Drying characteristics of Roselle (1): Mathematical Modeling and Drying Experiments

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ABSTRACT

The effects of drying conditions on the drying behavior of Roselle (*Hibiscus sabdariffa* .L) and the applicability of twelve thin-layer drying models to predict the drying curves of Roselle were studied. The experiments were conducted in 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 studied. Drying air temperature was found to be the main factor affecting the drying kinetics of Roselle; raising the drying temperature from 35°C to 65°C dramatically reduced the drying times. The effect of the relative humidity was lower than that of temperature; increasing the relative humidity resulted on longer drying times. Higher equilibrium moisture contents were obtained with high relative humidities and low temperatures. Furthermore, drying was observed only in the falling-rate period. Statistical analysis was carried out and comparison among drying models was made to select the best-fitted model for the drying curves. Among twelve tested models, the two-term exponential model was found to be superior to the other models in terms of fitting performance.

Keywords: Roselle, air drying, mathematical models

1. INTRODUCTION

Drying process plays an important role in the preservation of agricultural products (Waewsak *et al.*, 2006). It enhances the resistance of high humid products against degradation by decreasing their water activity (Doymaz & Pala, 2003; Hadrich *et al.*, 2008; Simal *et al.*, 2005), as the losses of fruits and vegetables in developing countries are estimated to be 30-40% of the production (Azharul Karim & Hawlader, 2006). Therefore, in many agricultural countries, large quantities of food products are dried to improve shelf life, reduce packaging costs, lower weights, enhance appearance, retain original flavor and maintain nutritional value (Baysal *et al.*, 2003; Demir *et al.*, 2007; Simal *et al.*, 2000; Sokhansanj & Jayas, 1987). However, utilization of high amount of energy in drying industry, makes drying one of the most energy-intensive operations with great industrial significance (Carsky, 2008; Dincer, 2000; Dincer & Cengel, 2001; Dincer & Sahin, 2004; Shi *et al.*, 2008). Conventional (air) drying is the most frequently used dehydration operation in food and chemical industry (Nicoleti *et al.*, 2001; Singh *et al.*, 2008), due to its controllable conditions and less dependency on climatic conditions (Lertworasirikul & Tipsuwan, 2008).

Drying kinetics is generally evaluated experimentally by measuring the weight of a drying sample as a function of time. Drying curves may be represented in different ways; averaged moisture content versus time, drying rate versus time, or drying rate versus averaged moisture content (Coumans, 2000). Several theories on the mechanism of moisture migration have been reviewed by Mujumdar (1980); however, only capillary and liquid diffusion theories are, generally, applicable to the drying of food materials. Drying process can be described completely using an appropriate drying model, which is made up by differential equations of heat and mass transfer in the interior of the product and at its inter phase with the drying agent. Thus, knowledge of transport and material properties is necessary to apply any transport equation (Karathanos, 1999). Such properties are the moisture diffusivity, thermal conductivity, density, and specific heat and inter phase heat and mass transfer coefficients. Sometimes, in the literature instead of these properties, the drying constant, is used. This is a lumped parameter of the properties.

Furthermore, most of the work done consisted of data on thin layer drying of agricultural crops (Sarsavadia *et al.*, 1999), which is due to the non-isotropic and non-homogenous nature of the agricultural products, along with their irregular shape and the changes in their shape during drying. However, mathematical modeling of the drying behavior of agricultural products often requires statistical methods of regression and correlation analysis (Waewsak *et al.*, 2006).

The necessity of high quality fast-dried foods is leading to a renewed interest in drying operations (Maskan, 2001a). In addition, there is an increased demand for convenient foods including ready to eat and instant products, which are desired to contain the minimum quantities of additives and preservatives (Alves-Filho, 2002; Hawlader *et al.*, 2006; Shi *et al.*, 2008).

Roselle is an annual herbaceous shrub of the Malvaceae family. The swollen calyces are the plant part of commercial interest. As the flowers fall off, the bright red calyces swell. These are harvested, dried, and sold whole to the herbal tea and beverage industry. The flavor is a combination of sweet and tart (Plotto, 2007). Moreover, thorough descriptions of Roselle plants, its varieties, environmental requirements, uses, history etc., can be read in Duke (1983) and Morton (1987).

In the cited literature, no works on the hot-air thin-layer dying of Roselle were found. Therefore, the objectives of this Part (I), were to determine the effects of drying conditions on the drying behavior of Roselle (variety Arab), and the applicability of twelve thin-layer drying models to predict the drying curves of Roselle.

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):

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

And on wet basis (%) by the formula (Hall, 1980; Rodrigues & Fernandes, 2007; Simpson, 1991):

$$\%MC_{wb} = \frac{W_w}{W_w + W_d}.100 \qquad (2)$$

The two ways of expressing moisture content are related by (Ekechukwu, 1999; Hall, 1980):

$$\% \, MC_{db} = \frac{MC_{wb}}{100 - MC_{wb}}.100 \qquad (3)$$

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):

$$MR = \frac{M - M_e}{M_o - M_e} \qquad (4)$$

2.3 Drying Rate (DR)

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

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (5)$$

2.4 Mass Shrinkage Ratio (SR)

The most important structural variation appeared on crops, due to the weight loss, is the mass shrinkage ratio (SR), which can be given as (Midilli, 2001; Shanmugama & Natarajan, 2006):

$$SR = \frac{W_t}{W_o} \qquad (6)$$

2.5 Drying Models

Drying process involves complex heat and mass transfer phenomena, which are difficult, mathematically, to be described in microscopic scale. For the purpose of design and analysis it is often sufficient to use simple semi-empirical expressions, which can adequately, describe the drying kinetics, when the external resistance to heat and mass transfer, is eliminated or minimized (Midilli *et al.*, 2002). A common way to achieve this is to carry out experiments using a thin-layer of the material being dried. Numerous experimental and modeling efforts on single layer drying have been proposed. Table1 presents twelve thin-layer drying models most frequently used by various authors.

2.6 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:

$$SSR = \sum_{i}^{N} \left(\hat{Y}_i - \overline{Y} \right)^2 \qquad (7)$$

The total sum of squares

$$SST = \sum_{i=1}^{N} \left(Y_i - \overline{Y} \right)^2 \qquad (8)$$

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

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \qquad (9)$$

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)

$$SEE = \sqrt{\frac{\sum_{i=1}^{N} \left(MR_{exp,\ i} - MR_{cal,\ i} \right)^2}{N - np}} \qquad (13)$$

c. Root mean square error (RMSE)

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

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left(MR_{exp,\ i} - MR_{cal,\ i} \right)^2}{N}} \qquad (15)$$

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:

$$MSE = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N - np} \qquad (16)$$

Table 1. Thin-layer drying models given by various authors for drying curves

Model name	Equation	References
Newton	$MR = \exp(-kt)$	Ayensu, (1997); Togrul & Pehlivan, (2004); Upadhyay *et al.,* 2008
Page	$MR = \exp(-kt^n)$	Kaleemullah & Kailappan,(2006); Saeed *et al.*, (2006); Senadeera *et al.*, (2003)
Modified Page	$MR = \exp(-(kt)^n)$	Goyal *et al.*, (2007); Ceylan *et al.*, (2007); Sogi *et al.*, (2003)
Modified Page II	$MR = \exp(-k(t/L^2)^n)$	Midilli *et al.*, (2002); Wang *et al.*, (2007); Yaldiz & Ertekin, (2001)
Henderson & Pabis	$MR = a.\exp(-kt)$	Kashaninejad *et al.*, (2007); Saeed *et al.*, (2006); Ozdemir & Devres, (1999)
Modified Hend. & Pabis	$MR = a.\exp(-kt)+b.\exp(-gt) +c.\exp(-ht)$	Karathanos, (1999); Kaya *et al.*, (2007b); Yaldiz & Ertekin, (2001)
Simplified Fick's diffusion	$MR = a.\exp(-kt)+c$	Babalis *et al.*, (2006); Celma *et al.*, 2007; Lahsasni *et al.*, (2004b)
Logarithmic	$MR = a.\exp(-c(t/L^2))$	Togrul & Pehlivan, (2002; 2003); Wang *et al.*, (2007)
Two-term	$MR = a.\exp(-k_o t)+ b.\exp(k_1 t)$	Lahsasni *et al.*, (2004b); Rahman *et al.*, (1998); Wang *et al.*, (2007)
Two-term exponential	$MR = a.\exp(-kt)+(1-a)\exp(-kat)$	Midilli & Kucuk, (2003); Sacilik *et al.*, (2006); Tarigan *et al.*, (2007)
Verma *et al.*	$MR = a.\exp(-kt)+(1-a)\exp(-gt)$	Doymaz, (2005b); Karathanos, (1999); Yaldiz & Ertekin, (2001)
Diffusion approach	$MR = a.\exp(-kt)+(1-a)\exp(-kbt)$	Wang *et al.*, (2007); Yaldiz & Ertekin, (2001); Togrul & Pehlivan, (2002)

3. DRYING EXPERIMENTS

Thin-layer drying experiments with Roselle were carried out in Constant Temperature and Humidity Chamber (Model TH-1-180-L. JEIO TECH Co., Ltd, KOREA). The system is under the Faculty of Engineering, National University of Malaysia (UKM); 43600 UKM Bangi, S.D.E, Malaysia. 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 collected from the farm of the Faculty of Science and Technology, UKM. 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). Photograph of the drying system is shown in Figure1. Fresh Roselle (with seed's capsules removing tool) and dried Roselle were shown in Figures 2 and 3, respectively. The moisture contents were expressed on dry basis, which is more convenient for modeling (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.

Figure1. Laboratory drying chamber.

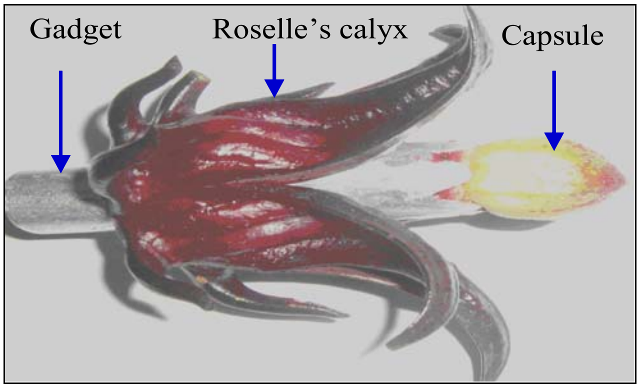

Figure 2. Fresh Roselle.

Figure 3. Dried Roselle.

4. RESULTS AND DISCUSSION

Fresh whole calyces of Roselle (60-61g) were dried from an average initial moisture content of 10.285db to an average final moisture content of 0.183db. The fit was performed using non-linear regression based on the minimization of the sum of squares; using least squares Levenberg-Marquardt algorithm implemented in the STATISTICA Version 6.0 computer program (Doymaz, 2005a; Doymaz, 2007; Saeed *et al.*, 2006). This method was used to estimate the drying constants (k) and the empirical coefficients of the drying models. Accordingly, the most suitable model in terms of fitting performance was selected to best describe the drying curves of Roselle.

4.1 Statistical Measures

The quality of the fitted drying models can be evaluated by different criteria. The values of the statistical measures, resulted from fitting of the twelve drying models to the experimental data, were presented in Table 2. In addition, the average, minimum, and maximum values of the whole models were also given. The model with the highest value for R^2 was selected to describe the drying curves. As well, the lowest the values of other parameters (SEE, RMSE, MSE) the good is the fit (Doymaz, 2004a; Kingsly & Singh, 2007; Saeed *et al.*, 2006).

It was noticeable that all the models showed high values for R^2 (Table 2). The two-term exponential model, compared to the others, produced the highest value for R^2. Table 3 presents the values of the statistics obtained from fitting of the model to the experimental data.

The values of R^2 and other statistical measures were better compared to the findings of several previous works in fitting the model to the experimental data. As an examples, drying of apple: R = 0.99869, $X^2 = 2.68\text{x}10^{-4}$ and pumpkin: R = 0.98952 and $X^2 = 2.31\text{x}10^{-3}$, Akpinar (2006); green table olives: r^2 = (0.9890 – 0.9987), RMSE = (0.009341 - 0.025469), and X^2 = (8.9 x10^{-5}- 6.54 x10^{-4}), Demir *et al.*(2007); drying of figs R^2 = 0.9912, X^2 = 7.06 x10^{-3}, and RMSE = 0.074918, Doymaz (2005b); black grapes R^2 = (0.9794-0.9989), X^2 = (1.01x10^{-4}-1.772x10^{-3}), Doymaz (2006); pumpkin slices R^2 = (0.9806-0.9890), X^2 (0.00122-0.00220), and RMSE (0.10495-0.18199), Doymaz (2007); prickly pear fruit r^2 = 0.9993 and X^2 = 1.1457x10^{-4}, Lahsasni *et al.* 2004b; golden apples RMSE = (0.00375-0.01136) and X^2 = (1.9x10^{-5}-1.66x10^{-4}), Menges *et al.* (2006); solar drying shelled pistachios r = 0.9668, X^2 = 4.756 x10^{-4}, and unshelled r = 0.970 and X^2 = 4.737x10^{-4}; natural solar drying of shelled pistachios r = 0.9380, X^2 = 4.521x10^{-4} and unshelled pistachios r = 0.9750 and X^2 = 3.360x10^{-4}, Midilli & Kucuk (2003); drying of single apricot: r = 0.990, RMSE = 0.0487 and X^2 = 0.002395, Togrul & Pehlivan (2003); solar drying of sultana grapes: r = 0.973 and X^2 = 0.005, Yaldiz *et al.* (2001).

Table 2. Statistical measures from modeling of drying curves: twelve drying models

Model	R^2	SEE	RMSE	MSE (X^2)
Newton	0.99626	0.024777	0.024569	0.000711
Page	0.99931	0.011624	0.011428	0.000140
Modified Page	0.99931	0.011624	0.011428	0.000140
Modified Page II	0.99931	0.011725	0.011428	0.000143
Henderson & Pabis	0.99786	0.018935	0.018616	0.000417
Modified Henderson & Pabis	0.99874	0.014307	0.013573	0.000285
Simplified Fick's diffusion	0.99852	0.015932	0.015528	0.000291
Logarithmic	0.99781	0.019296	0.018808	0.000433
Two-term	0.99874	0.014050	0.013573	0.000275
Two-term exponential	0.99939	0.010674	0.010495	0.000122
Verma *et al.*	0.99830	0.015524	0.015131	0.000363
Diffusion approach	0.99830	0.015564	0.015170	0.000364
Max	0.99939	0.024777	0.024569	0.000711
Min	0.99626	0.010674	0.010495	0.000122
Aver.	0.99849	0.015336	0.014979	0.000307

Table3. Statistical measures from modeling of drying curves: two-term exponential model

T (°C)	RH (%)	R^2	SEE	RMSE	MSE
35	30	0.999464	0.009690	0.009527	0.000094
	35	0.999772	0.007264	0.007142	0.000053
	40	0.999492	0.011270	0.011081	0.000127
	45	0.999726	0.008321	0.008181	0.000069
	50	0.999686	0.008392	0.008251	0.000070
45	30	0.999293	0.011919	0.011719	0.000142
	35	0.999068	0.012326	0.012119	0.000152
	40	0.998607	0.015353	0.015095	0.000236
	45	0.999300	0.011025	0.010840	0.000122
	50	0.999752	0.006501	0.006392	0.000042
55	30	0.999687	0.008200	0.008062	0.000067
	35	0.999053	0.013849	0.013616	0.000192
	40	0.999685	0.007831	0.007699	0.000061
	45	0.999646	0.008319	0.008179	0.000069
	50	0.999338	0.012302	0.012095	0.000151
65	30	0.999343	0.011945	0.011744	0.000143
	35	0.999209	0.012991	0.012773	0.000169
	40	0.999672	0.007837	0.007705	0.000061
	45	0.998557	0.017555	0.017260	0.000308
	50	0.999481	0.010594	0.010416	0.000112
Maximum		0.999772	0.017555	0.017260	0.000308
Minimum		0.998557	0.006501	0.006392	0.000042
Average		0.999392	0.010674	0.010495	0.000122

Drying Characteristics

The measurement of the material moisture content, as a function of time, under constant drying air conditions formed what is called the drying curves. To produce such curves, and to determine the effects of drying conditions on the drying behavior of Roselle, twenty thin-layers drying experiments were studied. The drying curves of Roselle at different drying conditions are shown in Figures 4 and 5.

Drying air temperature was found to be the main factor influenced the drying kinetics of Roselle (Saeed *et al.*, 2006). Table 4 shows the result of the ANOVA on the drying temperatures versus drying time. The effect of temperature on the drying time was very significant (p = 0.000). In addition, Figures 4a through 4e show the visual judgment of the effects of drying air temperature on the drying curves (DC) of Roselle (at constant relative humidity).

It is obvious that the drying process was enhanced substantially with the increment of the drying-air temperature. Similar behavior was reported by several authors (Akendo *et al.*, 2008; Belghit *et al.*, 2000; Falade & Abbo, 2007; Madamba *et al.*, 1996). This may be due to the fact that, higher temperature implies larger driving force for heat transfer (Methakhup *et al.*, 2005; Nimmol *et al.*, 2007). It also accelerates the drying process, as the temperature provides a larger water vapor pressure deficit (Prabhanjan *et al.*, 1995).

Table 4. One-way ANOVA: drying time versus temperature

```
Analysis of Variance for Drying Time
Source     DF        SS        MS        F        P
Temp        3    9585,1    3195,0   131,83    0,000
Error      16     387,8      24,2
Total      19    9972,9
                                   Individual 95% CIs For Mean Based on Pooled StDev

Level       N      Mean     StDev  ---+---------+---------+---------+---
1           5    74,467     7,176                              (-*--)
2           5    44,833     5,920               (-*--)
3           5    22,531     2,491    (-*--)
4           5    19,967     2,053   (-*-)
                                   ---+---------+---------+---------+---
Pooled StDev =    4,923              20        40        60        80
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The higher the temperature the bigger is the difference between the saturated and partial pressure of water vapor in the drying-air, which is one of the driving forces for drying; as there is a maximum amount of water (saturation) that air can hold at a given temperature. Moreover, the amount of free water present at the start is very important, since the rate of water removal is higher during this phase (Guine´ *et al.*, 2007). As the drying proceeds, the free water present decreases quite rapidly, so that at the final stages, water was hardly available and the drying becomes very slow.

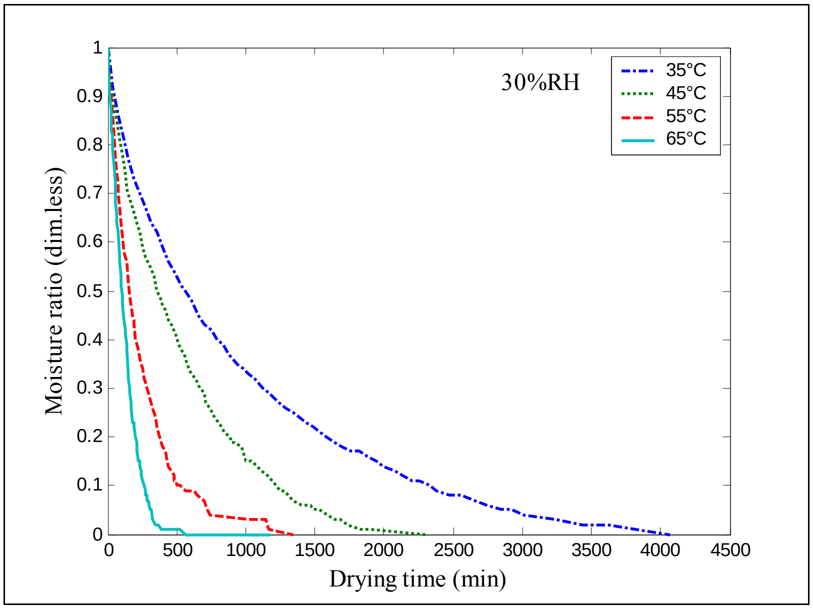

Figure 4a. Drying curves at 30%RH (35, 45, 55, and 65°C).

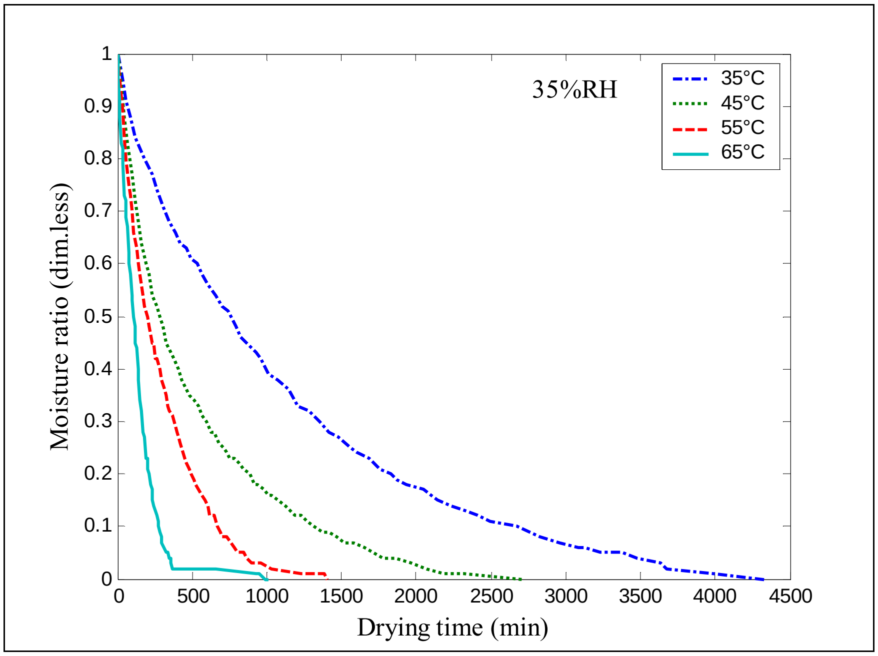

Figure 4b. Drying curves at 35%RH (35, 45, 55, and 65^{o}C).

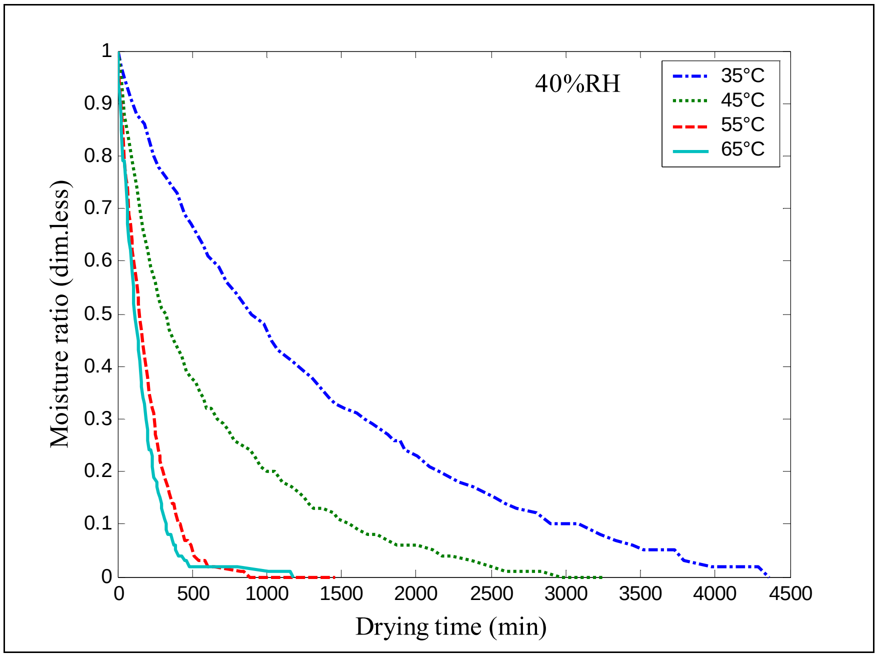

Figure 4c. Drying curves at 40%RH (35, 45, 55, and 65^{o}C).

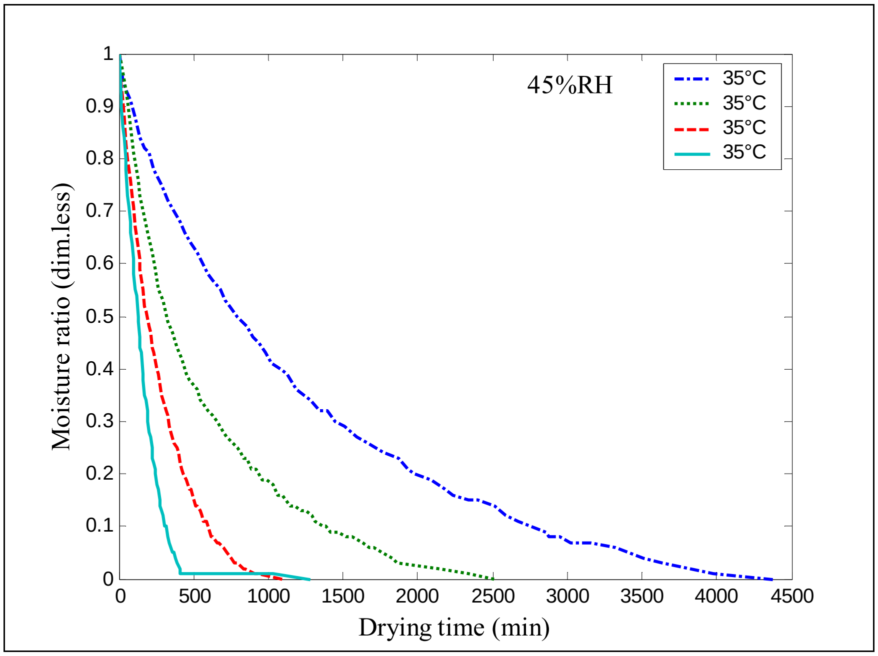

Figure 4d. Drying curves at 45%RH (35, 45, 55, and 65^{o}C).

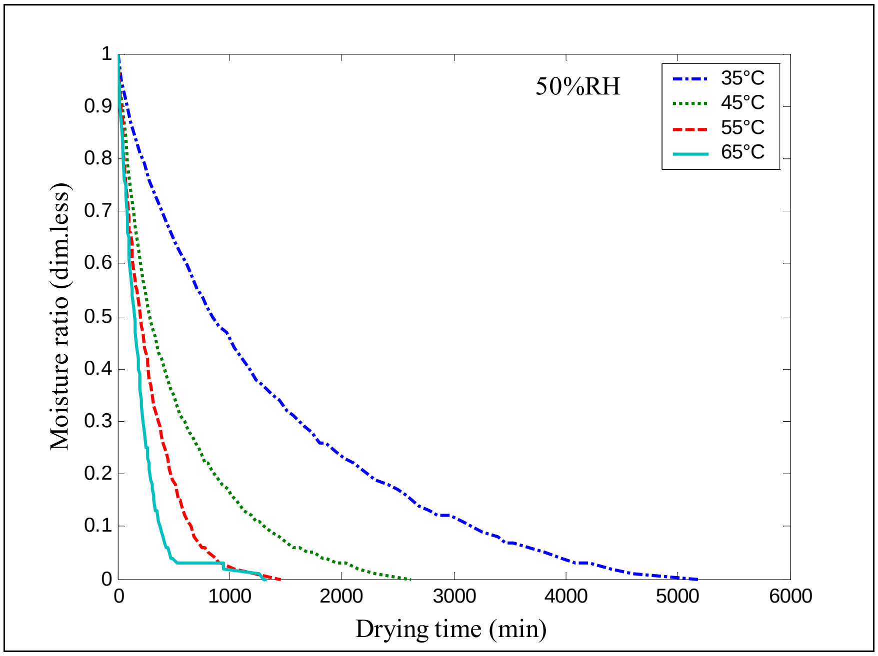

Figure 4e. Drying curves at 50%RH (35, 45, 55, and 65^{o}C).

The effect of the air-humidity on the acceleration of the drying progress is considered, in general, as much lower than that of air-temperature (Krokida *et al.*, 2003; Saeed *et al.*, 2006; Tarigan *et al.*, 2007). Table 5 presents the result of the ANOVA on the drying time versus relative humidity (RH). This result reveals that the effects of RH on the drying time was not significant (p= 0.994).

Figures 5a to 5d show the effects of drying-air RH on the drying behavior of Roselle (at constant temperature). The times were not varied a lot when the RH was increased from 30 to 50%.

Table 5. One-way ANOVA: drying time versus relative humidity (RH)

```
Analysis of Variance for Drying Time
Source     DF        SS        MS        F        P
RH          4       140        35     0,05    0,994
Error      15      9833       656
Total      19      9973
                                   Individual 95% CIs For Mean Based on Pooled StDev

Level       N      Mean     StDev  ------+---------+---------+---------+
1           4     37,10     22,13   (-------------*------------)
2           4     39,44     24,95    (-------------*------------)
3           4     42,75     25,21      (------------*-------------)
4           4     38,71     25,18    (------------*-------------)
5           4     44,25     29,93      (-------------*-------------)
                                   ------+---------+---------+---------+
Pooled StDev =    25,60                 20        40        60        80
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However, there was an acceleration of the drying process due to the decrease in humidity of the drying-air from 50% to 30%; similar result was found by many researchers (Krokida *et al.*, 2003; Steinfeld & Segal, 1986; Timoumi *et al.*, 2004). Farmer *et al.* (1983) concluded that, increasing the relative humidity (from 32 to 68%, at 20°C); increases the half time drying of blue grass seed (from 1.7 to 7.3 h). According to May *et al.* (1999) changing the air-humidly changes the constant-rate period but not the falling-rate period; where the later is the case in the Roselle drying (Saeed *et al.*, 2006).

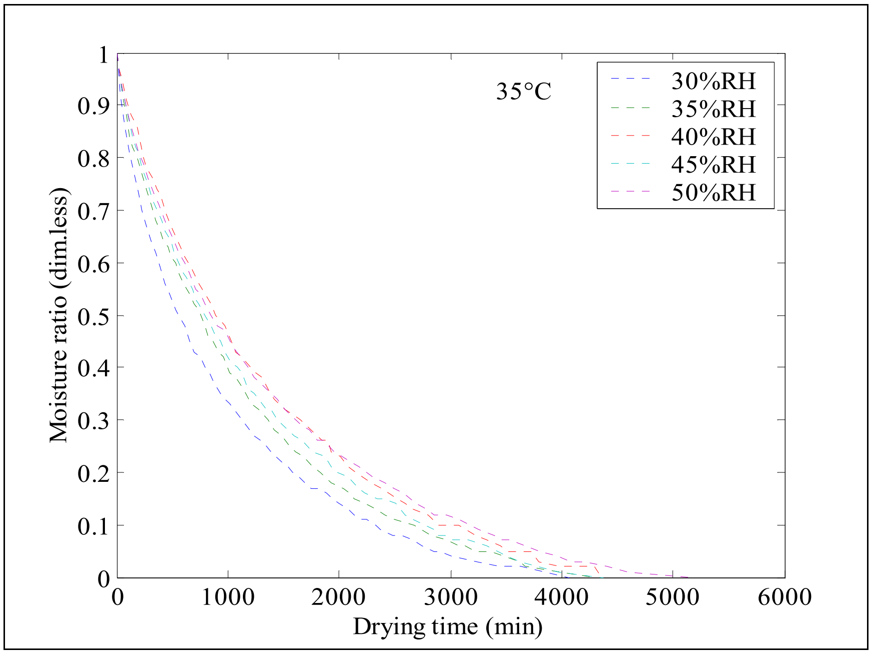

Figure 5a. Drying curves at 35°C (30, 35, 40, 45, and 50%RH).

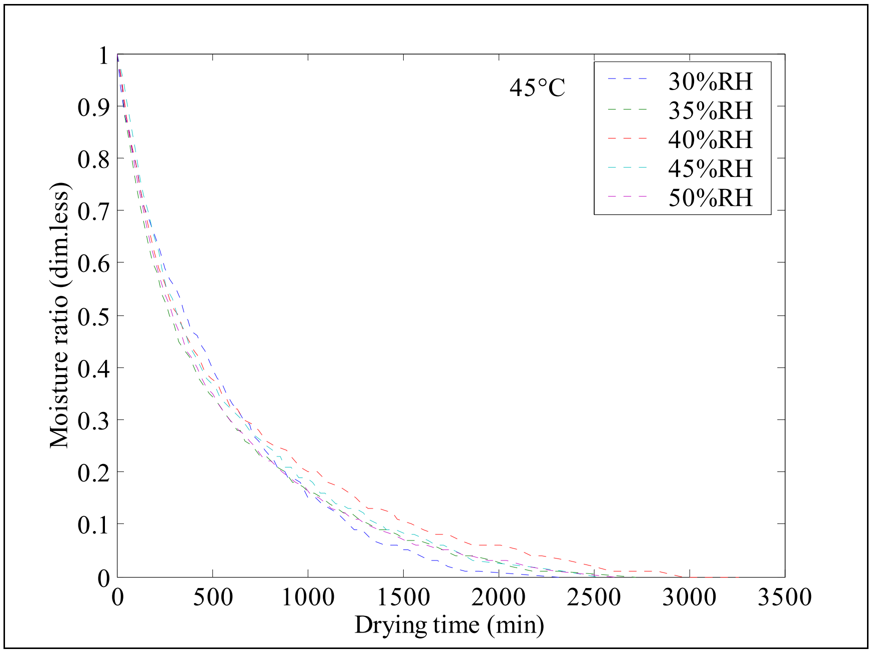

Figure 5b. Drying curves at 45^{o}C (30, 35, 40, 45, and 50%RH).

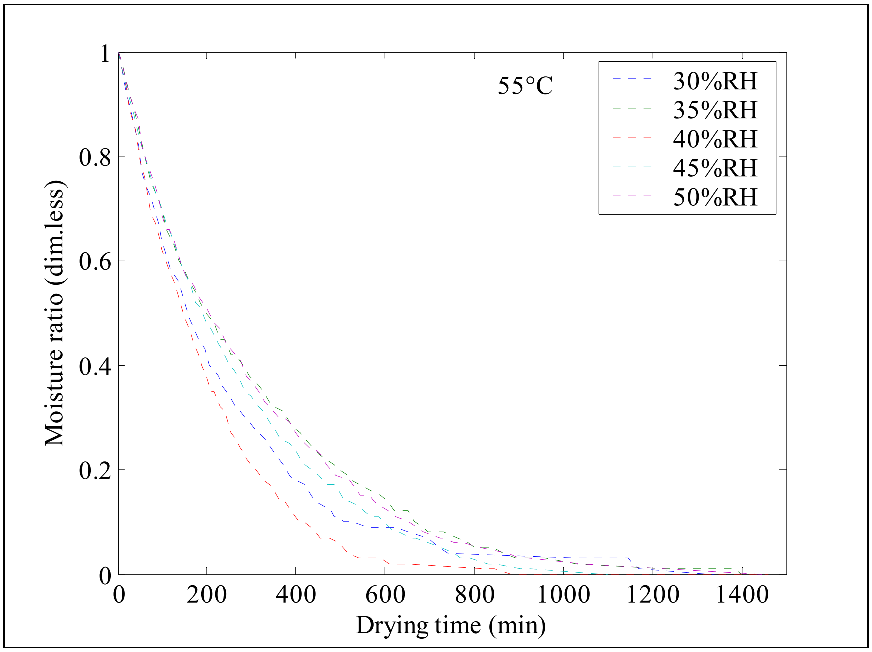

Figure 5c. Drying curves at 55^{o}C (30, 35, 40, 45, and 50%RH).

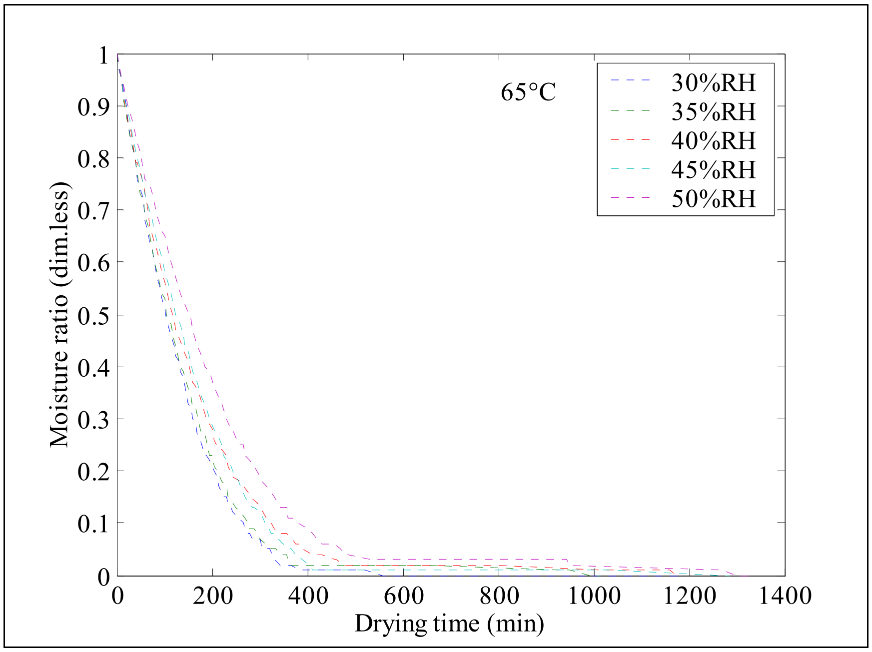

Figure 5d. Drying curves at 65°C (30, 35, 40, 45, and 50%RH).

Moreover, relative humidity of the drying air has a significant impact on the final moisture content of the material, because it controls the rate of water vapor transport from its surface to the air and influences the value of the equilibrium moisture content (Digvir *et al.* 1991).

Furthermore, the drying process was totally took place in the falling rate period (Falade & Abbo, 2007; Kaya *et al.*, 2007b; Nguyen & Price, 2007; Saeed *et al.*, 2006; Singh *et al.*, 2008). This means that diffusion is the dominant physical mechanism governing moisture movement in the material (Akpinar *et al.* 2003a; Doymaz 2007; Shanmugama & Natarajanb, 2006), which is dependent on the moisture content of the samples (Prachayawarakorn *et al.*, 2008). When drying processes are carried out at high air velocities; external resistance to mass transfer is neglected, and the resistance of solid is assumed to control the process (Kaymak-Ertekin, 2002; Singh *et al.*, 2008).

The falling rate period is behavior observed in drying of many biological products (Bellagha *et al.*, 2002; Cihan *et al.*, 2008; Doymaz, 2004a; Karathanos, 1999). Drying rate during the falling rate period is caused by the concentration gradient of moisture inside the food matrix. The internal moisture movement results from a number of mechanisms such as liquid diffusion, capillary flow, flows due to shrinkage and pressure gradients (Nguyen & Price, 2007).

The time required for drying Roselle was considerably decreased with the increment of the drying-air temperature, as it was also found by Saeed *et al.*, (2006). Faster evaporation rates were observed at higher temperatures, thus, the drying time needed to reach specified moisture content was decreased. This observation was reported by others (Fumagalli & Freire, 2007; Shivhare *et al.*, 2000; Vengaiah & Pandey, 2007).

Table 6 presents the drying time required to achieve 0.90, 0.50, 0.20, 0.10, 0.05, 0.02, and 0.01 moisture ratio (MR); i.e., 10%, 50%, 80%, 90%, 95%, 98% and 99% of the drying process, respectively. For instance, in drying at 30% relative humidity; the drying time needed to reach moisture ratio of 0.1 (i.e., 90% of the drying process) was 2320 and 265 minutes, for drying at 35°C and 65°C, respectively. In contrast, increasing the drying air humidity from 30% to 50% at 35°C increased the drying time required to achieve MR of 0.01 from 2320 to 3105 minutes, while for 65°C it increased by only 110 minutes. This is because moist air has a lesser water holding capacity than dry air (Cruess, 1958; Fellows, 1988; Sigge *et al.*, 1998).

The drying process was continued until no significant change in Roselle's mass was observed with the increment of the drying time; the moisture content was then considered as the dynamic equilibrium moisture content (Basunia & Abe, 2001a; Saeed *et al.*, 2006; Togrul & Pehlivan, 2003). The values of the equilibrium moisture content (EMC) were determined by convective-oven drying method (Belghit *et al.*, 2000; Cletus *et al.*, 2008; Falade & Abbo, 2007; Kouhila *et al.*, 2002).

Figures 6a and 6b show the plotting of the EMC versus the equilibrium temperature (ET) and relative humidity (ERH), respectively. It is obviously that the equilibrium moisture content decreases with increasing of the drying-air temperature (Kaya *et al.*, 2007a; Saeed *et al.*, 2006); as well the time needed to reach this moisture content was decreased (Vergara *et al.*, 1997; Salgado *et al.*, 1994; Maskan & Fahrettin, 1998). This may be because when the temperature is increased, some water molecules are activated to energy levels that allow them to break away from their sorption sites, thus decreasing the equilibrium moisture content (Kouhila *et al.*, 2002).

Table 6. Moisture ratio (MR) and drying times

MR			35°C					45°C		
		Relative humidity (%)					Relative humidity (%)			
(-)	30	35	40	45	50	30	35	40	45	50
0.90	50	70	110	85	90	40	35	40	55	40
0.50	555	740	905	795	855	360	270	310	315	285
0.20	1600	1805	2150	2010	2245	880	865	1000	940	860
0.10	2320	2535	3030	2810	3105	1210	1350	1505	1385	1295
0.05	2895	3295	3605	3445	3815	1480	1695	1990	1735	1695
0.02	3520	3670	4255	3875	4415	1715	2065	2440	2045	2105
0.01	3885	3985	4350	4035	4730	1840	2260	2650	2225	2320
			55°C					65°C		
0.90	25	30	20	25	30	15	15	15	15	20
0.50	155	200	145	185	210	100	100	115	125	150
0.20	370	490	310	430	485	195	210	240	240	290
0.10	515	665	415	590	630	265	270	325	310	375
0.05	710	805	510	720	805	305	330	390	360	460
0.02	1155	980	625	880	1045	360	370	480	405	950
0.01	1170	1385	695	915	1450	385	915	1010	430	1270

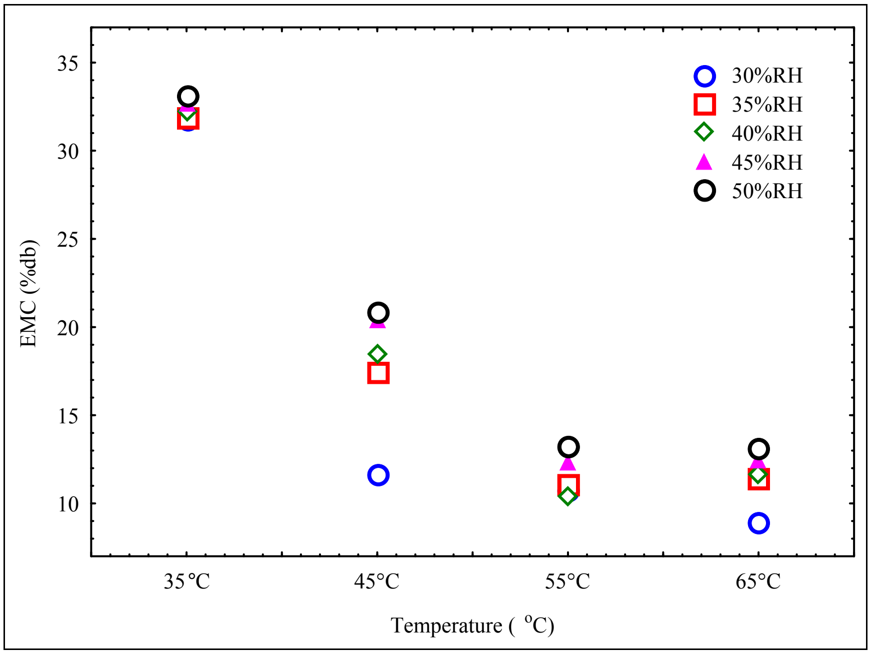

Figure 6a. EMC vs. equilibrium temperature.

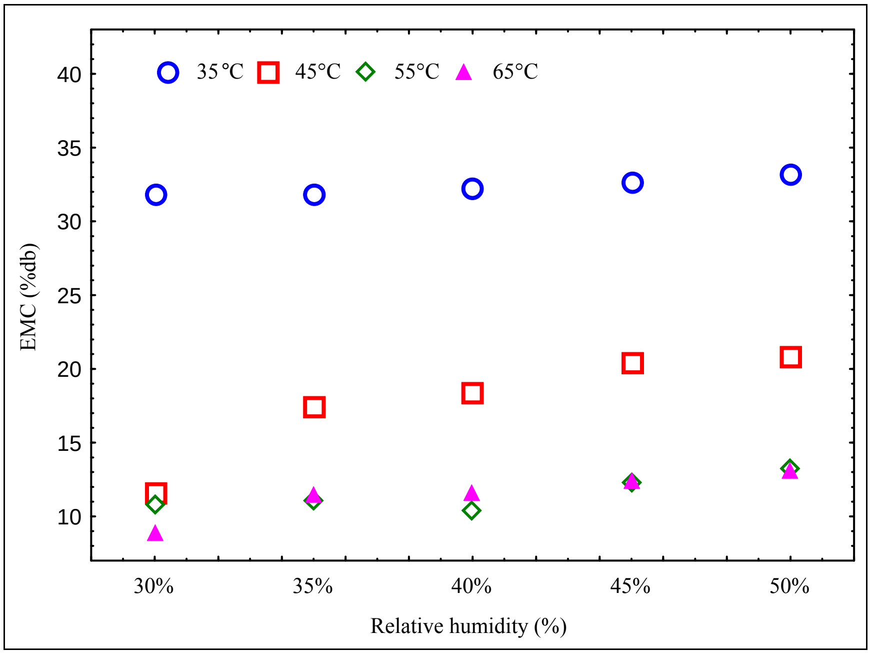

Figure 6b. EMC vs. Equilibrium relative humidity.

On the other hand, EMC was increased with increasing the relative humidity of the drying-air (Kaya *et al.*, 2007a; Saeed *et al.*, 2006). Tables 7 and 8 show the ANOVA for EMC versus temperature and relative humidity, respectively.

Table 7. One-way ANOVA: EMC versus Temperature

```
Analysis of Variance for EMC
Source     DF        SS        MS        F        P
Temp        3  0,147135  0,049045   121,85    0,000
Error      16  0,006440  0,000403
Total      19  0,153575
                                   Individual 95% CIs For Mean Based on Pooled StDev

Level       N      Mean     StDev  -------+---------+---------+---------
1           5   0,32400   0,00548                                (-*--)
2           5   0,17800   0,03493            (-*--)
3           5   0,11400   0,01140   (-*--)
4           5   0,11400   0,01517   (-*--)
                                   -------+---------+---------+---------
Pooled StDev =  0,02006                 0,140     0,210     0,280
```

Generally, the lower the desired moisture content the lower the relative humidity of the drying-air should be (Coumans, 2000). Furthermore, knowledge about the required final moisture content will prevent over-drying and thus decrease drying time, energy costs, mass losses and the risk of quality deterioration; as drying to lower moisture content would cause additional operation costs and mass losses without increasing storage safety.

Table 8. One-way ANOVA: EMC versus RH

```
Analysis of Variance for EMC
Source     DF        SS        MS        F        P
RH          4   0,00370   0,00093     0,09    0,983
Error      15   0,14988   0,00999
Total      19   0,15358
                                   Individual 95% CIs For Mean Based on Pooled StDev

Level       N      Mean     StDev  ---+---------+---------+---------+---
1           4   0,16000   0,10739   (--------------*--------------)
2           4   0,18000   0,09899     (---------------*--------------)
3           4   0,18000   0,09933     (---------------*--------------)
4           4   0,19250   0,09912       (---------------*--------------)
5           4   0,20000   0,09452        (---------------*--------------)
                                   ---+---------+---------+---------+---
Pooled StDev =  0,09996             0,070     0,140     0,210     0,280
```

According to Midilli (2001) and Shanmugama & Natarajan (2006), the most important structural variation appeared on the crops is the mass shrinkage ratio (SR). Mass shrinkage ratio for Roselle was varied between 0.08987 and 0.11416, as show in Table 9. In general, mass shrinkage ratio increased with the relative humidity, and decreased as the temperature is raised from 35^{o}C to 65^{o}C. It might be also affected by initial moisture contents of Roselle.

Table 9. Mass shrinkage ratio (SR)

T	Relative humidity (%)				
(°C)	30	35	40	45	50
35	0.1067	0.1139	0.1081	0.1094	0.1142
45	0.0916	0.1062	0.1048	0.0991	0.1106
55	0.1133	0.1058	0.0916	0.0997	0.1087
65	0.0899	0.0978	0.1133	0.1048	0.1137
Aver.	0.1004	0.1059	0.1044	0.1032	0.1118

5. CONCLUSIONS

Drying air temperature was found to be the main factor influenced the drying kinetics of Roselle. The drying process of Fresh whole calyces of Roselle took place in the falling-rate period, starting from an average IMC content of 10.285db to the final average moisture content of and 0.183db. The time required for drying Roselle was considerably decreased with the increment in the drying air temperature. There was an acceleration of the drying process due to the decrease of the air humidity from 50% to 30%. The EMC and the times needed to reach this equilibrium were reduced with increasing the drying-air temperature. On the other hand, EMC was increased with increasing the relative humidity of the drying-air. The two-term exponential model, compared to the others, produced the highest value for R^2 (0.999392) and it can be used, sufficiently, to describe the drying behavior of Roselle in the range of the tested drying conditions.

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7. NOMENCLATURE

df	number of degrees of freedom.	M_{t+dt}	moisture content at (t+dt) $(g_w.g_{dm}^{-1})$
DR	drying rate $(g_w.min^{-1})$	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)
MC_{dw}	moisture content wet basis $(g_w.g_{dm}^{-1})$	W_d	weight of dry matter (g)
M_e	equilibrium moisture $(g_w.g_{dm}^{-1})$	W_o	weight at $t_{=0}$ (kg)
M_o	initial moisture content $(g_w.g_{dm}^{-1})$	W_t	weight at any time (t) (kg)
MR	moisture ratio (-)	W_w	weight of water (g)
$MR_{cal,i}$	simulated value of $MR_{exp,i}$	Y_i	experimental data (g)
$MR_{exp,i}$	experimental value	$\overline{Y}$	average value of Y_i (g)
M_t	moisture content at time t $(g_w.g_{dm}^{-1})$	$\hat{Y}$	estimated value of Y_i (g)