Effects of vibration, vacuum, and material thickness on infrared drying of *Cissus quadrangularis* Linn.

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ABSTRACT

Infrared (IR), vibratory bed assisted infrared (VIR), vacuum infrared (VC-IR), and vibratory bed assisted vacuum infrared (VC-VIR) drying of *Cissus quadrangularis* Linn. (CQ) were conducted. The objective was to investigate the effects of vibration, vacuum, and material thickness on IR drying of CQ. VC-VIR drying of 5-mm CQ provided the highest maximum drying rate (DR) of 0.258 g water/g dry matter·min. Although the vacuum operation contributed to improved effective moisture diffusivity (D_{eff}), it consumed high energy and degraded active compounds of CQ. VIR drying could be a more promising technique. VIR drying of 15-mm CQ produced the greatest total phenolic content (TPC) and quercetin content of 1083.62 mg GAE/100 g dry matter and 3.472 mg/100 g dry matter, respectively. The lowest total color difference (ΔE) of 13.69 was also obtained. It required low specific energy consumption (SEC) of 17.62 kWh/kg and provided maximum DR of 0.112 g water/g dry matter·min.

1. Introduction

Cissus quadrangularis Linn. (CQ) is one of the most frequently used medicinal plants in Thailand and many countries in Asia and Africa (Thiangtham, 2003). The stout fleshy quadrangular stem of CQ has been used for treating diverse physical conditions such as rheumatic disease, allergies, skin diseases, piles, hemorrhoid and irregular menstruation (Bhujade et al., 2012; Vijayalakshmi et al., 2013). It also accelerates bone fracture healing (Lekshmi et al., 2015). It is rich in phenolic compounds and flavonoids such as kaempferol and quercetin (Kumar et al., 2015; Lekshmi et al., 2015). CQ however cannot be consumed raw as it contains calcium oxalate that causes throat irritation. Like most herbal plants, it must be dried, ground and encapsulated in capsules for consumption. Therefore, calcium oxalate would have no effect on throat irritation.

Drying is a critical process in CQ manufacturing because this process may affect the pharmacological properties of dried CQ. The traditional drying process for most herbal plants is sun dry. It is time-consuming and weather-dependent. Hot air (HA) drying has been alternatively used in commercial manufacturing; however, long drying period causes very high degradation of the product (Kumar et al., 2006; Siriamornpun et al., 2012). Alternatively, infrared (IR) has been reported to be successfully

applied in drying of foods and agricultural products. IR has been shown to cleave covalent bonds and liberate antioxidant compounds such as flavonoids, carotene, tannin, ascorbate, flavoprotein, and polyphenols in repeating polymers (Rho et al., 2010).

Unfortunately, IR does not penetrate deeply into materials and it has been considered for surface heating only. Mechanical system like vibration would be useful for allowing the material to be irradiated by IR uniformly. It has been reported that there was no significant effect of material bed depth on drying rate when drying paddy by vibration-aided IR drying (Das et al., 2004). In addition, drying in vacuum has been proved favorable for heat-sensitive material. Lower pressure leads to lower boiling point of water; hence, drying could be achieved at lower temperature. As a result, heat damage during drying is minimal.

Up to date, research on vibration-aided vacuum IR drying is very rare. This technique is expected to be a promising technique for drying herbal plants as IR radiation has been renowned for the enhancement of many active compounds in biological materials (Rho et al., 2010; Azad et al., 2018). IR also has many further intrinsic advantages such as simplicity of equipment set up, fast transient response, and energy saving (Rastogi, 2012). In this study, vibration and vacuum systems were added to IR drying to improve its limited surface heating.

Therefore, the aim of this study was to conduct vibratory bed assisted vacuum infrared (VC-VIR) drying of CQ. The effects of vibration, vacuum, and material thickness on drying characteristics, energy consumption during drying, and physicochemical properties of dried CQ were investigated. The promising technique for improving drying characteristic and quality of dried CQ would be reported. It should be good for energy saving and for application in industrial processes as well.

2. Materials and methods

2.1. Sample

Fresh CQ (Fig. 1) was purchased from an herbal supplier in Prachin Buri province, Thailand. The whole plant was cleaned with tap water, air dried, packed in a polyethylene zip lock bag, and stored at 4 °C. It was allowed to equilibrate to room temperature prior to experiments. Top and bottom portions of the CQ aerial part were excluded in this study. The initial moisture content of the samples was 10.10 ± 0.15 g water/g dry matter.

2.2. Schematic of a vibratory bed assisted vacuum infrared dryer

Schematic of the VC-VIR dryer is shown in Fig. 2. It consisted of four main components: an IR heating unit, a vibratory bed, a vacuum system, and a control system. A drying chamber was cylindrical with a diameter and length of 30 and 60 cm, respectively. Two 800-W IR (far infrared rays) heaters (CF Series, Sang Chai Meter Co., Ltd., Bangkok, Thailand) were fixed on the inside at the top of the chamber. The distance between the heater and the drying tray was fixed at 20 cm. The drying tray was made of perforated stainless steel with dimensions of 40 cm×20 cm×5 cm. It was mounted on the vibratory bed. A variable speed motor was attached to an eccentric joint to transmit vertical vibration to the drying tray. A vacuum pump (ENWA 1EN-030-01, Norta MIT GmbH, Hamburg, Germany) was used to maintain the vacuum condition of the system. A centrifugal fan was driven by a 0.5 kW motor to provide air ventilation in case no vacuum was required.

2.3. Experimental procedure

CQ stem pieces were dried by four drying techniques—infrared (IR), vibratory bed assisted infrared (VIR), vacuum infrared (VC-IR), and vibratory bed assisted vacuum infrared (VC-VIR) drying—in order to investigate the effects of vibration and vacuum on IR drying of CQ. The thickness of CQ stem pieces was also varied from 5, 10, to 15 mm. IR intensity of 7496 W/m^2 was selected based on previous work on the effect of IR intensity on the quality of CQ and used for all drying techniques. There are many works on IR drying using the same IR intensity (Eskandari et al., 2018; Wu et al., 2019; Lara et al., 2019). The driving motor of 800 rpm provided vibration for the drying tray for VIR and VC-VIR drying. When vacuum is not needed (IR and VIR drying), air velocity of 1 m/s, measured by a vane anemometer with a precision of ±0.1 m/s (Wilh. Lambrecht GmbH, Göttingen, Germany), was applied for ventilation. An absolute air pressure of 5 kPa was maintained for VC-IR and VC-VIR drying condition. At the beginning of the experiment, two hundred and sixty grams of CQ was placed on the drying tray. The mass of this CQ was measured repeatedly at some intervals in order to determine its moisture content (see Section 2.4). Moisture ratio (MR), drying rate (DR), and effective moisture diffusivity (D$_{eff}$) were calculated

Fig. 1. Fresh CQ stems.

as respectively shown in Section 2.4 and 2.5 to present moisture transport properties of CQ during drying. Drying time to achieve the CQ final moisture content of 0.10 g water/g dry matter was determined. Energy consumption during the drying process was measured (Section 2.6). Physicochemical properties of the dried CQ as listed in Section 2.7 were also evaluated. In this regard, hot air (HA) drying of CQ with piece thickness of 5 mm was conducted at 60 °C to produce a reference treatment. Fresh CQ was also used as a control to compare the physicochemical properties.

2.4. Determination of drying characteristics

Moisture content of CQ was determined by drying 5 g of CQ in a HA oven (ULM 500, Memmert GmbH+Co.KG, Schwabach, Germany) at 105 °C for 24 h (AOAC, 2005). Moisture content in dry basis was calculated as follows:

$$M = \frac{m_w - m_d}{m_d} \qquad (1)$$

where M, m_w, and m_d are moisture content (g water/g dry matter), wet mass of the material (g), and dry mass of the material (g), respectively.

The moisture content of the CQ was used to calculate MR and DR as follows (Xie et al., 2017):

$$MR = \frac{M_t - M_e}{M_i - M_e} \qquad (2)$$

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

where M_i, M_t, M_e, and $M_{t+\Delta t}$ are moisture content (g water/g dry matter) at the initial time, at a specific time, at equilibrium, and at $t+\Delta t$, respectively; t is drying time (min). M_e was assumed to be zero for radiative drying (Sripinyowanich and Noomhorm, 2011).

2.5. Calculation of effective moisture diffusivity

Mechanism of moisture movement within a biological material during the falling rate period is dominated by a diffusion phenomenon as explained by Fick's second law of diffusion. The moisture diffusion derived from the Fick's law can be expressed as follows:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial M}{\partial x}\right) \qquad (4)$$

This equation was solved by Crank (1975) for various regular geometries with the application of several boundary conditions. Based on the assumption that mass transfer is symmetric and uniform and by diffusion only, diffusion coefficient and temperature are constant, shrinkage and external resistance is negligible, and CQ stem pieces are infinite slabs, the D_{eff} within the materials can be estimated by the following equation (Deng et al., 2018):

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2D_{eff}t}{4L^2}\right) \qquad (5)$$

where D_{eff} is the effective moisture diffusivity (m^2/s) and L is the half-thickness of slab (m).

For long periods of CQ drying, only the first term ($n = 0$) of the Eq. (5) was used (Sadin et al., 2014; Agnihotri et al., 2017). Hence, it becomes:

$$MR = \frac{8}{\pi^2}exp\left(-\frac{\pi^2D_{eff}}{4L^2}t\right) \qquad (6)$$

The above equation can be simplified to a straight-line equation by taking the natural logarithm of both sides as follows:
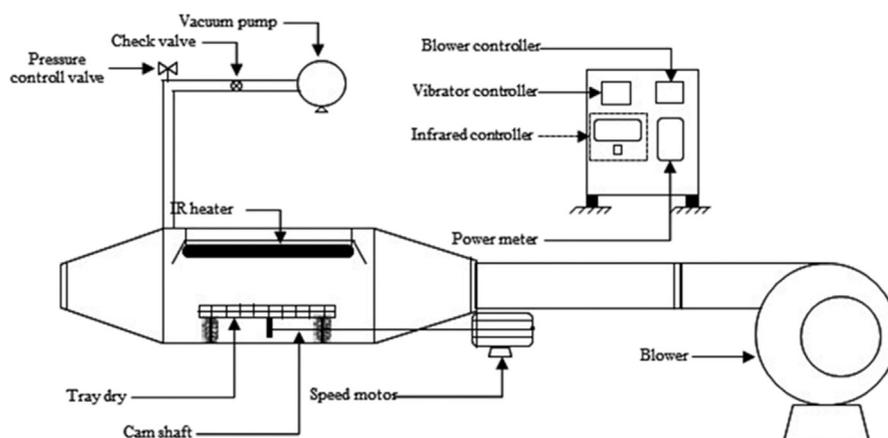
Fig. 2. A VC-VIR dryer.

$$ln\ MR = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}t\right) \tag{7}$$

By plotting ln *MR* versus drying time (t) in second, the slope of the Eq. (7) can be used to determine D_{eff} using the following equation:

$$D_{eff} = -\frac{\text{Slope}4L^2}{\pi^2} \tag{8}$$

2.6. Analysis of specific energy consumption

Total energy required for CQ drying was measured by a multifunction energy meter (KM-06-N, Primus Company Limited, Bangkok, Thailand). The energy used in heating the system up was excluded. Specific energy consumption (SEC) reported in this research was defined as the energy required to remove 1 kg of water from the material and hence expressed as kWh/kg as follows:

$$SEC = E_t/W_0 \tag{9}$$

where E_t is the required total energy (kWh) and W_0 is the weight of water removed (kg).

2.7. Determination of physicochemical properties

2.7.1. Total phenolic content
Total phenolic content (TPC) of the dried CQ was determined by Folin-Ciocalteu method (Chen et al., 2017). Dried CQ was ground and passed through a 180 mesh screen. A sample of 0.2 g was put in a 10-ml round flask and mixed with 5 ml of 70% methanol. The mixture was under a reflux condenser and extracted at 70 °C for 2 h. The resulting extract was vigorously agitated with a vortex mixer (G-560E, Scientific Industries, Inc., Bohemia, NY, USA) for 5 min and centrifuged at 3500 rpm for 10 min. The supernatant was stored at 4 °C in darkness for subsequent TPC analysis. The TPC analysis was conducted with a UV-vis spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan) with an absorbance of 765 nm. Pure ethanol was used as a calibrating agent. TPC was reported as gallic acid equivalents (mg GAE/100 g dry matter).

2.7.2. Quercetin content
Quercetin content in the dried CQ was determined by using a quantitative HPLC method modified from a method reported by Thiangtham (2003). The HPLC system (SPD-10A, Shimadzu Co., Kyoto, Japan) with C-18 reverse phase was connected to a 260-nm UV diode-array detector. A hydrosphere column (particle size = 5 μm and L × I.D. = 250 × 4.6 mm^2) was used in conjunction with a mobile phase of 65:35 v/v of 0.05% ortho-phosphoric acid: acetonitrile at a flow rate of 1 mL/min. Trans-resveratrol was used as a standard agent. The retention time of

quercetin was 8.78 min.

2.7.3. Total color difference
Dried CQ was ground and sieved through a 180 mesh screen for color determination. Color of the dried CQ was measured in CIE *L** (lightness (100) to darkness(0)), *a** (redness (+60) to greenness (-60)), and *b** (yellowness (+60) to blueness (-60)) system using a spectrocolorimeter (ColorFlex, Hunter Associates Laboratory, Inc., VA, USA). These values were converted into ΔE according to Eq. (10). In this study, ΔE was calculated in relation to the fresh CQ.

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{10}$$

2.8. Statistical analysis

All experiments were done in triplicates, unless otherwise specified. Data were presented as mean ± standard deviation. Factorial experiments in completely randomized design were conducted to determine the effect of different drying methods and thicknesss of CQ pieces on the physicochemical properties of CQ. Two-way analysis of variance with Duncan's multiple range test was performed to determine significant differences between treatments among all treatments at 95% confident level.

3. Results and discussion

3.1. Drying characteristics

Drying time and maximum *DR* of IR, VIR, VC-IR, and VC-VIR drying of CQ with different piece thickness are presented in Table 1. The shortest

Table 1
Drying time and maximum *DR* of CQ drying.

Drying method	Thickness (mm)	Drying time (min)	Maximum *DR* (g water/g dry matter·min)
IR	5	110	0.147 ± 0.001
	10	140	0.121 ± 0.005
	15	180	0.107 ± 0.002
VIR	5	95	0.160 ± 0.003
	10	120	0.130 ± 0.002
	15	160	0.112 ± 0.002
VC-IR	5	75	0.238 ± 0.001
	10	90	0.200 ± 0.001
	15	100	0.193 ± 0.001
VC-VIR	5	70	0.258 ± 0.001
	10	85	0.202 ± 0.001
	15	90	0.197 ± 0.010

drying time of 70 min and the highest maximum *DR* of 0.258 g water/g dry matter·min were achieved by VC-VIR drying with the shortest thickness (5 mm) of CQ. As expected, IR drying of CQ with the thickest pieces of 15 mm, resulted in the longest drying time of 180 min and the lowest maximum *DR* of 0.107 g water/g dry matter·min. This result supported the idea that vibration, vacuum, and material size had an effect on drying characteristics of CQ. Positive effects of vibration and vacuum on IR drying characteristics were also reported by Jongyingcharoen et al. (2015). Das et al. (2009) also found that *DR* of IR drying could be improved by combining vibration in the system and decreasing material thickness.

MR and *DR* curves for IR, VIR, VC-IR, and VC-VIR drying of CQ with piece thickness of 15 mm are respectively shown in Figs. 3 and 4 which demonstrate the effects of vibration and vacuum on the drying characteristics of CQ. To illustrate the effect of material thickness on the drying characteristics of CQ, representative *MR* curves and *DR* curves for VIR drying of CQ with piece thickness of 5, 10, and 15 mm are presented in Figs. 5 and 6, respectively. From the *DR* curves, two *DR* periods were observed including a heating-up period from beginning to the peak *DR*, followed by a falling rate period which the *DR* decreased. Similar trend was also observed for the rest of the treatments. No constant rate period was also reported by Das et al. (2009) during VIR drying of paddy.

It can be clearly seen that vacuum exerted more effect on drying time and *DR* than vibration did. The maximum *DR*s were about 80% and 76% higher on average when using vacuum in IR drying and VIR drying, respectively. On the other hand, when the material was vibrated, the maximum *DR*s of VIR drying and VC-VIR drying were only about 5% and 2% higher than those of IR and VC-IR drying alone. As seen in Fig. 3, IR or VIR drying with vacuum operation led to considerably lower *MR* than those without vacuum operation for the same drying time. It is because evaporation of water under vacuum operation occurs at lower temperature; therefore, the onset of moisture transfer was at early stage. In combining with IR drying of which the penetration of IR into the materials causes a rapid increase in water vapor pressure, additional vacuum operation leads to extreme pressure gradient of water vapor and then substantially increased rate of moisture diffusion (Salehi and Kashaninejad, 2018).

As expected, higher rate of moisture removal was observed for smaller pieces of CQ (Fig. 4). This result is similar to that of a study on VIR drying of paddy (Das et al., 2009) and a study on VC-IR drying of banana slice (Swasdisevi et al., 2009). The increased *DR* with decreased material thickness could be due to higher radiant energy input per unit mass of material and decreased distance over which the moisture had to travel inside the material before being removed from the material surface.
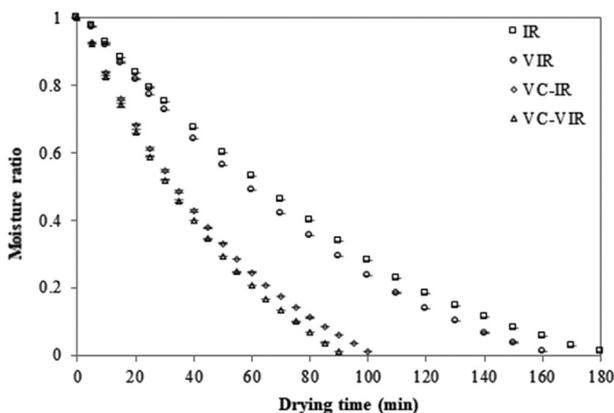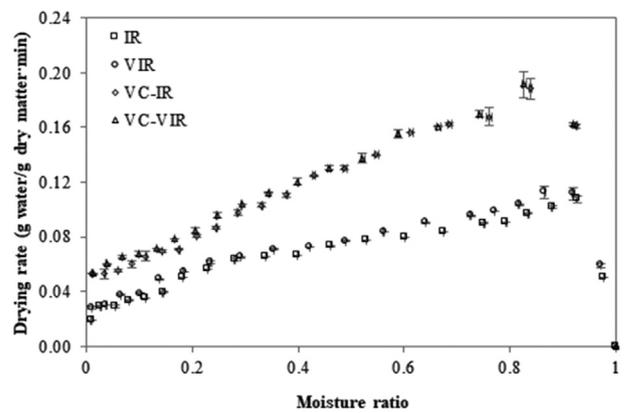
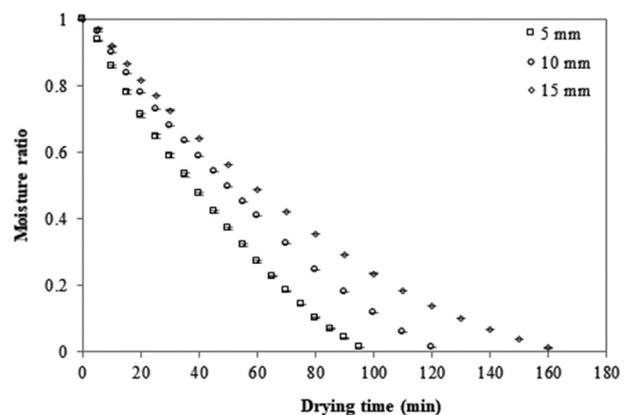**Fig. 4.** *DR* curves of IR, VIR, VC-IR, and VC-VIR drying of CQ with the thickness of 15 mm.

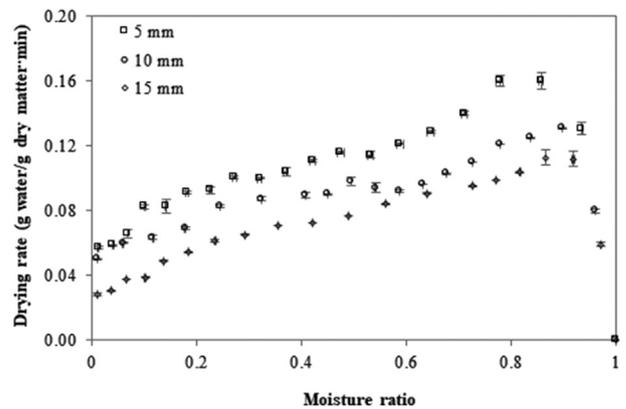**Fig. 5.** *MR* curves of VIR drying of CQ of different material thicknesses.

Fig. 6. *DR* curves of VIR drying of CQ of different material thicknesses.

3.2. Effective moisture diffusivity

D_{eff} characterizes intrinsic moisture transport property of a material subjected to drying. Fig. 7 shows the D_{eff} of CQ drying as affected by vibration, vacuum, and material thickness. The values of D_{eff} mostly conformed to the typical range of 10^{-11} to 10^{-9} m^2/s for drying of food and agricultural materials (Sripinyowanich and Noomhorm, 2011). For any particular drying method, the D_{eff} values were observed to substantial increase with an increase in material thickness. CQ with the thickness of 15 mm had almost double the D_{eff} of the 10 mm pieces and nearly quadruple the D_{eff} of the 5 mm pieces. Thickness dependence of D_{eff} were
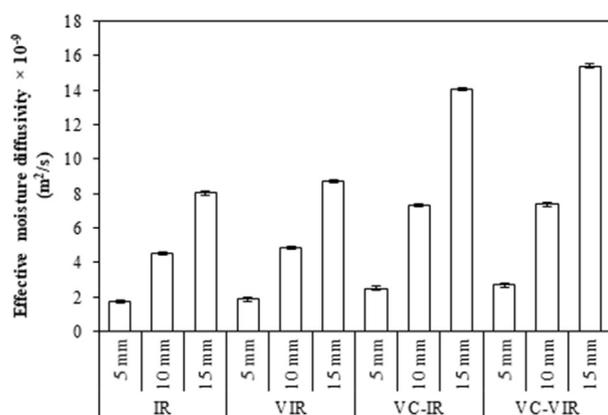
Fig. 3. *MR* curves of IR, VIR, VC-IR, and VC-VIR drying of CQ with the thickness of 15 mm.

Fig. 7. Effective moisture diffusivity of CQ during the infrared drying process.

Fig. 8. Specific energy consumption (bars) vs. drying time (plots) of CQ drying.

reported for various agricultural materials in literatures (Sadin et al., 2014; Das and Arora, 2018; Cuevas et al., 2019). Based on the assumption of the Fick's diffusion model, diffusion takes place from inside to the surface of slabs only in one direction. This assumption is valid for thin slabs with negligible lateral diffusion. However, in thick slabs, lateral diffusion might occur and result in elevated value of D_{eff}.

In this study, the D_{eff} was also vacuum dependent. The D_{eff} values tended to be higher when drying CQ in vacuo. It can be clearly seen that the D_{eff} values for VC-IR and VC-VIR drying of CQ were about 50% higher than those for IR and VIR drying, respectively. This could be due to quicker evaporation of moisture from the material surface under vacuum condition. In addition, high water vapor pressure gradient during vacuum operation could enhance the removal of moisture from the material.

Although vibration led to an increase in the values of D_{eff} of CQ drying for any particular material thickness, the differences between the treatments with and without vibration were relatively small from 0.05×10^{-9} to 1.47×10^{-9} m^2/s.

3.3. Specific energy consumption

Fig. 8 presents the energy required by IR, VIR, VC-IR, and VC-VIR drying to remove 1 kg water of CQ. Two groups of low SEC and high SEC were observed. The vacuum system consumed considerably high energy, hence SECs of VC-IR and VC-VIR drying of CQ were classified into the high SEC group. The results are similar to those reported by Motevali et al. (2011) for pomegranate aril drying; SEC of vacuum drying was four times higher than that of IR drying. It is interesting that vibration had no significant effect on SEC. Regarding the effect of material size, a reduction in SEC was obtained with smaller size. From the graph, inverse relationship between SEC and drying time was also observed. Although the vacuum system consumed high energy, it has the advantage of rapid drying.

3.4. Physicochemical properties of dried Cissus quadrangularis Linn.

3.4.1. Total phenolic and quercetin contents

Two important chemical constituents presented in CQ stem are phenolics and flavonoids. Its phenolic compounds were reported to possess potent antioxidant activity (Lekshmi et al., 2015). Regarding flavonoids, there has been a report that quercetin is the active component found in CQ stem (Kumar et al., 2015). Quercetin exhibits DPPH radical scavenging activity and high antioxidant capacity (Thiangtham, 2003).

Amounts of TPC and quercetin content of dried CQ are shown in Tables 2 and 3. From a statistical analysis, there was an interaction effect between drying method and material thickness on TPC and quercetin content ($p < 0.05$). Vibration tended to improve TPC and quercetin content while vacuum tended to degrade them. It is also significant that an increase in the thickness resulted in an increase in TPC and quercetin
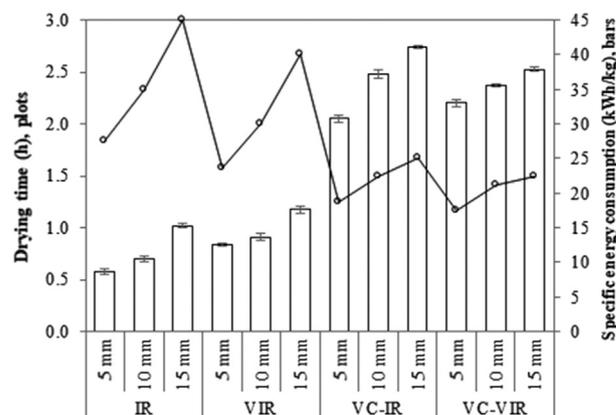
Table 2
TPC (mg GAE/100 g dry matter) of dried CQ as affected by vibration, vacuum, and material thickness.

Drying method	Material thickness (mm)		
	5	10	15
IR	870.82 ± 14.14[ns,b]	873.72 ± 8.67[ns,b]	868.93 ± 8.42[ns,d]
VIR	912.44 ± 9.83[c,a]	964.94 ± 11.37[b,a]	1083.62 ± 6.84[a,a]
VC-IR	832.72 ± 7.31[b,c]	835.50 ± 11.02[b,c]	962.20 ± 8.55[a,c]
VC-VIR	839.91 ± 11.43[c,c]	873.06 ± 10.86[b,b]	1046.92 ± 9.04[a,b]
HA	1060.25 ± 6.73		
Fresh	1012.38 ± 6.73		

Note: The HA dried and fresh samples were not included in the two-way analysis of variance.
Same first superscript indicates no significant difference within the same row ($p < 0.05$).
Same second superscript indicates no significant difference within the same column ($p < 0.05$).

Table 3
Quercetin contents (mg/100 g dry matter) of dried CQ as affected by vibration, vacuum, and material thickness.

Drying method	Thickness (mm)		
	5	10	15
IR	1.477 ± 0.044[ns,b]	1.596 ± 0.115[ns,b]	1.651 ± 0.088[ns,c]
VIR	1.647 ± 0.036[c,a]	2.627 ± 0.108[b,a]	3.472 ± 0.353[a,a]
VC-IR	0.921 ± 0.021[b,c]	0.903 ± 0.023[b,d]	1.273 ± 0.121[a,c]
VC-VIR	0.897 ± 0.029[c,c]	1.166 ± 0.015[b,c]	2.312 ± 0.145[a,b]
HA	0.997 ± 0.009		
Fresh	0.888 ± 0.004		

Note: The HA dried and fresh samples were not included in the two-way analysis of variance.
Same first superscript indicates no significant difference within the same row ($p < 0.05$).
Same second superscript indicates no significant difference within the same column ($p < 0.05$).

content, except CQ dried by IR drying technique ($p < 0.05$). An increase in TPC and quercetin content of CQ undergoing vibration could be due to the main effect of thorough exposure to IR of the material. IR has a capability to cleave covalent bonds and liberate low molecular weight antioxidants such as flavonoids, carotene or polyphenols from repeating polymers (Rho et al., 2010). Lower phenolic and flavonoid contents of dried material undergoing vacuum operation were also reported by Zheng et al. (2015) for drying of loquat flower and Uribe et al. (2016) for drying of peppermint. This could be due to the weakened browning reaction of material under vacuum; however, there has also been a report that products of browning reaction formed during the process of drying

exhibit antioxidant activity (Chan et al., 2009; Samoticha et al., 2016). Regarding the effect of material thickness, thicker CQ piece is less prone for its cell walls to be disrupted during the drying process. Less disruption of cell walls leads to less release of oxidative and hydrolytic enzymes and less phytochemical degradation (Wojdyło et al., 2016; Chen et al., 2017). In addition, oxidative degradation of bioactive compounds could freely occur at the liquid-atmosphere interface during drying (Ren et al., 2018). This effect would be higher in the samples with thinner piece, i.e. higher exposure area.

Comparing to fresh CQ, all dried CQ had higher quercetin which is the most important active compound in CQ. The highest TPC and quercetin content were produced by VIR drying of CQ with the thickness of 15 mm. The highest contents were 1083.625 mg GAE/100 g dry matter and 3.472 mg/100 g dry matter, respectively. Considerably, the quercetin content of the VIR-dried CQ was about 3.5 times of the value obtained by HA drying of CQ. It was surprising that the quercetin content of the VIR-dried was almost quadruple (290.99% retention) than that of the fresh CQ. According to Ren et al. (2018), retention percentages of quercetin content in hot air dried and freeze dried onion were in the range of 70.5–115.3% and 76.0–154.9%, respectively. It is clear that the drying technique in this research enhanced retention of quercetin.

3.4.2. Total color difference

The magnitude of overall color change of dried CQ from fresh CQ was expressed by ΔE value. The dried CQ samples were found to have ΔE in the range of 13.69 and 16.40 as shown in Table 4. An interaction effect between drying method and material thickness was observed on the ΔE value of dried CQ ($p < 0.05$). There was also a significant difference in the ΔE value in response to the material thickness at a specific drying method, and vice versa ($p < 0.05$). However, there was no clear trend in a change in the ΔE value with the material thickness or drying method. This result was not coincident with the conclusion of Das and Arora (2018) that ΔE value increased with an increase in thickness of mushroom slice. It should be noted that convective air drying resulted in darker dried CQ. All of the IR dried samples had lower ΔE values as compared to the reference HA dried sample.

4. Conclusions

In IR drying of CQ, vibration, vacuum, and material thickness had considerably effect on drying characteristics, energy consumption during drying, and the amount of active compounds of dried product. Drying operation with vibration, vacuum, and reduced material thickness improved the drying rate and shortened the drying time. The D_{eff} of CQ was also positively related to these three drying factors of study. Vacuum system consumed the most energy during the process of drying. Vibration had a positive effect on TPC and quercetin content of dried CQ while vacuum degraded these contents. Thicker piece of CQ allowed these compounds to be better preserved. In conclusion, VC-VIR drying showed the best improvement of drying characteristics of CQ. However, VIR

drying could be a promising drying technique in terms of best preservation of TPC and quercetin contents. A lower SEC was also observed during the operation without vacuum.

Table 4

ΔE of dried CQ as affected by vibration, vacuum, and material thickness.

Drying method	Material thickness (mm)		
	5	10	15
IR	$14.83 \pm 0.02^{b,d}$	$14.41 \pm 0.03^{c,b}$	$15.23 \pm 0.03^{a,c}$
VIR	$14.98 \pm 0.02^{a,c}$	$14.05 \pm 0.01^{b,d}$	$13.69 \pm 0.03^{c,d}$
VC-IR	$16.40 \pm 0.01^{a,a}$	$14.55 \pm 0.03^{c,a}$	$15.40 \pm 0.03^{b,b}$
VC-VIR	$15.55 \pm 0.02^{b,b}$	$14.23 \pm 0.02^{c,c}$	$15.81 \pm 0.02^{a,a}$
HA	17.71 ± 0.11		

Note: The HA dried sample was not included in the two-way analysis of variance. Same first superscript indicates no significant difference within the same row ($p < 0.05$).
Same second superscript indicates no significant difference within the same column ($p < 0.05$).

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