Drying kinetics and quality of *Cissus quadrangularis* Linn. dried by convective hot air

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Abstract: This research aimed to determine a suitable drying model of convective hot air drying of *Cissus quadrangularis* Linn. (CQ), determine the effective moisture diffusivity of the drying process and the activation energy of CQ, and investigate the effects of drying temperatures on energy consumption and quality of dried CQ. Experiments were performed at 40°C, 60°C, 80°C, and 100°C drying temperature and 1 m s^{-1} air velocity to dry CQ from 10 g water/g dry matter to 0.1 g water/g dry matter. The generalized linear-plus-exponential-type model has been used to fit the drying kinetics of CQ and demonstrates, among others, the moisture data of hot air drying of CQ at the validation temperature of 50°C satisfactorily with an R^2 of 0.9977. The effective moisture diffusivity was in the range of 0.7302-9.1281 $\times10^{-9}$ m^2 s^{-1}, a positive relationship was observed between this parameter and drying temperature. The activation energy of CQ was 39.78 kJ mol^{-1}. The lowest energy consumption of 3.40 kWh was required when the highest drying temperature of 100°C was applied. The quality was well preserved when CQ was dried at a lower drying temperature. Drying at 60°C produced dried CQ with the lowest total color difference (16.76), shrinkage percentage (88.47%), and bulk density (0.1817 g cm^{-3}) as well as the highest total phenolic (1062 mg GAE/100 g dry matter) and quercetin contents (0.955 mg/100 g dry matter).

Keywords: *Cissus quadrangularis*, hot air drying, drying kinetic, drying model, quercetin

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1 Introduction

Cissus quadrangularis Linn. (CQ) is a perennial plant of the Vitaceae (grape) family. It is considered as a useful medicinal plant. Its stem has been used for treating many physical disorders such as rheumatic disease, allergies, piles, hemorrhoid, and irregular menstruation (Bhujade et al., 2012; Vijayalakshmi et al., 2013). It also accelerates bone fracture healing (Lekshmi et al., 2015). CQ stems are full of phenolics and flavonoids. Its phenolic compounds have been reported to possess potent antioxidant activity (Lekshmi et al., 2015). Regarding flavonoids, there has been a report that quercetin is an active component found in CQ stem (Kumar et al., 2015). Quercetin exhibits a strong 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity and high antioxidant capacity (Thiangtham, 2003). Unfortunately, CQ stem contains calcium oxalate that can cause throat irritation; hence, for oral consumption, it must be encapsulated after dried and ground.

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Drying is one of the most efficient preservation techniques in herbal medicine industry. Sun drying is widely used to dry medicinal herbs in Thailand. However, this drying method is influenced strongly by the weather. In addition, many environmental factors affect its process reliability and the quality of obtained products. Hot air drying has a good potential for bulk drying of herbs due to its easy operation, controllability, and faster drying rate. Promnuch et al. (2017) dried CQ using tray and fluidized bed drying and found insignificant difference in total flavonoids of CQ dried by these methods.

In order to achieve an effective and economical drying operation, it is imperative to find the optimum process parameters. A moisture transfer model is a very useful tool for investigating the intrinsic kinetics of a drying process. Although many mathematical models have been developed for various drying conditions and materials, no information is available for the moisture transfer mechanism of succulent stems of CQ under hot air drying conditions. A good model of hot air drying kinetics of CQ will enable an accurate prediction of the drying time required for a set temperature, which will result in less variation in the final moisture content of the product, i.e., good and consistent quality.

Therefore, the aim of this research was to investigate the drying kinetics of hot air drying of CQ in the temperature range of 40°C -100°C. The effective moisture diffusivity of the drying process and the activation energy of CQ were determined. The effects of drying temperature on energy consumption and quality of dried CQ were also studied. Hopefully, these results will lead readers to a clearer understanding of the drying kinetics of hot air drying of CQ and the effects of drying temperature on the dried CQ quality.

2 Materials and methods

2.1 Sample preparation

Fresh CQ stems were acquired from an herbal farm in Prachin Buri province, Thailand. They were cleaned and air dried before getting packed in a polyethylene bag for storage at 4°C. Prior to each experiment, the stems were allowed to warm-up to ambient conditions and cut into 5 mm pieces (thickness), both the ends of them were discarded. Dimension of the stems was approximately 12 mm×7 mm×5 mm. The average initial moisture content was 10.10±0.15 g water/g dry matter (AOAC, 2005).

2.2 Drying experiment

Experimental runs of convective hot air drying of CQ were conducted with a hot air dryer designed and constructed at the Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang, Thailand, shown in Figure 1. The cylindrical drying chamber had a diameter of 30 cm and a length of 60 cm. The volume of the perforated drying tray was 40 cm × 20 cm × 5 cm. Hot air was generated by a 4-kW electrical air heater (FU Series, Sang Chai Meter Company Limited, Bangkok, Thailand) and a centrifugal fan driven by a 0.75-kW motor (HA 801-2, Hascon Electric Motor, T.N. Metal Works Company Limited, Samutsakorn, Thailand). A Proportional–Integral–Derivative (PID) controller (MD-700A, Sang Chai Meter Company Limited, Bangkok, Thailand) was used to control the temperature of hot air with an accuracy of ±1°C. Motor speed of the centrifugal fan blower was controlled by regulating the frequency of the supplied voltage, which was correlated to air velocity in the drying chamber measured by vane anemometer (DA-43A, DIGICON, Japan).

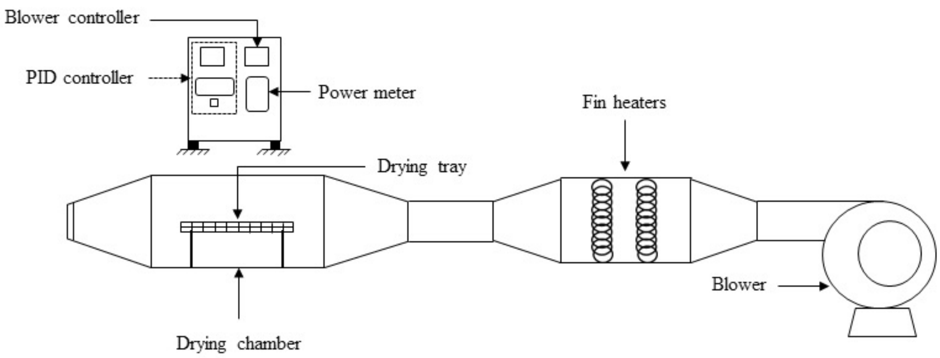

Figure 1 A schematic view of the convective hot air dryer

Experimental drying runs were conducted at temperatures of 40° C, 60° C, 80° C, and 100°C. Air velocity of 1 m s^{-1} was used. Before each run, the heating system was allowed to stabilize at the selected temperature for 30 min. Meanwhile, pieces of fresh CQ stem (260 g) were placed into a single layer on the drying tray. For moisture content determination, the total weight of CQ was monitored at predetermined intervals during the drying process. Drying was continued until a dried CQ moisture content of 0.1 g water/g dry matter was reached. The weight of dry CQ matter was determined by drying a CQ sample in a hot air oven at 105°C for 24 h (AOAC, 2005).

In addition, the total electrical energy required for a complete convective hot air drying of CQ was measured by a multifunction energy meter (KM-06-N, Primus Company Limited, Bangkok, Thailand) and reported in the unit of kWh.

2.3 Drying kinetic modeling

The weights of CQ samples recorded during the drying process and the weight of dry CQ matter were used to calculate moisture content on a dry basis of the CQ samples according to Equation 1. The moisture content data were then converted into the moisture ratio (MR) according to Equation 2.

$$M = (W_w - W_d)/W_d \tag{1}$$

$$MR = (M_t - M_e)/(M_i - M_e) \tag{2}$$

In the above equations, M and MR are the moisture content (g water/g dry matter) and moisture ratio (unitless); W_w and W_d are the wet weight (g) and dry matter weight (g); and M_i, M_t, and M_e are the moisture content (g water/g dry matter) at initial, specific time, and equilibrium, respectively.

The relationship between moisture ratio and time was curve fitted with eight different empirical or semi-empirical drying models (Table 1). The best model that was able to describe the drying kinetics of convective hot air drying of CQ in the drying temperature range of 40°C -100°C to a satisfying extent was investigated. The coefficient of determination (R^2, Equation 3) and root mean square error ($RMSE$, Equation 4) were used to evaluate the goodness of fit of tested models to the experimental data:

$$R^2 = \sum_{i=1}^{n}(MR_{pre,i} \times MR_{exp,i}) \Big/ \left[\sum_{i=1}^{n} MR_{pre,i}{}^2 \times \sum_{i=1}^{n} MR_{exp,i}{}^2\right]^{1/2} \tag{3}$$

$$RMSE = \left[1/N \times \sum_{i=1}^{n}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \tag{4}$$

where $MR_{\mathrm{exp,i}}$ is i^{th} experimental moisture content; $MR_{\mathrm{pred,i}}$ is i^{th} predicted moisture content; and N is the number of observations.

Table 1 Thin layer drying models for convective hot air drying of CQ

No.	Model name	Model	Reference
1	Lewis	$MR = \exp(-kt)$	Bruce,1985
2	Page	$MR = \exp(-kt^n)$	Page, 1949
3	Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis, 1961
4	Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Henderson, 1974
5	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Yaldiz et al., 2001
6	Midilli et al.	$MR = a\exp(-kt^n) + bt$	Midilli et al., 2002
7	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh, 1978
8	The linear-plus-exponential-type model	$MR = a\exp(-kt^n) + bt + c$	Sripinyowanich and Noomhorm, 2011

For generalizing the use of the best model to a certain drying temperature range, the relationship between the constants and coefficients (coc) of the model at studied drying temperatures (T) was determined by multiple regression analysis of the data with the equations representing the models below:

Linear type $$coc = a + bT \tag{5}$$

Power type $$coc = aT^b \tag{6}$$

Exponential type $$coc = a\exp(bT) \tag{7}$$

Arrhenius type $$coc = a\exp(-b/8.314T) \tag{8}$$

Logarithmic type $$coc = a + b\ln(T) \tag{9}$$

Polynomial type $$coc = a + bT + cT^2 \tag{10}$$

R^2 was used as the statistical selection criterion for the most suitable equation that describes the coc as a function of drying temperature.

Validation of the generalized drying model was conducted using empirical testing. Drying temperature of 50°C was selected in this case. The other drying condition was the same as shown in Section 2.2. Drying curves of the experimental and predicted data were plotted and compared. Comparative plot of experimental and predicted moisture ratios was also made for model validation.

2.4 Calculation of effective moisture diffusivity

In general, the moisture movement mechanism in a sample during the period of falling drying rate is mainly due to moisture diffusion as elucidated by Fick's second law. From the law, an unsteady state moisture diffusion rate can be derived and shown in Equation 11. The solutions of this equation for many common geometries were introduced by Crank (1975). The effective moisture diffusivity (D_{eff}) within an infinite slab CQ stem can be calculated according to Equation 12.

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial M}{\partial x}\right) \tag{11}$$

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{12}$$

where D_{eff} and L are the effective moisture diffusivity (m^2 s^{-1}) and half-thickness of a slab (m), respectively. To simplify this equation, n was set as zero as only the first term of the series can be accounted with increasing drying time and assuming the left-hand side of the equation to be less than 0.6 (Zogzas and Maroulis, 1996).

The first term of the series in Equation 12 was then analyzed and the equation was simplified by taking the natural log of both sides to be the expression below,

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}t\right) \tag{13}$$

To continue with our report, we calculated the effective moisture diffusivity (D_{eff}) from the slope of the straight line equation of ln (MR) versus drying time, of which the R^2 values for all drying temperatures were determined and reported.

2.5 Calculation of activation energy

An Arrhenius-type relationship between effective moisture diffusivity and drying temperature (Equation 14) can be used to calculate the activation energy (E_a) required for the CQ drying process.

$$D_{eff} = D_0\exp(-E_a/RT) \tag{14}$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2 s^{-1}); E_a is the activation energy (kJ mol^{-1}); R is the universal gas constant (kJ mol^{-1} K^{-1}); and T is the absolute temperature (K).

2.6 Evaluation of dried CQ quality

2.6.1 Color and total color difference

The values of CIE L*, a*, and b* color parameters of ground dried CQ (particle size ≤ 90 μm) were measured with a Hunter spectrocolorimeter (ColorFlex, version 1.72, Hunter Associates Laboratory, Inc., USA). The total color difference (ΔE) as compared to the color of fresh CQ was calculated as follows:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{15}$$

2.6.2 Shrinkage

To determine the shrinkage of dried CQ, its volume was first measured with a pycnometer; n-heptane was used as the displacement fluid. Shrinkage of dried CQ is expressed as percentage change to the dried volume (V_{d}) of CQ from its fresh volume (V_{i}) as follows:

$$\%\text{Shrinkage} = (V_i - V_d)/V_i \times 100 \tag{16}$$

2.6.3 Bulk density

The bulk density of dried CQ was calculated as its weight over its volume. Dried CQ was filled into a 25-mL cylinder and tapped three times which resulted in a sample in the cylinder with a known volume of 25 mL. The weight of the 25-mL dried CQ sample was then measured and its bulk density was determined.

2.6.4 Total phenolic content

A Folin-Ciocalteu method was used to determine total the phenolic content (TPC) of dried CQ (Chen et al., 2017). Ground dried CQ (particle size ≤ 90 μm, 0.2 g) and 70% methanol (5 mL) was mixed thoroughly in a 10-mL round flask. The mixture was refluxed and extracted at 70°C for 2 h. The extract was then agitated with a vortex mixer for 5 min and centrifuged at 3500 rpm for 10 min. The supernatant was stored in darkness at 4°C before a subsequent TPC analysis using UV-vis spectrophotometer (UV-1800, Shimadzu company, Kyoto, Japan) at an absorbance of 765 nm. The calibrating agent was pure ethanol. TPC was expressed as gallic acid equivalents (mg GAE/100 g dry matter).

2.6.5 Quercetin content

A quantitative high-performance liquid chromatography (HPLC) method modified from that reported by Thiangtham (2003) was used for analysis of quercetin content of dried CQ. A C-18 reverse phase HPLC system (SPD-10A, Shimadzu Company Limited, Kyoto, Japan) with a 260-nm ultraviolet diode-array detector and a hydrosphere column (L × I.D. = 250 × 4.6 mm^2, particle size = 5 μm) was employed. A mobile phase of a mixture of 0.05% ortho-phosphoric acid and acetonitrile at a 65:35 v/v ratio was used at a flow rate of 1 mL min^{-1}. The standard was trans-resveratrol. Quercetin had a retention time of 8.78 min.

2.7 Statistical analysis

All experiments were run in triplicate. Mean ± standard deviation was a format that we used for reporting values. To test significant differences among all treatments, one-way analysis of variance (ANOVA) was performed at 95% confident level. The post hoc test was Duncan's multiple range test.

3 Results and discussion

3.1 CQ drying characteristics and energy consumption during CQ drying

Drying curves of CQ undergoing hot air drying at a temperature in the range of 40°C -100°C are presented in Figure 2. The drying temperature had a substantial effect on the drying process of CQ. Drying at a low temperature of 40°C required 32 h to reach the desirable 0.1 g water/g dry matter moisture content of the dried CQ. The moisture ratio decreased more rapidly when the drying temperature was set to medium or high level, i.e. 60°C onwards. To complete the drying process, the drying times required were 3.83, 2.17, and 1.42 h for drying temperatures of 60°C, 80°C, and 100°C, respectively. It is interesting that an enormous decrease in drying time of about 28 h was achieved by a change of only 20°C in the drying temperature, e.g., a change from a medium temperature of 40°C to a still medium level of 60°C.

Figure 3 shows the energy required to remove water from CQ, also known as energy consumption. The drying temperature is one of the most important energy consumption factors in a hot air drying process. The amounts of energy consumed were consistently and significantly different at different temperatures. At a low drying temperature of 40°C, the drying process needed the significantly highest energy of 25.05 kWh while at a high temperature of 100°C, it needed the significantly lowest energy of 3.40 kWh. The energy values needed by the process operating at high temperatures of 80°C and 100°C were not significantly different. The energy consumption was found to be negatively correlated to drying temperature. On the contrary, positive correlation was observed between energy consumption and drying time, i.e., a higher drying time resulted in a higher energy consumption. These results resembled those from other researchers (Aghbashlo et al., 2008; Motevali et al., 2011).

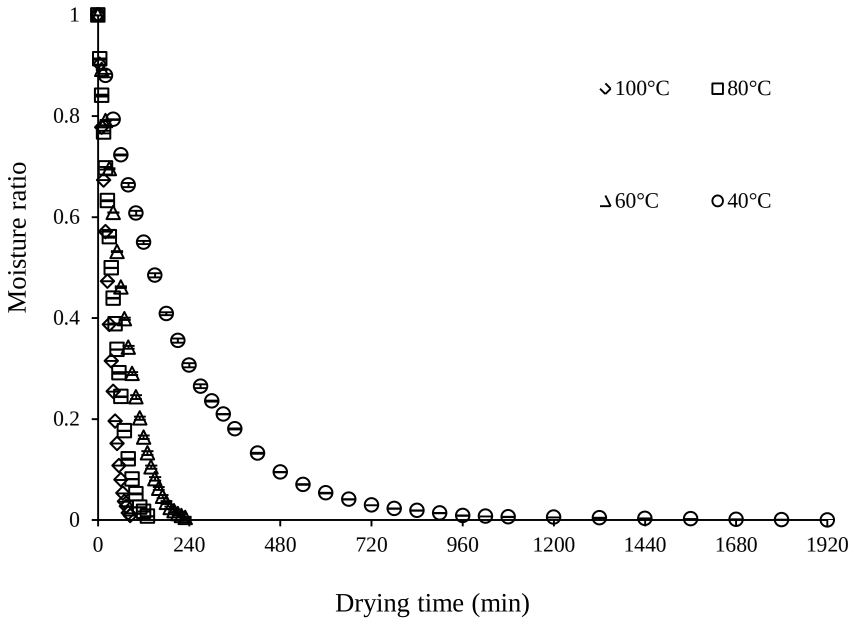

Figure 2 Drying curves of hot air CQ drying at different drying temperatures

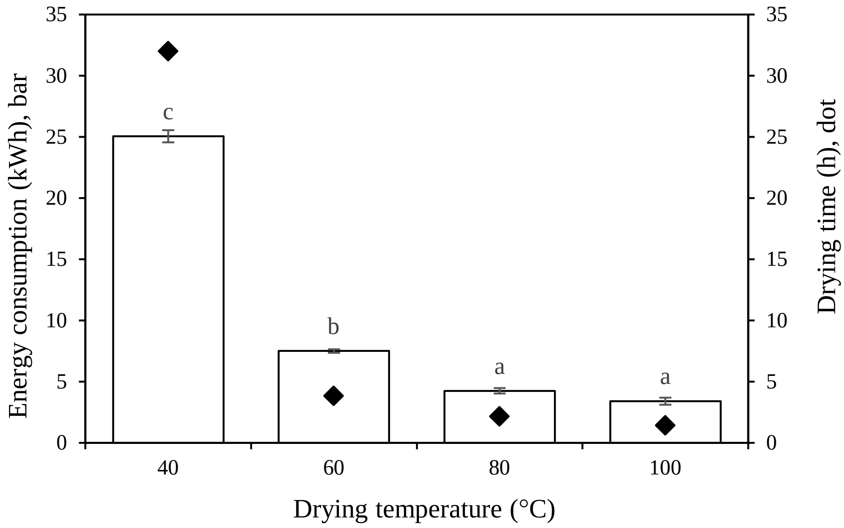

Figure 3 Energy consumption and drying time of hot air CQ drying at different drying temperatures (The same letter over the bars means that the energy consumption values are not significantly different at p<0.05.)

3.2 Drying kinetics model

The drying constants and coefficients in the hot air CQ drying model as well as R^2 and *RSME* are shown in Table 2. Among the studied models, the linear-plus-exponential-type model exhibited the highest average R^2 of 0.9997 and the lowest average *RMSE* of 0.0059; therefore, this model was considered as the best model representing the drying curves of hot air drying of CQ.

A generalized model was then constructed that takes in account the effect of drying temperature on the drying constants and coefficients of the linear-plus-exponential-type model. A polynomial type relationship was found to provide the most accurate regression model for the drying constants and coefficients. The following generalized model can be used to estimate the moisture content in a CQ sample during any time of hot air drying and is fully effective in the temperature range of 40°C -100°C.

$$MR(b,c,k,n,t) = \exp(-kt^n) + bt + c \quad (17)$$

where

$$b = 0.0001 - (2.158 \times 10^{-6}T) - (1.903 \times 10^{-8}T^2),\ R^2 = 0.97 \quad (18)$$

$$c = 0.0145 - (8.908 \times 10^{-6}T) + (6.751 \times 10^{-6}T^2),\ R^2 = 0.98 \quad (19)$$

$$k = 0.0106 - (2.005 \times 10^{-4}T) + (2.139 \times 10^{-6}T^2),\ R^2 = 0.99 \quad (20)$$

$$n = 0.3488 - (0.0194T) - (1.021 \times 10^{-4}T^2),\ R^2 = 0.99 \quad (21)$$

Table 2 Mathematical models applied to CQ drying curves and their statistical results

Model*	T (°C)	Constants and coefficients				R^2	*RMSE*
1	40	k = 0.0049				0.9992	0.0085
	60	k = 0.0142				0.9857	0.0329
	80	k = 0.0220				0.9916	0.0419
	100	k = 0.0340				0.9712	0.0074
2	40	k = 0.0063	n = 0.9543			0.9996	0.0057
	60	k = 0.0056	n = 1.2100			0.9982	0.0128
	80	k = 0.0078	n = 1.2710			0.9992	0.0138
	100	k = 0.0106	n = 1.3290			0.9989	0.0106
3	40	k = 0.0048	a = 0.9781			0.9996	0.0058
	60	k = 0.0149	a = 1.0520			0.9903	0.0286
	80	k = 0.0235	a = 1.0590			0.9940	0.0361
	100	k = 0.0364	a = 1.0760			0.9828	0.0396
4	40	k_0 = 2.1630	k_1 = 0.0047	a = 0.0339	b = 0.9661	0.9998	0.0034
	60	k_0 = 0.0237	k_1 = 0.0243	a = 28.41	b = -27.48	0.9956	0.0189
	80	k_0 = 3.9800	k_1 = 0.0244	a = -0.0970	b = 1.0970	0.9971	0.0252
	100	k_0 = 0.0572	k_1 = 0.0585	a = 28.81	b = -27.81	0.9969	0.0170
5	40	k = 0.0052	a = 0.0856	b = 0.9512		0.9992	0.0085
	60	k = 0.0076	a = 100.50	b = 0.9937		0.9989	0.0098
	80	k = 0.0162	a = 3.6660	b = 0.8905		0.9952	0.0323

	100	k = 0.0155	a = 65.42	b = 0.9874		0.9961	0.0193
6	40	k = 0.0057	n = 0.9709	a = 0.9878	b = -3.92×10^{-7}	0.9997	0.0051
	60	k = -0.0014	n = 1.2070	a = 0.9539	b = -0.0112	0.9939	0.0234
	80	k = 0.0080	n = 1.2440	a = 0.9836	b = -2.72×10^{-4}	0.9998	0.0075
	100	k = 0.0121	n = 1.2740	a = 0.9949	b = -3.60×10^{-4}	0.9997	0.0053
7	40	a = -0.0020	b = 8.63×10^{-7}			0.8075	0.1719
	60	a = -0.0101	b = 2.60×10^{-5}			0.9968	0.0174
	80	a = -0.0167	b = 7.06×10^{-5}			0.9998	0.0068
	100	a = -0.0248	b = 1.56×10^{-4}			0.9993	0.0083
8	40	k = 0.0059	n = 0.9597	b = 7.35×10^{-6}	c = -0.0115	0.9997	0.0048
	60	k = 0.0066	n = 1.1560	b = -1.05×10^{-4}	c = -0.0110	0.9995	0.0063
	80	k = 0.0080	n = 1.2410	b = -1.55×10^{-4}	c = -0.0172	0.9998	0.0074
	100	k = 0.0120	n = 1.2740	b = -2.98×10^{-4}	c = -0.0058	0.9997	0.0052

Note: *Model name: 1 Lewis, 2 Page, 3 Henderson and Pabis, 4 Two term, 5 Approximation of diffusion, 6 Midilli et al., 7 Wang and Singh, and 8 The linear-plus-exponential-type model

The generalized model was validated by conducting CQ drying at 50°C and comparing the experimental moisture ratio values at any drying time to the model-predicted values. The comparison results for the selected drying temperature are shown in plots in Figures 4 and 5. Figure 4 shows plots of the experimental drying curves in comparison to the predicted drying curves. In Figure 5, the datapoints in the plots were well aligned around the 1:1 line (an ideal fitting line), indicating that the generalized linear-plus-exponential-type model was suitable for describing the change in moisture ratio with drying time during hot air CQ drying. The average R^2 calculated from the experimental and predicted moisture ratio values was 0.9977, illustrating an excellent fitting of these values.

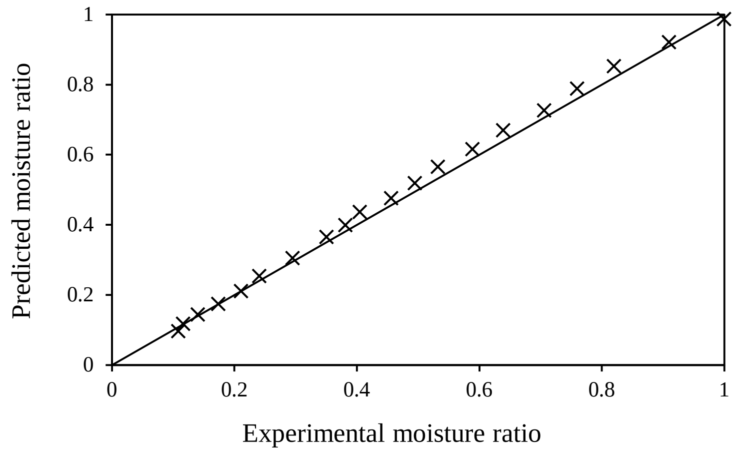

Figure 4 Comparative plot of experimental and predicted moisture ratios by the generalized linear-plus-exponential-type model at the validation drying temperature of 50°C over the ideal 1:1 line

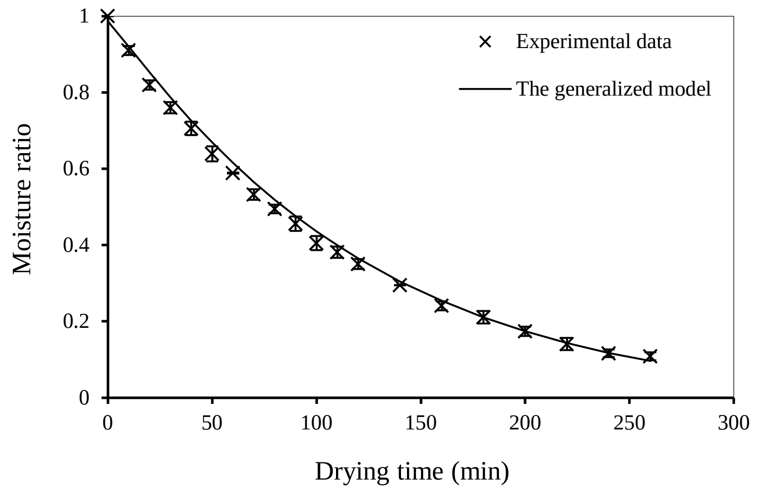

Figure 5 Experimental and predicted drying curves of hot air CQ drying at the validation drying temperature of 50°C

3.3 Effective moisture diffusivity and activation energy of CQ drying process

Effective moisture diffusivity (D_{eff}) is useful for indicating the rate of moisture transport during the process of drying, as moisture within the material is dominantly transferred by diffusion. The diffusivity values obtained for the hot air drying process (Table 3) were considered high compared to a typical effective moisture diffusivity of food materials which is in the range of 10^{-11} to 10^{-9} m^2 s^{-1} (Sripinyowanich and Noomhorm, 2011). It is obvious that the effective moisture diffusivity increased with increasing drying temperature. The high effective moisture diffusivity provided by this process could be due to the increased energy absorbed by the moisture within CQ (Zheng et al., 2015). Zhu et al. (2015) also reported that the absorbed energy increased as the drying temperature increased. Furthermore, because of the high initial moisture content, tissue, and infrequent structure of CQ, the effective moisture diffusivity of CQ is high (Aghbashlo et al., 2008).

Figure 6 displays the linear equation derived from an Arrhenius-type relationship between the effective moisture diffusivity and the temperature of hot air of the CQ drying process. Calculated from the slope of the plot, the value of the activation energy of the drying process for CQ was 39.78 kJ mol^{-1}. This value is higher than that of the drying process for vegetable waste (19.82 kJ mol^{-1}), but lower than that for garlic (54.9 kJ mol^{-1}) (Akgun and Doymaz, 2005). This high activation energy of CQ could be due to its very thick stem wall as well as high moisture content.

Table 3 Effective diffusivity of hot air drying of CQ at different drying temperatures

Temperature (°C)	Effective diffusivity (m^2 s^{-1})	R^2
40	0.7302×10^{-9}	0.978
60	3.6918×10^{-9}	0.963
80	6.0043×10^{-9}	0.958
100	9.1281×10^{-9}	0.959

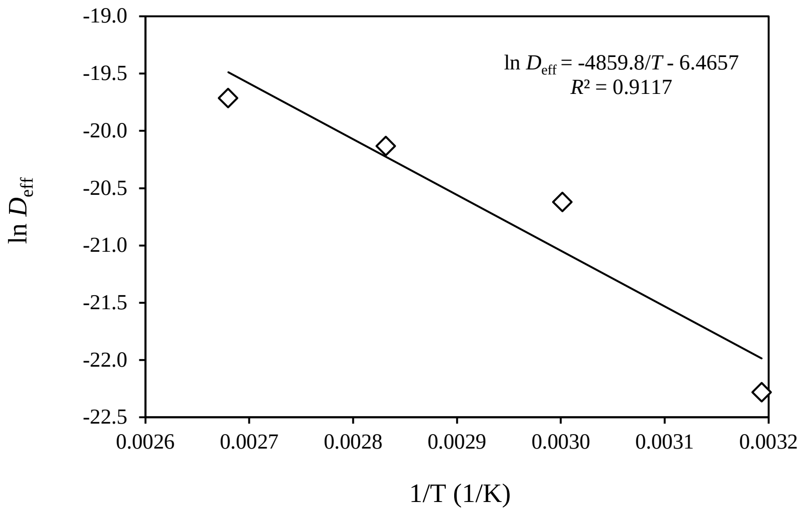

Figure 6 Plot of Natural logarithm of effective moisture diffusivity vs. reciprocal of absolute temperature of hot air drying of CQ

3.4 Color and total color difference

Table 4 shows the results of color and total color difference of CQ dried at different temperatures against fresh CQ as control. All samples dried under different drying temperatures and the control exhibited significantly different color values (for all of these color parameters: L^*, a^*, b^* and ΔE) at $P < 0.05$. Fresh CQ was found to be darker and greener than dried CQ and had lower L^* and a^* values. The greenness of any materials can be represented by a negative value of a^*. In this study, the greenness of CQ depended on the drying temperature. Increasing the drying temperature resulted in decreased greenness. In addition, the yellowness (positive b^*) was the highest for CQ dried at 100°C, indicating a progressively browner color for CQ samples dried at higher and higher temperatures in the test range. This change in color could be because of a non-enzymatic browning reaction induced by high-temperature drying (Mitra et al., 2015). Regarding total color difference, the color of CQ samples dried at 60°C was well preserved. However, the color of CQ samples dried at a lower temperature of 40°C was less well-preserved due to an extremely long drying time required.

Table 4 L^*, a^*, b^*, and total color difference (ΔE) of fresh and dried CQ samples at different temperatures

Temperature (°C)	Color			
	L^*	a^*	b^*	ΔE
Fresh	39.39±0.02[a]	-8.06±0.02[a]	25.50±0.06[b]	0±0.00[a]
40	57.69±0.14[e]	-0.19±0.04[b]	26.81±0.18[c]	19.99±0.02[e]
60	54.31±0.09[d]	-0.08±0.02[c]	20.26±0.13[a]	16.76±0.04[b]
80	53.51±0.07[c]	3.03±0.09[d]	28.66±0.06[d]	17.71±0.02[c]
100	51.56±0.34[b]	3.18±0.01[e]	29.19±0.05[e]	18.42±0.01[d]

3.5 Shrinkage and bulk density

Figure 7 shows the significant effects of drying temperature on shrinkage and bulk density of dried CQ (p<0.05). Increasing the drying temperature resulted in increased shrinkage percentage and bulk density of the materials. Both the shrinkage percentage and bulk density increased and decreased together because it can be taken as a fact that shrinkage is actually a reduction in volume, and where no material loss occurs, the density consequently increases. The shrinkage of the dried CQ was likely to be caused by moisture removal and stresses developed in the CQ sample during drying (Pan et al., 2008). In terms of desirable shrinkage and bulk density properties of CQ, 40°C and 60°C drying temperatures were considered good for our purpose as they provided the significantly lowest values of shrinkage percentage and bulk density.

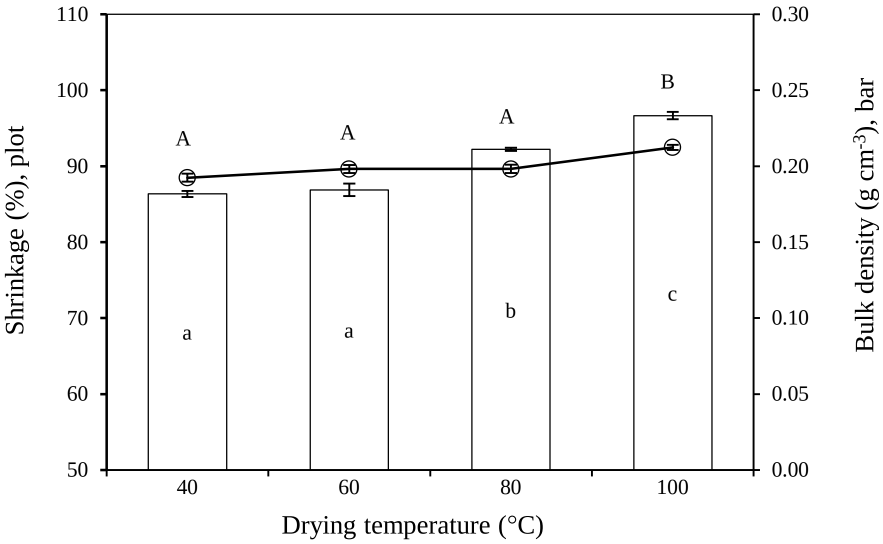

Figure 7 Shrinkage percentage and bulk density of dried CQ at different drying temperatures.

Note: The same capital letter in the line plot means that those shrinkage percentage values are not significantly different at p<0.05, and the same small letter in the bars means that the bulk density values are not significantly different at p<0.05.

3.6 Total phenolic content and quercetin content

The total phenolic content (TPC) and quercetin content of dried CQ at different temperatures are shown in Table 5. The TPC and quercetin contents of CQ samples dried at different temperatures were significantly different at p<0.05. It was found that the minimum TPC and quercetin contents were found in CQ samples dried at 40°C. This could be due to the adverse effect of low browning reaction induced by this drying treatment as there has been a report that browning reaction products formed during drying have a high antioxidant activity (Chan et al., 2009). Of note is that the highest TPC and quercetin contents were found in CQ samples dried at 60°C. A higher drying temperature would better disrupt the cell wall of CQ sample and led to more release of oxidative and hydrolytic enzymes and degradation of its phytochemicals. However, drying CQ samples at a lower temperature of 40°C did not preserve the TPC and quercetin contents quite as well because of the adverse effect of low browning reaction that was mentioned above.

Table 5 TPC and Quercetin contents of dried CQ samples

Temperature (°C)	TPC (mg GAE/100 g dry matter)	Quercetin (mg/100 g dry matter)
40	1009.880± 6.734[a]	0.887±0.004[a]
60	1061.999± 4.346[d]	0.995±0.008[d]
80	1039.452± 5.852[b]	0.957±0.007[c]
100	1022.904± 5.135[c]	0.891±0.008[b]

4 Conclusions

The drying time and energy consumption of the convective hot air drying process of CQ were negatively dependent on the drying temperature. The effective moisture diffusivity and activation energy of the drying process for CQ was high at 10^{-9} m^2 s^{-1} and 39.78 kJ mol^{-1}. Among the eight thin-layer drying models considered, the linear-plus-exponential-type model provided the best fit for all drying temperatures. The generalized model as a function of drying temperature also exhibited a high R^2 of 0.9977. The drying temperature of 60°C gave better quality dried CQ. This drying condition produced dried CQ with the lowest total color difference, shrinkage percentage, and bulk density and the highest total phenolic content and quercetin content. Some results from this study should benefit other researchers who may consider developing other new CQ drying methods, especially the exact values of the energy consumption of and the quercetin and TPC contents achieved by this drying method.

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References

Aghbashlo, M., M. H. Kianmehr, and H. Samimi-Akhijahani. 2008. Influence of drying conditions on the effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of berberis fruit (Berberidaceae). *Energy Conversion and Management*, 49(10): 2865–2871.

Akgun, N. A., and I. Doymaz. 2005. Modelling of olive cake thin-layer drying process. Journal of Food Engineering, 68(4): 455–461.

AOAC (Association of Official Agricultural Chemists). 2005. *Official Methods of Analysis*. 18th ed. Washington, DC.: AOAC.

Bhujade, A. M., S. Talmale, N. Kumar, G. Gupta, P. Reddanna, S. K. Das, and M. B. Patil. 2012. Evaluation of *Cissus quadrangularis* extracts as an inhibitor of COX, 5-LOX, and proinflammatory mediators. *Journal of Ethnopharmacology*, 141(3): 989-996.

Bruce, D. M. 1985. Exposed-layer barley drying, three models fitted to new data up to 150°C. *Journal of Agricultural Engineering Research*, 32(4): 337-348.

Chan, E. W. C., Y. Y. Lim, S. K. Wong, K. K. Lim, S. P. Tan, F. S. Lianto, and M. Y. Yong. 2009. Effects of different drying methods on the antioxidant properties of leaves and tea of ginger species. *Food Chemistry*, 113(1): 166-172.

Chen, Q., Z. Li, J. Bi, L. Zhou, J. Yi, and X. Wu. 2017. Effect of hybrid drying methods on physicochemical, nutritional and antioxidant properties of dried black mulberry. *LWT-Food Science and Technology*, 80: 178-184.

Crank, J. 1975. *The Mathematics of Diffusion*. 2nd ed. London: Oxford University Press.

Henderson, S. M., and S. Pabis. 1961. Grain drying theory II. Temperature effects on drying coefficients. *Journal of Agricultural Engineering Research*, 6: 169-174.

Henderson, S. M. 1974. Progress in developing the thin layer drying equation. *Transactions of ASABE*, 17(6): 1167-1168.

Kumar, R., K. Y. Gupta, S. Singh, and S. Arunraja. 2015. *Cissus quadrangularis* attenuates the adjuvant induced arthritis by down regulating pro-inflammatory cytokine and inhibiting angiogenesis. *Journal of Ethnopharmacology*, 175: 346-355.

Lekshmi, R. K., R. Rajesh, and S. Mini. 2015. Ethyl acetate fraction of *Cissus quadrangularis* stem ameliorates hyperglycaemia-mediated oxidative stress and suppresses inflammatory response in nicotinamide/streptozotocin induced type 2 diabetic rats. *Phytomedicine*, 22(10): 952-960.

Midilli, A., H. Kucuk, and Z. A. Yapar. 2002. New model for single-layer drying. *Drying Technology*, 20(7): 1503-1513.

Mitra, J., S. L. Shrivastava, and P. S. Rao. 2015. Non-enzymatic browning and flavour kinetics of vacuum dried onion slices. *International Agrophysics*, 29: 91-100.

Motevali, A., S. Minaei, and M. H. Khoshtagaza. 2011. Evaluation of energy consumption in different drying methods. *Energy Conversion and Management*, 52(2): 1192-1199.

Page, G. E. 1949. Factors influencing the maximum rates of air drying shelled corn in thin layers. M.S. thesis, Mechanical Engineering Dept., Indiana.

Pan, Z., C. Shih, T. H. McHugh, and E. Hirschberg. 2008. Study of banana dehydration using sequential infrared radiation heating and freeze-drying. *LWT-Food Science and Technology*, 41(10): 1944-1951.

Promnuch, J., N. Junka, C. Wongs-Aree, S. Soponronnarit, N. Srisang, and C. Rattanamechaiskul. 2017. Increasing energy efficiency of the *Cissus quadrangularis* drying by hot air fluidization technique. *Energy Procedia*, 138: 889-894.

Sripinyowanich, J., and A. Noomhorm. 2011. A new model and quality of unfrozen and frozen cooked rice dried in a microwave vibro-fluidized bed dryer. *Drying Technology*, 29(7): 735-748.

Thiangtham, J. 2003. Determination of antioxidant constituents in the medicinal plant *Cissus quadrangularis* Linn. M.S. thesis, Pharmaceutical Chemistry Dept., Chulalongkorn Univ., Bangkok, Thailand.

Vijayalakshmi, A., P. R. Kumar., S. S. Priyadarsini, and C. Meenaxshi. 2013. *In vitro* antioxidant and anticancer activity of flavonoid fraction from the aerial parts of *Cissus quadrangularis* Linn. against human breast carcinoma cell lines. *Journal of Chemistry*, 123: 150675.

Wang, C. Y., and R. P. Singh. 1978. Use of variable equilibrium moisture content in modeling rice drying. *Transactions of American Society of Agricultural Engineers*, 11: 668-672.

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

Zheng, M., Q. Xia, and S. Lu. 2015. Study on drying methods and their influences on effective components of loquat flower tea. *LWT-Food Science and Technology*, 63(1): 14-20.

Zhu, J. F., J. Z. Liu, J. H. Wu, J. Cheng, J. H. Zhou, and K. F. Cen. 2015. Thin-layer drying characteristics and modeling of Ximeng lignite under microwave irradiation. Fuel Processing Technology, 130: 62-70.

Zogzas, N. P., and Z. B. Maroulis. 1996. Effective moisture diffusivity estimation from drying data. A comparison between various methods of analysis. *Drying Technology*, 14(7-8): 1543-1573.1