Solar drying of Roselle (*Hibiscus sabdariffa* L.): Mathematical modelling, drying experiments, and effects of the drying conditions

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Abstract: Thin-layer drying experiments were conducted in a solar-assisted dehumidification drying system for agricultural products. The experiments were carried out to determine the influences of drying conditions on the drying behaviour of Roselle's calyces (*Hibiscus sabdariffa* L.). The Investigations were carried out at five different air temperatures and two different air velocities. Drying air temperature was the main factor affecting the drying behaviour of Roselle since raising the temperature (from 35℃ to 65℃) dramatically reduced the drying time. At the low temperature (35℃), increasing the drying-air velocity (from 1.5 m/s to 3.0 m/s) resulted in shorter drying time. Twelve thin-layer drying models were fitted to the solar drying experimental data. Statistical analysis was carried out and comparison between drying models was made to select the best-fitting model for the drying curves. Among the 12 tested models, the logarithmic model was found to be superior to other models; and it adequately represents the drying characteristics of Roselle in the range of applied drying conditions.

Keywords: Roselle (*Hibiscus sabdariffa* L.), solar drying, drying kinetics, mathematical models

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1 Introduction

Drying is probably the oldest and the most important method of food preservation practiced by humans (Midilli, Kucuk and Yapar 2002; Sacilik 2007). It is one of the main post-harvest operations for biological materials (Janjai and Tung 2005), since it has great effects on the quality of the dried products. Most cereals, vegetables and fruits can be preserved after drying (Doymaz 2004). Moreover, the main purpose of drying the products is to allow longer periods of storage, minimize packaging requirements and reduce shipping weights (Vengaiah and Pandey 2007). The traditional open sun drying method utilized widely by rural farmers has inherent limitations; high crop losses ensue from inadequate drying which results to fungal attacks, insects, birds and rodents encroachment, unexpected down pour of rain and other weathering effects (Ekechukwu and Nortonb 1999). In such conditions, solar-energy crop dryers increasingly appear to be attractive as viable alternative to open sun drying, where a quicker and controlled drying process can be achieved, and the crops are well protected during the process. Dehydration is dependent on two fundamental processes; the transfer of heat into the product and subsequent removable of moisture from it, which are, heat and mass transfer processes, respectively (Potter and Hotchkiss 1995). Togrul and Pehlivan (2003) stated that in carrying out an effective drying operation, not only at small-scale open-sun drying, but also in large-scale industrial drying, the information on the moisture removal mechanism during the drying operation and modelling expressions is very useful for the design and optimization of the dryers. Moreover, the understanding of the drying process and characteristics of raw material can lead to effective optimization of the drying operation

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(Kashaninejad and Tabil 2004). Drying process can be described completely using an appropriate drying model, which is made up of 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 (heat and mass transfer) 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 equations, the drying constant (k), which is a lumped parameter of these properties, is used (Karathanos 1999). For the purpose of design and analysis, it is often sufficient to use simple semi-empirical expressions, which can describe, adequately, the drying kinetics, when the external resistance to heat and mass transfer is eliminated or minimized (Midilli, Kucuk and Yapar 2002). A common way to achieve this is to carry out experiments using a thin-layer of the materials. Numerous experimental and modelling efforts on single-layer drying have been proposed in the literature (Midilli, Kucuk and Yapar 2002). Furthermore, most of the work done, consisted of data on thin layer drying of agricultural crops (Sarsavadia et al. 1999). This may be due to the use of semi-empirical model for design and analysis, in addition 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. Morton (1987) described Roselle plant (*Hibiscus sabdariffa* L.) as annual, erect, bushy plant, which has edible calyces, and is valuable in traditional medicine. The fleshy calyces are used fresh for making Roselle jelly, syrup, gelatin, refreshing beverages, pudding, and cakes (Duke 1983). Dried Roselle is used for tea, marmalade, ices, ice cream, sherbets, butter, pies, sauces, tarts, and other desserts (Duke 1983). The aqueous extract was found to be effective against Ascaris gallinarum in poultry. In East Africa, the calyx infusion, which is called "Sudan tea", is taken to relieve coughs (Morton 1987). In the cited literature, there is no information on the modelling of the solar drying of Roselle. Therefore, the objectives of this work are, i) to study the effects of the drying conditions on the drying behaviour of Roselle (variety Arab) dried in a solar assisted dehumidification drying system for drying of agricultural products, and, ii) to select a suitable mathematical model to describe the drying of Roselle in the solar assisted dehumidification drying system.

2 Materials and methods

2.1 Mathematical modelling

2.1.1 Drying models

Table 1 presents twelve thin-layer drying models most frequently used by various authors. Moisture ratio was simplified to the form (M/M_0) instead of ($(M-M_e)/(M_0-M_e)$) as it used by various authors (Midilli, Kucuk and Yapar 2002; Kingsly and Singh 2007). This is because the relative humidity of the drying-air fluctuates continuously in the solar drying (Doymaz 2004, 2005; Midilli and Kucuk 2003). Besides, the values of the equilibrium moisture content (M_e) are relatively small, compared to M or M_0 (Goyal et al. 2007; Doymaz and Pala 2002).

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

Model name	Equation	References
Newton	$MR = \exp(-kt)$	Celma et al. 2007; Togrul and Pehlivan 2004
Page	$MR = \exp(-kt^n)$	Saeed, Sopian and Abidin 2006; Senadeera et al. 2003
Modified Page	$MR = \exp(-(kt)^n)$	Ceylan, Aktas and Doğan 2007; Goyal et al. 2007
Modified Page II	$MR = \exp(-k(t/L^2)^n)$	Midilli, Kucuk and Yapar 2002; Wang et al. 2007
Henderson and Pabis	$MR = a\exp(-kt)$	Saeed, Sopian and Abidin 2006; Saeed, Sopian and Abidin 2008
Modified Hend. and Pabis	$MR = a\exp(-t)+b\exp(-gt) +c\exp(-ht)$	Karathanos 1999; Togrul and Pehlivan 2002
Simplified Fick's diffusion	$MR = a\exp(-kt)+c$	Celma et al. 2007; Lahsasni et al. 2004b
Logarithmic	$MR = a\exp(-c(t/L^2))$	Togrul and Pehlivan 2002, 2003; Wang et al. 2007
Two-term	$MR = a\exp(-k_0t) + b\exp(k_1t)$	Lahsasni et al. 2004b; Wang et al. 2007
Two-term exponential	$MR = a\exp(-kt)+(1-a)\exp(-kat)$	Midilli and Kucuk 2003; Sacilik 2007; Tarigan et al. 2007
Verma et al.	$MR = a\exp(-kt)+(1-a)\exp(-gt)$	Doymaz 2005; Karathanos 1999
Diffusion approach	$MR = a\exp(-kt)+(1-a)\exp(-kbt)$	Togrul and Pehlivan 2002; Wang et al. 2007

2.1.2 Goodness-of fit statistics

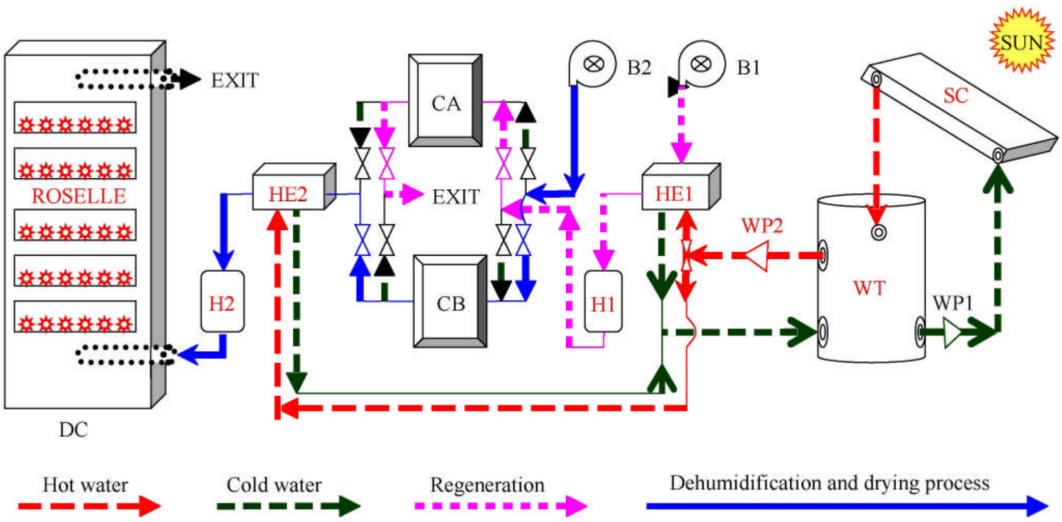
Thin-layer drying models (Table 1) were evaluated and compared by using ten statistical parameters (Table 2).

Table 2 Statistical parameters

Parameters	Formula	References
Coefficient of determination	$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST}$	Doymaz 2007; Saeed, Sopian and Abidin 2006, 2008
The adjusted- R^2 (AR^2)	$AR^2 = 1 - \frac{SSE/(df_{error})}{SST/(df_{total})}$	Keller 2001; Peck, Olsen and Devore 2001
The error (residual) sum of squares (SSE)	$SSE = \sum_{i=1}^{N}(MR_{\exp,i} - MR_{cal,i})^2$	Queiroz and Nebra 2001; Sun 1999
The standard error of estimate (SEE)	$SEE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{cal,i})^2}{N - n_P}}$	Sun 1999; Basunia and Abe 1999
The reduced sum square error ($RSSE$)	$RSSE = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{cal,i})^2}{N}$	Erenturk, Gulaboglu and Gultekin 2004; Vega et al. 2007):
The root mean square error ($RMSE$)	$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{cal,i})^2}{N}}$	Doymaz 2005; Wang et al. 2007
The mean sum of squares of errors (MSE)	$MSE = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{cal,i})^2}{N - n_P}$	Iguaz et al. 2003; Panchariya, Popovic and Sharma 2002
The mean bias error (MBE)	$MBE = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{cal,i})}{N}$	Goyal et al. 2007; Kingsly and Singh 2007; Togrul and Pehlivan 2002
Mean standard deviation between experimental and calculated values	$SD = \frac{1}{N}\left[\sum_{i=1}^{N}(MR_{cal\ i} - MR_{\exp,i})/MR_{\exp,i}\right]$	Krokida et al. 2003
Mean relative deviation between moisture levels	$MRD = \frac{1}{N} * \sum \left| \frac{MR_{\exp,i} - MR_{cal,i}}{MR_{\exp,i}} \right| \times 100\%$	Basunia and Abe 1999; Sun 1999

2.2 Drying experiments

The drying experiments were carried out in solar assisted dehumidification drying system for drying of agricultural products (10 kg of fresh Roselle were used in each run). A flat-plate solar collector (five panels connected in parallel), was used. In addition, electric air-heaters were used as auxiliary heating source. A cabinet-type drying chamber was used (inside: 100 cm × 100 cm ×240 cm *L*, *W*, and *H*, respectively). In addition, the distance between the shelves could be adjusted to different heights. The configuration of the system's components was as shown in Figure 1. The dry and wet bulb temperatures at different locations in the system were measured on-line using thermocouples (T-type, RoHs, UK). The total intensities of solar radiation were measured using Eppley pyranometer (model 8-48 Eppley Radiometer, the Eppley Laboratory, USA). Thermocouples and the pyranometer were connected to 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 air velocity. Two silica gel columns were used alternatively for the dehumidification and regeneration processes (25 cm × 25 cm × 125 cm *L*, *W* and *H*, respectively). Furthermore, the silica gel height was about 85 cm (42.5 kg silica gel/column). A digital balance with a capacity of 2200g, and an accuracy of 0.01 g (Shimadzu; model UX2200H Shimadzu Corporation, Japan) was used to weigh Roselle samples. About 10 kg of fresh Roselle's calyces (variety Arab) was used in each run. The seed capsules removed before commencing the drying experiments. Samples of about 0.2 kg of whole (uncut) Roselle's calyces were suspended to digital balance. The data was recorded on personal computer at five minutes intervals using Fuji Micro-jet recorder (type PHA, Fuji Electric Co., Ltd, Tokyo, Japan). A convective oven (Venticell, MMM, Medcener) was used to determine the initial and final moisture content at 105℃ (Ruiz 2005). Five average drying temperatures (35℃, 45℃, 55℃, 60℃, and 65℃) and two air velocities were used. Thin-layer drying models were fitted to the experimental data using non-linear regression based on the minimization of the sum of squares; using least squares Levenberg-Marquardt algorithm (Doymaz 2007; Saeed, Sopian and Abidin 2006, 2008). The twelve thin layer-drying models in Table 1 were fitted to the observed data, and comparison between these drying models was done using goodness-of fit statistical parameters. The best-fitted model was selected to describe the thin-layer drying characteristics of Roselle dried in the solar assisted dehumidification drying system.



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

Figure 1 Configuration of the components of the solar-assisted dehumidification drying system: The regeneration of column (A) and dehumidification column (B)

3 Results and discussion

3.1 Mathematical model selection

Fresh and dried Roselle is shown in Figure 2. The calyces were dried from average initial moisture content of 9.88% db (dry basis) to an average final moisture content of 0.19% db. Table 3 presents the average values of the statistical measures of performance obtained from fitting of the twelve drying models to the experimental data. The model with the highest values for R^2 and AR^2 was selected to describe the drying curves. Higher value of R^2 means that the model predicted well on the drying behaviour of the Roselle. In addition, the lowest the values of other parameters (*SSE*, *SEE*, *RSSE*, *RMSE*, *MSE*, *MBE*, *SD*, and *MRD* %), demonstrate a good fit (Kingsly and Singh 2007; Saeed, Sopian and Abidin 2006). It was observed that all the models showed high values for R^2 (average of 0.99914) and AR^2 (average of 0.99912). Moreover, the average values of the other statistics were low; *SSE* = 0.007530, *SEE* = 0.010492, *RSSE* = 0.000125, *RMSE* = 0.010257, *MSE* = 0.000131, *MBE* = 0.001568, *SD* = 0.121219, and *MRD* = 15.40%. Compared to the other models, the logarithmic model showed the highest value for R^2 and AR^2 (0.99953 and 0.99952, respectively). Similar observations were made by other researchers (Erenturk, Gulaboglu and Gultekin 2004; Goyal et al. 2007; Wang et al. 2007). This value of R^2 was higher compared to several previous works on drying of different agricultural products such as, hull-less seed pumpkin (Sacilik, 2007); kiwi, avocado and banana (Ceylan, Aktas and Doğan 2007); and apple pomace (Wang et al. 2007).

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

Table 3 Statistical results obtained from fitting of 12 thin- layer drying models to experimental data

Model	R^2	AR^2	*SSE*	*SEE*	*RSSE*	*RMSE*	*MSE*	*MBE*	*SD*	*MRD*/%
1	0.99817	0.99817	0.016150	0.015786	0.000269	0.015654	0.000247	-0.00312	0.189705	22.25
2	0.99921	0.99920	0.006935	0.010613	0.000116	0.010135	0.000120	-0.00287	0.123037	14.73
3	0.99921	0.99920	0.006940	0.010610	0.000120	0.010440	0.000120	0.03196	0.119110	11.57
4	0.99921	0.99919	0.006940	0.010710	0.000120	0.010440	0.000120	0.00879	0.123060	14.28
5	0.99885	0.99883	0.010196	0.012883	0.000170	0.012666	0.000176	-0.00305	0.181509	20.57
6	0.99952	0.99948	0.004278	0.007331	0.000071	0.006955	0.000079	-0.00146	0.092442	11.69
7	0.99953	0.99952	0.004016	0.007578	0.000067	0.007386	0.000070	0	-0.02702	8.02
8	0.99885	0.99881	0.010196	0.012995	0.000170	0.012666	0.000179	-0.00305	0.181515	20.57
9	0.99948	0.99945	0.004500	0.008260	0.000075	0.007798	0.000080	-0.00167	0.070136	12.18
10	0.99941	0.99940	0.004516	0.008282	0.000075	0.008143	0.000078	-0.00235	0.096500	11.64
11	0.99916	0.99913	0.007450	0.010220	0.000120	0.009960	0.000130	0.00226	0.147020	18.14
12	0.99906	0.99903	0.008260	0.010640	0.000140	0.010370	0.000150	-0.00210	0.157610	19.15
Average	0.99914	0.99912	0.007530	0.010490	0.000130	0.010260	0.000130	0.00157	0.121220	15.40

Table 4 Values of statistical measures obtained from fitting of the logarithmic model to the experimental data obtained from different drying conditions. The values agreed well with values obtained by Midilli et al. (2002), Sacilik (2007), Wang et al, (2007) and Togrul and Pehlivan (2002).

T	*V*	R^2	AR^2	*SSE*	*SEE*	*RSSE*	*RMSE*	*MSE*	*MBE*	*SD*	*MRD*/%
35	1.5	0.99988	0.99988	0.001220	0.004620	0.000200	0.004500	2.1E-05	0	0.00315	1.58
	3	0.99860	0.99855	0.011680	0.014310	0.000200	0.013950	0.000210	0	0.00930	2.99
45	1.5	0.99955	0.99953	0.004200	0.008590	0.000070	0.008380	7.4E-05	0	0.00838	3.25
	3	0.99906	0.99902	0.008170	0.119710	0.000140	0.011670	0.000140	0	0.03029	6.92
55	1.5	0.99995	0.99995	0.000514	0.003004	0.000009	0.002928	0.000009	0	-0.00812	2.54
	3	0.99966	0.99965	0.002714	0.006900	0.000045	0.006725	0.000048	0	-0.04387	11.73
65	1.5	0.99750	0.99974	0.002180	0.006190	3.6E-05	0.006030	3.8E-05	0	-0.15010	22.34
	3	0.99983	0.99983	0.001451	0.005046	0.000024	0.004918	0.000025	0	-0.06519	12.81
Average		0.99953	0.99952	0.004016	0.007578	0.000067	0.007386	0.000070	0	-0.02702	8.02

3.2 Drying characteristics

Figures 3a and 3b show the drying curves of Roselle at 1.5 m/s and 3.0 m/s at 35–65℃. The figure shows that the drying process is enhanced substantially with the increase in drying air temperature. Similar behaviour was reported by Belghit, Kouhila and Boutaleb (2000); Saeed, Sopian and Abidin (2006). This may be due to the fact that, higher temperature improves the heat transfer coefficient, resulting in a faster rate of frying (Methakhup, Chiewchan and Devahastin 2005). Table 5 present the result of the ANOVA on the drying time versus temperature.

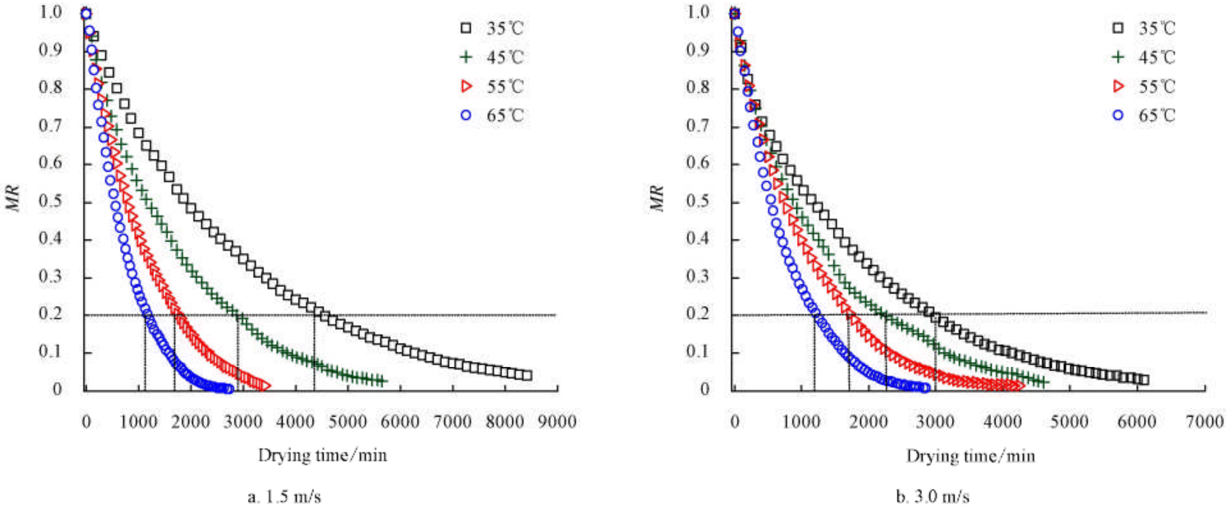


Figure 3 Drying curves at 1.5 and 3.0 m/s (35–65℃)

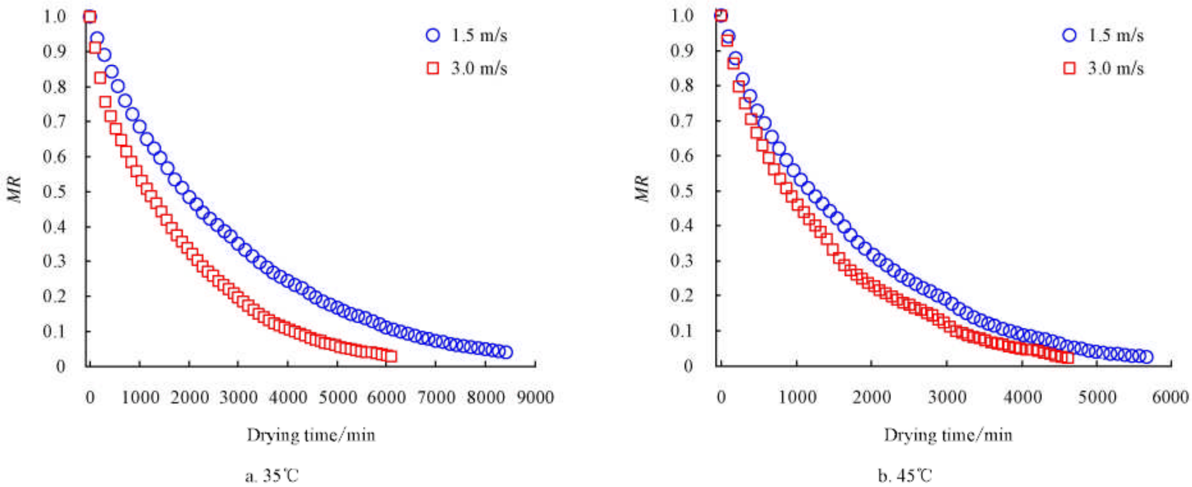
Table 5 One-way ANOVA: drying time versus temperature

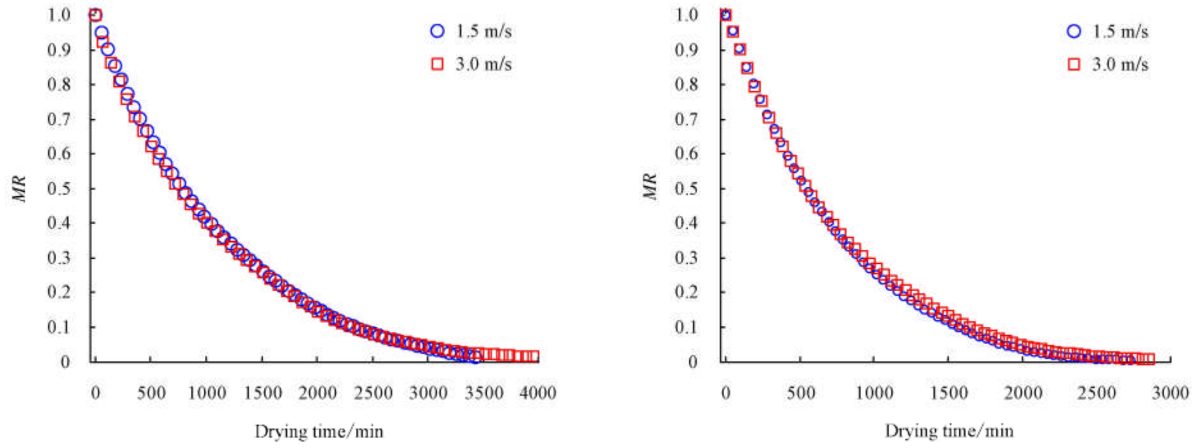
Source	DF	SS	MS	F	P
Temp	3	6391	2130	8.29	0.034
Error	4	1027	257		
Total	7	7418			
S = 16.03	R-Sq = 86.15%	R-Sq(adj) = 75.77%			

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	StDev	-----+---------+---------+---------+----
35	2	123.09	27.81	(--------*--------)
45	2	86.88	12.55	(--------*--------)
55	2	64.88	9.72	(--------*--------)
65	2	47.38	1.35	(--------*--------)
				-----+---------+---------+---------+----
				35 70 105 140
Pooled StDev = 16.03				

Figures 3c to 3f show the effect of air velocity on the drying performance of Roselle. It is noticeable that at the low temperature (35℃ and 45℃), the drying process was enhanced by increasing the airflow rate (Figures 3c to 3f); which agrees with similar results reported by Iguaz et al (2003). On the other hand, at high temperatures (55℃, and 65℃) increasing air velocity extended the drying time (Figures 3c and 3f). This may be attributed to the quick formation of hard layer (case hardening) at high air temperature and velocity. This layer increases resistance to transport and thereby prevents water vapour concentration to reach equilibrium. This phenomenon was also reported by (Togrul and Pehlivan 2003). It is also clear that higher drying temperatures accelerated the drying process, as this temperature provided a larger water vapour pressure deficit (Prabhanjan, Ramaswamy and Raghavan 1995). The high temperatures increase the difference between saturated and partial pressure of water vapour in the drying air, resulting in high drying rate. In addition, compared to the effect of drying-air temperature, increasing the air velocity did not considerably accelerate the drying process. This was in agreement with previous observations (Krokida et al. 2003; Lahsasni et al. 2004b; Tarigan et al. 2007).





c. 55℃ d. 65℃

Figure 4 Drying curves at 35, 45, 55 and 65℃ (1.5, 3 m/s)

According to May et al (1999) changing air velocity affects the constant-rate period but not the falling-rate period, and the later is the case of Roselle, where the drying processes were observed only to follow the falling rate drying period. This is the behaviour of many agricultural products (Doymaz 2004; Saeed, Sopian and Abidin 2006). The results of ANOVA on the influence of velocity on the drying are presented in Table 6.

It is evident that the time required for Roselle drying considerably decreased with the increment in drying air temperature (Tables 5 and 7). For instance, the drying period needed to reach moisture ratio of 0.02 at 35℃ (and air velocity of 1.5 and 3.0 m/s), were 7,480 and 5,305 minutes, respectively; compared to 2,125 and 2,270 minutes for drying at 65℃ (and 1.5 and 3.0 m/s air speed). However, increasing the drying-air velocity at 65℃ increased the drying time, since the time required, to attain a moisture ratio of 0.01 was 2,295 and 2,500 minutes for drying at 1.5 m/s and 3.0 m/s, respectively. Similar behaviour was observed by (Saeed, Sopian and Abidin 2006, 2008).

Table 6 One-way ANOVA: drying time versus air velocity

Source	DF	SS	MS	F	P
Vel	1	214	214	0.18	0.687
Error	6	7204	1201		
Total	7	7418			

S = 34.65 R-Sq = 2.89% R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	StDev	
				-------+---------+---------+---------+--
1.5	4	85.73	43.46	(----------------*----------------)
3.0	4	75.38	22.64	(----------------*----------------)
				-------+---------+---------+---------+--
				50 75 100 125

Pooled StDev = 34.65

Table 7 Moisture ratio (MR) and drying time

Drying process /%	MR (-)	35℃		45℃		55℃		65℃	
		1.5 m/s	3.0 m/s	1.5 m/s	3.0 m/s	1.5 m/s	3.0 m/s	1.5 m/s	3.0 m/s
		Drying time/min							
0	1.00	0	0	0	0	0	0	0	0
10	0.90	245	110	150	110	115	95	95	95
50	0.50	1,800	1,110	1,130	850	770	735	535	540
80	0.20	4,155	2,790	2,710	2,110	1,720	1,695	1,150	1,210
90	0.10	5,580	3,710	3,535	2,995	2,250	2,220	1,545	1,615
95	0.05	6,545	4,545	4,345	3,560	2,705	2,715	1,835	1,920
98	0.02	7,480	5,305	4,890	4,255	3,095	3,190	2,125	2,270
99	0.01	7,955	5,740	5,190	4,420	3,255	3,465	2,295	2,500

4 Conclusions

Drying air temperature was found to be the main factor affecting the drying behaviour of Roselle, where raising the air temperature dramatically reduced the drying time (p=0.034). In addition, the effect of increasing the air velocity from 1.5 m/s to 3.0 m/s was not significant as that of the temperature (p=0.687). The twelve fitted models showed a good fit to the experimental data (with an average values for R^2= 0.99914 and AR^2 = 0.99912). Comparisons between models confirmed the superiority of logarithmic model to the others (average value for R^2 = 0.99953 and AR^2 = 0.99952).

Nomenclature

a	empirical constant in the drying model	$MR_{exp,i}$	experimental or observed MR
AR^2	adjusted coefficient of determination	MSE	mean sum of squares of the errors
b	empirical constant in the drying model	n	empirical constant (drying models)
c	empirical constant in the drying model	N	number of data points
df	degrees of freedom	n_p	number of unknown parameters
exp	exponential	R^2	coefficient of determination
g	empirical constant in the drying model	$RSSE$	reduced sum square error
h	empirical constant in the drying model	SD	mean standard deviation
k	drying constant (min^{-1})	SEE	standard error of estimate
k_0	empirical constant in the drying model	SSE	error sum of squares
k_1	empirical constant in the drying model	SSR	regression sum of squares
L	empirical constant in the drying model	SST	total sum of squares
M	instantaneous moisture content ($g_w.g_{dm}^{-1}$)	t	drying time (min)
M_0	initial moisture content ($g_w.g_{dm}^{-1}$)	T	temperature (℃)
MBE	mean bias error	V	air velocity (ms^{-1})
MC_{db}	moisture content on dry basis ($g_w.g_{dm}^{-1}$)	$\bar{Y}$	average value of Y_i
MC_{wb}	moisture content on wet basis($g_w.g_m^{-1}$)	$\hat{Y}$	estimated value of Y_i

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