35, 40, 45, and 50%RH).

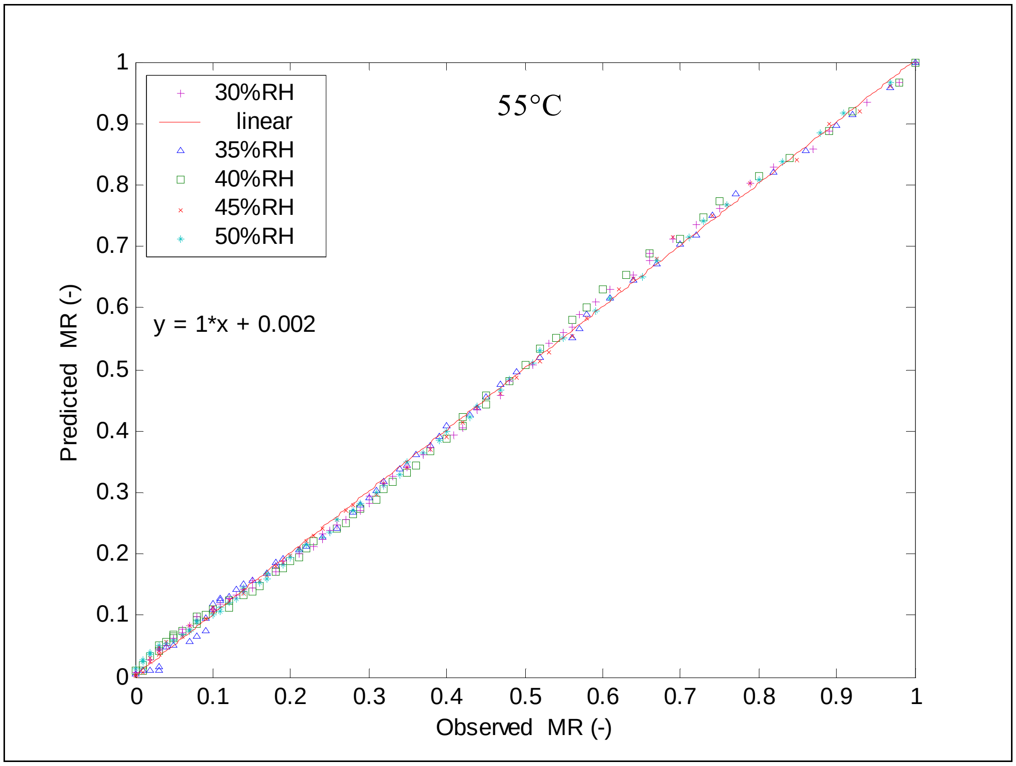

Figure 9c. MR_{pred} vs. MR_{obser} (55°C; 30, 35, 40, 45, and 50%RH).

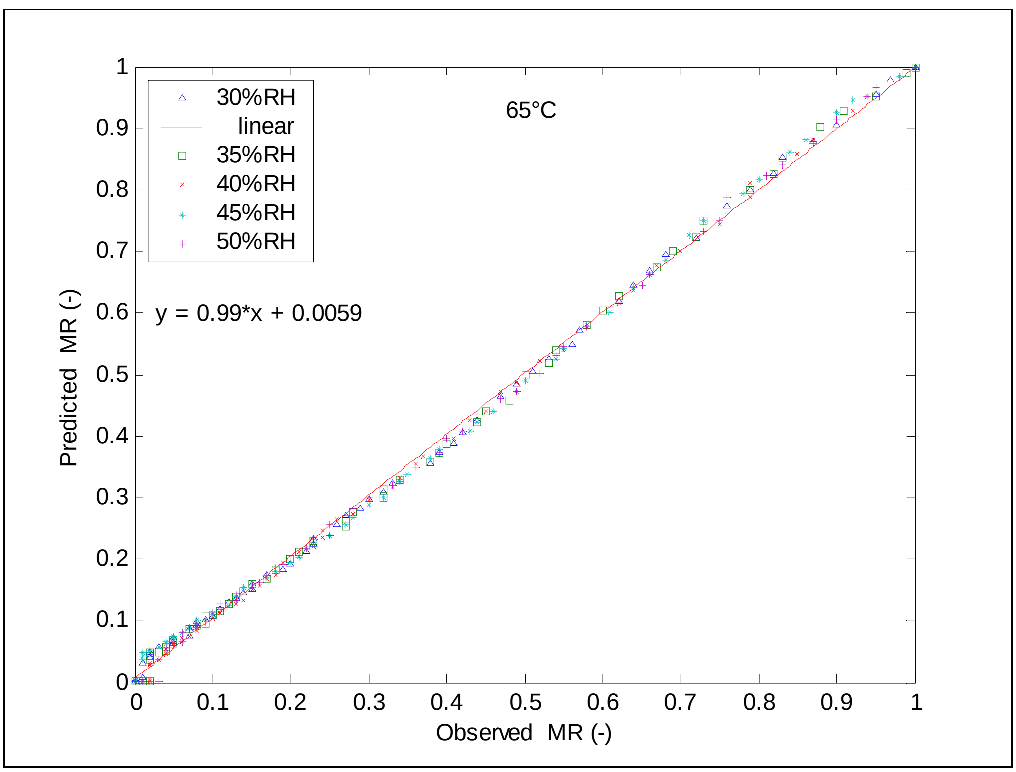

Figure 9d. MR_{pred} vs. MR_{obser} (65°C; 30, 35, 40, 45, and 50%RH).

Another criterion is used to validate the two-term exponential model, i.e. the plotting of the residual versus the predicted values by the model (Keller, 2001; Peck *et al.*, 2001; Spatz, 2001; Vardeman & Jobe, 2001).

Figures 10a through 10d show the plotting of the residual and predicted values resulted from fitting of the two-term exponential model to the experimental data. The residual were randomly scattered around the "zero-line" indicating that the model describes the data well.

No systematically positive or negative of the residual data for much of the data range, and the data points were not skewed or displayed systematic tendencies toward a clear pattern (Chen & Morey, 1989; Xanthopoulos *et al.*, 2007). These signify the suitability of the two-term exponential model to, adequately, describe the drying behaviour of the Roselle.

In the main, the residual plots proved that no systematic error was involved. It is noticeable from Table 11, that the model predicts the drying behaviour of Roselle at low temperatures a little bit better ($r^2 = 0.999$) than at higher temperatures ($r^2 = 0.998$).

The model over estimates the moisture contents at the start and the end of the drying processes, while under estimating the "mid way" of the drying.

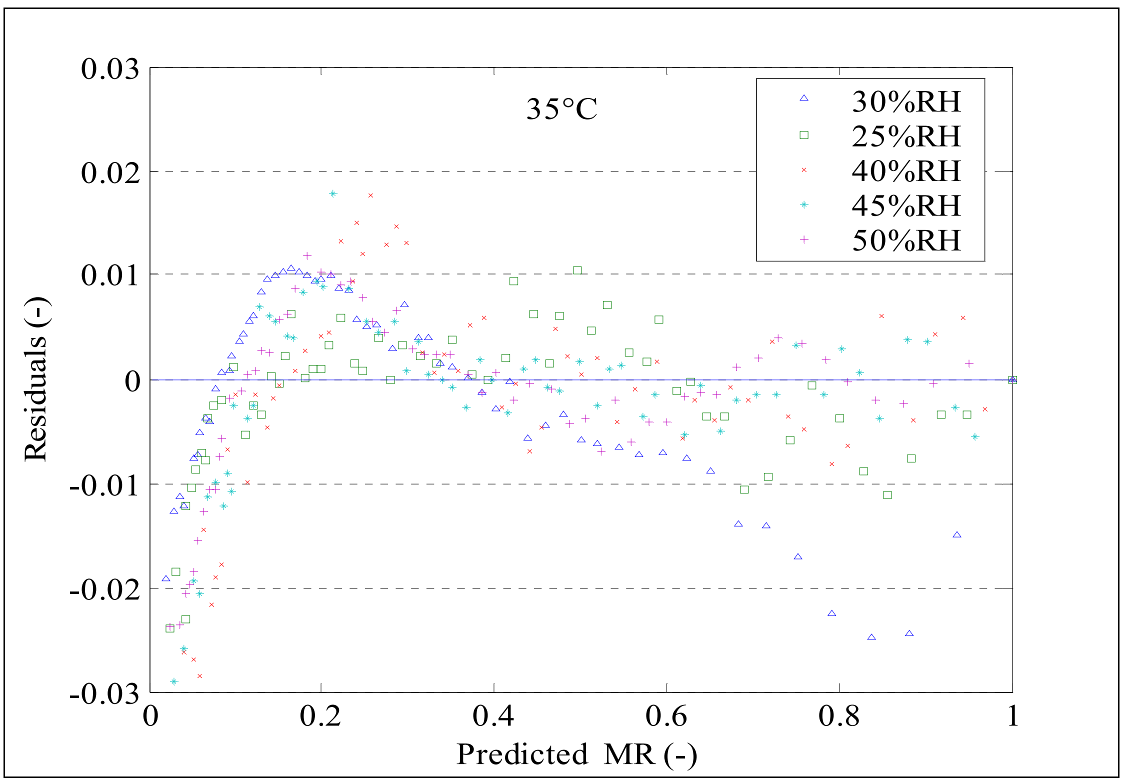

Figure 10a. Residuals vs. MR_{pred} at 35°C (30, 35, 40, 45, and 50%RH).

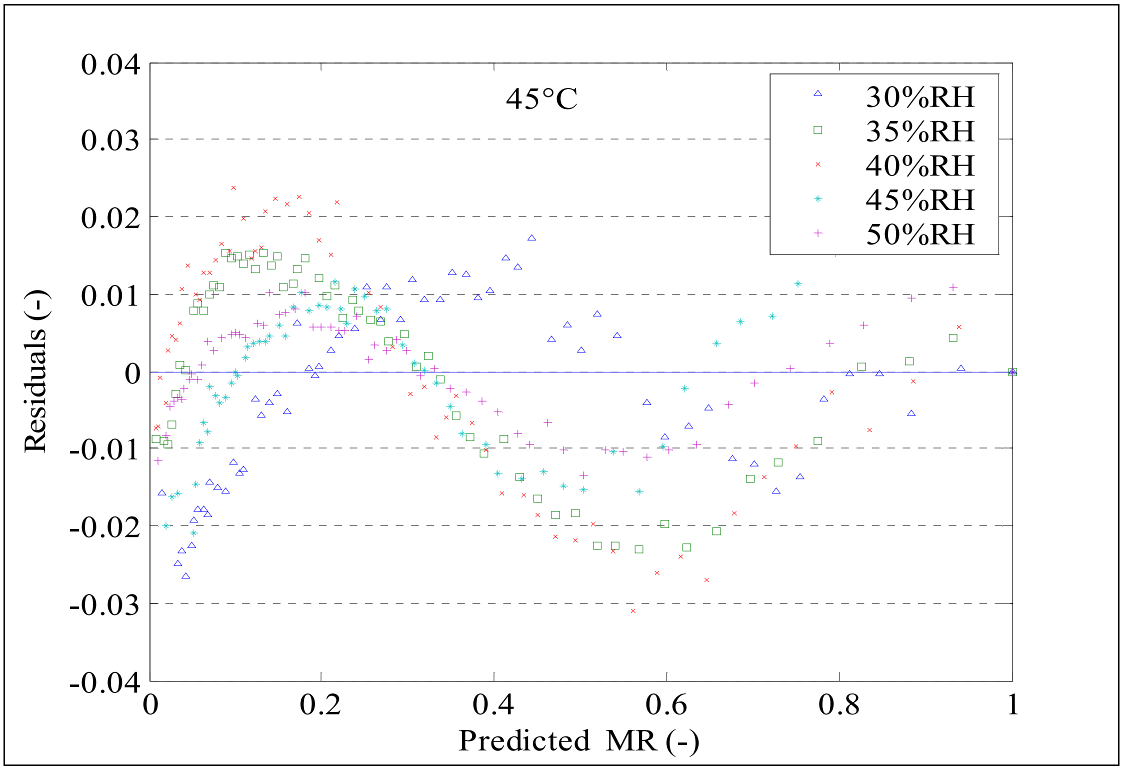

Figure 10b. Residuals vs. MR_{pred} at 45°C (30, 35, 40, 45, and 50%RH).

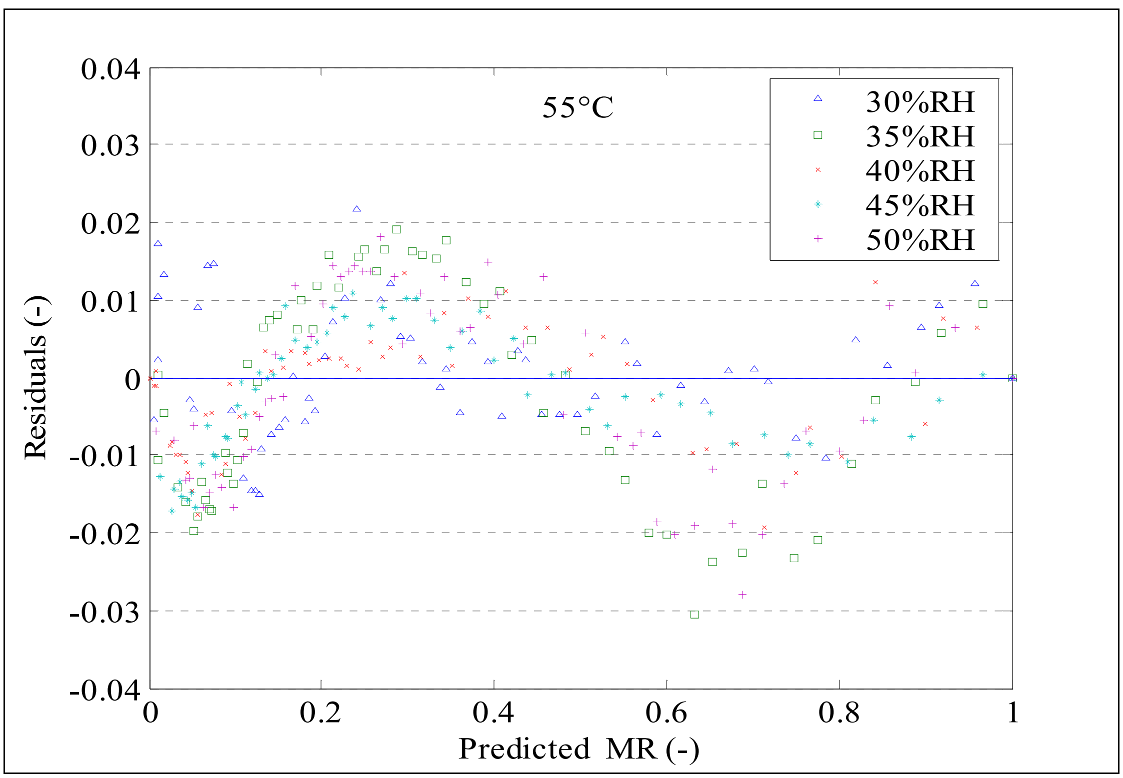

Figure 10c. Residuals vs. MR_{pred} at 55°C (30, 35, 40, 45, and 50%RH).

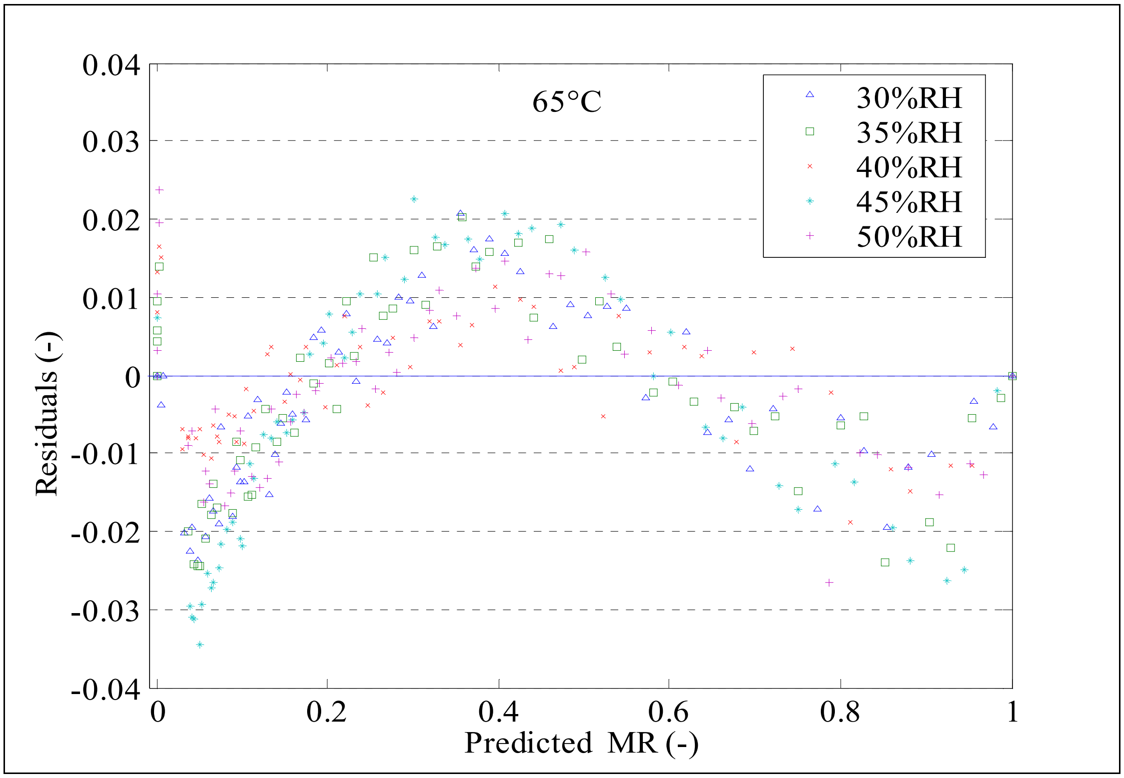

Figure 10d. Residuals vs. MR_{pred} at 65°C (30, 35, 40, 45, and 50%RH).

5. CONCLUSIONS

The drying process of Roselle is observed in the falling rate period only. The drying rates were enhanced as the temperature was increased from 35°C to 65°C. In contrast, an increase in air-relative humidity, at constant temperature, decreases the drying rates. The drying constant was not significantly effected by the temperature (p = 0.239) and relative humidity of the drying-air (p = 0.701). The drying parameter (a) is significantly effected by drying temperature (p = 0.000), and it is slightly effected by the relative humidity (p = 0.989). Two criterions were applied to validate the two-term exponential model, i.e., the plotting of the MR_{pred} against MR_{exp}, and the residual versus MR_{pred}. The results confirmed the suitability of the model to predict the drying characteristics of the Roselle, satisfactorily, in the range of the tested drying conditions.

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7. APPENDIX

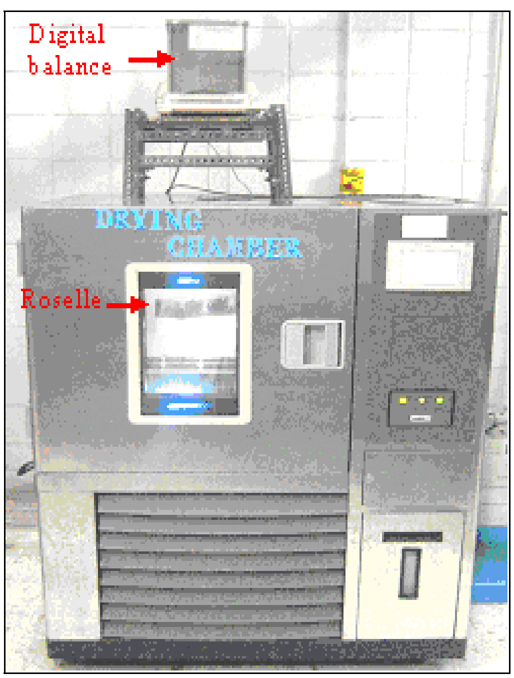

Figure A1. Laboratory drying chamber.

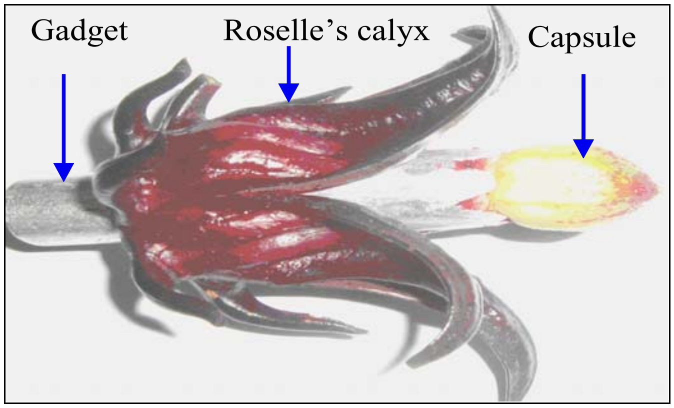

Figure A2. Fresh Roselle.

Figure A3. Dried Roselle.

8. NOMENCLATURE

a	drying parameter	M_t	moisture content at time t ($g_w.g_{dm}^{-1}$)
DR	drying rate ($g_w.g_{dm}^{-1}min^{-1}$)	M_{t+dt}	moisture content at (t+dt) ($g_w.g_{dm}^{-1}$)
k	drying constant (min^{-1})	N	number of data points (observations)
M	instantaneous moisture ($g_w.g_{dm}^{-1}$)	n_p	number of unknown parameters
MC_{db}	moisture content dry basis ($g_w.g_{dm}^{-1}$)	t	drying time (min)
M_e	equilibrium moisture ($g_w.g_{dm}^{-1}$)	W_d	weight of dry matter (g)
M_o	initial moisture content ($g_w.g_{dm}^{-1}$)	W_w	weight of water (g)
MR	moisture ratio (-)	Y_i	experimental data (g)
$MR_{exp,i}$	experimental value	$\overline{Y}$	average value of Y_i (g)
$MR_{pred,i}$	simulated value of $MR_{exp,i}$	$\hat{Y}$	estimated value of Y_i (g)