Pulsed vacuum drying kinetics of Goji berry (*Lycium barbarum* L.)

Yang Xuhai[1], Zhang Qian[1], Deng Lizhen[2], Xie Long[2],
Fang Xiaoming[3], Gao Zhenjiang[2], Kan Za[1*]

(1. *College of Mechanical and Electric Engineering, Shihezi University, Shihezi 832001, China*;
2. *College of Engineering, China Agricultural University, P.O. Box 194, No. 17 Qinghua East Road, Beijing 100083, China*;
3. *Bee Research Institute of Chinese Academy of Agricultural Sciences, Beijing 100093, China*)

Abstract: In order to explore a more efficient and safer drying technology for Goji berry processing, pulsed vacuum drying was applied for Gojiberry dehydratation. The drying kinetics of Goji berry were investigated in a pulsed vacuum dryer under different normal atmosphere holding time (2, 4, 6, 8, and 10 min), vacuum holding time (5, 10, 15, 20, and 25 min), and drying temperatures (50°C, 55°C, 60°C, 65°C, and 70°C). It was found that all the three parameters, namely drying temperature, normal atmosphere holding time, and vacuum holding time had significant effect on drying time. Drying temperature had the most obvious effect among the three parameters. The calculated moisture diffusion coefficient of Goji berry increased from 1.95×10^{-9} to 5.43×10^{-9} m^2/s as the drying temperature increased from 50°C to 70°C. The activation energy (Ea) was 46.54 kJ/mol calculated by the Arrhenius equation. Considering the drying behavior and dried product quality, pulsed vacuum drying at 60°C with 15 min and 2 min as the normal atmosphere and vacuum holding time, respectively, was proposed as the most favorable drying conditions for Goji berry drying. The findings of current work contribute to a better understanding of the drying characteristics of Goji berry under pulsed vacuum drying, which can enhance the drying process of Goji berry.
Keywords: pulsed vacuum drying, Goji berry, moisture diffusion coefficient, activation energy

Citation: Yang, X. H., Q. Zhang, L. Z. Deng, L. Xie, X. M. Fang, Z. J. Gao, and Z. Kan. 2017. Pulsed vacuum drying kinetics of Goji berry (*Lycium barbarum* L.). International Agricultural Engineering Journal, 26(3): 130–140.

1 Introduction

Goji berry (*Lycium barbarum* L.) is one of the most popular herbs in China, commonly known as wolfberry in the western world. It is a good source of health-promoting compounds such as carotenoids, polysaccharides and flavonoid compounds that show preventive effect against cardiovascular disease and cancer (Lin et al., 2014). Nowadays, Goji berry is widely consumed as traditional medicine or functional food in China.

Fresh Goji berry, having relatively high moisture contentgenerally about 80% (wet basis, w.b.), is very sensitive to microbial spoilage and not suitable for long-term storage after being harvested. It is reported that the storage time of Goji berry is only 2-3 days at normal temperature condition or 7 days at refrigerated conditions (Li et al., 2011). Therefore, fresh Goji berry should either be consumed or processed into various products. Drying is the most frequently used technology for Goji berry processing. It can be processed into raisins for longer shelf-life by reducing the moisture content to a low level, so as toprevent the growth and reproduction of microorganisms which cause decay, and to hinder the moisture-mediated deteriorative reactions (Xie et al., 2017a; Bai et al., 2013b; Ju et al., 2016b). The Goji berry raisins can be consumed either directly as traditional Chinese medicine, function food or as ingredients in biscuits, breads and porridges.

Currently the natural open sun drying is widely used to dry Goji berry and other agricultural products, due to the low investments and operation simplicity. Although this drying practice can be used for large quantities of products with no-cost energy, it exhibits several drawbacks. One of them is the great exposure to

Received date: 2017-05-18 **Accepted date:** 2017-08-04
* **Corresponding authors: Kan Za,** Professor, College of Mechanical and Electric Engineering, Shihezi University, Shihezi 832001, China. Email address: kanza_shz@163.com.

environmental contamination, such as bacterial pollution, dust and sand, insects, rodents, and birds (Xiao et al., 2015). In addition, it is strongly dependent on weather conditions and the rewetting or rotting problem of Goji berry becomes serious under rainy weather (Xiao, 2010b). Furthermore, chemical pretreatments are often used to improve the drying rate of Goji berry, by dipping them into an alkaline emulsion for several minutes to reduce the wax layer covering on the berry surface (Xiao et al., 2017; Wang et al., 2017a and b). However, this method can cause many water soluble nutrition lost by leaking out into the solutions during the dipping pretreatment (Bai et al., 2013a; Xiao et al., 2017). Also the chemical dipping method has an adverse impact on Goji berry appearance and easily to trigger food safety issues due to chemical reagent residues on Goji berry surface (Xie et al., 2017a and b). For example, it was observed that the polysaccharide content of dried Goji berry decreased from 9.77% to 9.23% after one min dipping pretreatment with 3% alkali solution at drying pretreatment (Wu et al., 2015). Therefore, in order to improve the quality of dried Goji berry, the traditional natural open sun drying method and the chemical dipping pretreatment should be replaced by more efficient, safe and controllable industrial drying methods.

With high sugar content and compact tissue of Goji berry pulp and a wax coating covered on the Goji berry skin (Li et al., 2006), drying of Goji berry is more difficult than traditional fruits and vegetables (Hashemi et al., 2009). So, there has been substantial interest to develop new drying methods for Goji berry's drying and several studies have also been conducted. Convective drying is a popular and cost-effective method for drying of agri-food products, but hot air drying is time consuming and low energy efficiency, in particular during the falling-rate period (Zielinska and Markowski, 2016; Ju et al., 2016c). In addition, long time exposure to high temperatures may result in substantial deterioration of food quality, such as loss of nutrients and color, structural changes, severe shrinkage, reduced rehydration capacity (Zielinska et al., 2016). In order to shorten the drying time and improve the quality of dried product, Wu et al. (2015) applied multi-stage varying temperatures hot air drying to dry Goji berry. It was observed that the drying time was decreased extensively from above 48 to 15 h as the drying air temperature increased from 40°C to 60°C while high drying temperature had a negative effect on product quality such as color and polysaccharide content.

Zheng et al. (2012) also observed that drying air temperature was the decisive parameter on the drying rate of Goji berry, and the products' quality was affected by the drying temperature, velocity and humidity in the process of hot air drying. Microwave drying is a promising approach in food and bioproducts processing as it is a rapid, more uniform and energy efficient way compared to the conventional hot-air drying (Zhang et al., 2006). Zhao et al. (2013) investigated the influence of different microwave power density on drying kinetics of polysaccharide extract of Goji berry. The results showed that drying rate increased with the increase of the microwave power density. In addition, Zhang et al. (2010) explored the effect of freeze drying parameters on drying energy consumption, drying time and product quality, such as Goji berry polysaccharide. It was found that freeze drying obtained better quality products compared with hot air drying as freeze drying can minimize nutrition loss in dried products due to the low temperature used in drying process. However, freeze drying is one of the most expensive processes because of the slow drying rate and high energy consumption, and large capital investments, which hinder the application of this drying technology (Duan et al., 2016).

Pulsed vacuum drying (PVD) is an innovative drying technology. During the drying process of PVD, the chamber pressure is alternating between vacuum and normal atmosphere condition, which breaks the balance condition of water vapor partial pressure between material surface and the drying medium, by thus enhancing drying rate extensively (Chua and Chou, 2004). Meanwhile, as the PVD process occurs at lower pressure, the boiling point of the water is depressed; therefore moisture evaporation can take place at lower temperature (Thorat et al., 2012). Compared to the conventional atmospheric drying, PVD can not only enhance the drying rate but preserve the quality of the dried product as well (Xie et al., 2017a; 2017b). It is a very feasible drying technology for heat-sensitive biomaterials as the oxygen deficient environment during PVD process prevents oxidative reactions. It was found that sharp decline of pressure inside the vacuum drier could form partial water vapor pressure and lead to a porous structure inside the products (Haddad et al., 2004). Maache et al. (2001) found that pulsed vacuum drying could form the capillary structure in the material and accelerate the diffusion of water during the drying of scleroglucan. Chua and Chou (2004)explored the effects of pressure cycle time, pressure amplitude and drying temperature on material drying kinetics, product color and pore structure inside material during pulsedvacuum drying. Experimental results showed that the PVD technology can not only enhance drying kinetics but also the drying quality attributes of carrots and potato cues such as its color. Fang et al. (2016) found that pulsed vacuum drying can enhance drying process and quality of lotus pollen. Xie et al. (2017a and b) investigated the effect of far-infrared radiation heating assisted pulsed vacuum drying on drying kinetics and quality of Goji berry. It was observed that porous and fissured microstructure was formed on the surface, which can enhance drying kinetics and rehydration process. Xie et al. (2017c) explored the application of PVD on drying kinetics and quality of rhizoma dioscoreae slices and found that pulsed vacuum environment was helpful in inhibiting browning and puffed structure was formed which was benefit for enhancing rehydration capacity. Deng et al. (2017) observed that PVD resulted in higher rehydration ratio, water holding capacity, red pigment and ascorbic acid content, brighter colour, lower non-enzyme browning index and comparable antioxidant capacity of red pepper compared to samples dried by infrared assisted hot air drying and hot air drying at the same drying temperature. However up to date, rare information is available in the literature about the PVD drying characteristics of Goji berry. Therefore, in current work, the effects of different drying temperatures, normal atmosphere pulse time and vacuum pulse time on drying characteristics and quality of Goji berry were investigated in order to explore a new feasible drying technology for Goji berry.

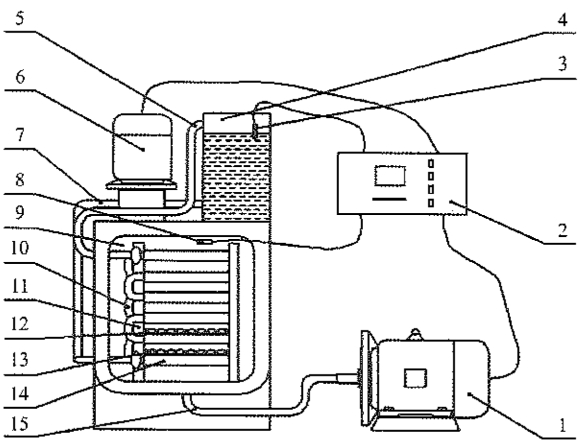
2 Material and methods

2.1 Material

Fresh Goji berry was purchased from Kuitun city Xinjiang Uygur Autonomous Region, China. Fresh red uniform and surface intact fresh Goji berry was selected as testing material, which was free from rotting and insect damage. The short axis diameter and long axis diameter of Goji berry were 9.71×10^{-3} m and 17.55×10^{-3} m, respectively. The average weight of Goji berry was 1.12±0.08 g per granule and the initial moisture content was 80.00%±0.09% in wet basis, which was determined by vacuum drying at 70°C for 24 h following the AOAC method no.934.06 (AOAC, 1990). Soluble solid was about 24°Brix determined by anAbberefractometer (AR4 Series, A. Kruss Optonic, Hamburg, Germany). The weight of fresh Goji berry was controlled between 200-300 g and spread in a single layer on a silica gel plate. Prior to experiments fresh wolfberries were preserved on plate (free from squeezing) and stored in a refrigerator at 3°C±1°C and 90% relative humidity.

2.2 Pulsed vacuum drying equipment

The schematic diagram of equipment used for pulsed vacuum drying is shown in Figure 1. This apparatus basically consists of vacuum system (mainly including water ring vacuum pump, vacuum pipelines and drying chamber), heating system (including heating water box, temperature sensor, circulating water and heating plate) and control system. The vacuum system can reach to the lowest pressure of 3 kPa in drying chamber. An 8-bit microcontroller (PIC 16F877A, Microchip Technology Inc, Chandler, United States) was used to control the time of ambient pressure duration and vacuum pressure duration according to the different drying requirements. The air flowing into the drying chamber through electromagnetic valve is at temperature of 30°C–35°C and humidity of 20%-30% with the flow rate of 0-60 m/s. The drying temperature can be controlled in the range of room temperature to 80°C. The control system is used to set and control the vacuum holding time and normal atmosphere holding time. A Proportional-Integral-Derivative (PID) controller (Omron, model E5CN, Tokyo, Japan) with accuracy of ±0.1°C was used to control the temperature of water tank and pressure in the drying chamber. All the experiments were started when the drying temperature reached to the setting value and was stable with setting vacuum holding time and normal atmosphere holding time.



1. Vacuum pump 2. Control box 3. Water level sensor 4. Water tank 5. Outlet pipe 6. Hot water pump 7. Inlet pipe 8. Pressure sensor 9. Drying chamber 10. Circulating pipe 11. Heating plate bracket 12. Material tray 13. Material 14. Heating plate 15. Intake pipe

Figure 1 Schematic diagram of equipment used for pulsed vacuum drying

2.3 Experimental method

Prior to the experiments, the wolfberries were taken out from refrigerator to recover its temperature to the room temperature about 20°C. It was washed with tap water and drained with a towel, then spread in a single layer on a silica gel plate. To investigate the effects of drying temperature, normal atmosphere pulse time and vacuum pulse time on PVD drying characteristics and quality of Goji berry, experiments were performed according to Table 1.

Table 1 Schedule of pulsed vacuum drying experiment

No.	Drying temperature, °C	Vacuum holding time, min	Normal atmosphere time, min
1	60	5	4
2	60	10	4
3	60	15	4
4	60	20	4
5	60	25	4
6	60	15	2
7	60	15	6
8	60	15	8
9	60	15	10
10	50	15	2
11	55	15	2
12	65	15	2
13	70	15	2

During the experiments, the weight loss was measured by an electronic balance (YP, Jingke, Shanghai, China) with the accuracy of ±0.01 g at one hour intervals. Drying process was stopped till the final moisture content of the samples decrease to 13.4%-13.7% (w.b.). After drying, the dried samples were cooled at the environment temperature, then were put in polyethylene bags and stored in drying dish for measuring other parameters. All the drying experiments were conducted in triplicate and samples were packed using vacuum packaging machine (DZQ400/2D, Tianyueyuan Instrument Co. Ltd., Beijing, China).

2.4 Calculation method of relevant parameters

2.4.1 Drying kinetics

The moisture ratio (*MR*) of wolfberries during drying experiments was calculated using Equation (1) (Wang et al., 2015; Borah et al., 2015).

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where, M_0 is the initial moisture content and unit is g/g; M_e is the equilibrium moisture content (g/g); M_t is the moisture content at time t (g/g).

The values of the equilibrium moisture content M_e are relatively small compared to M_t or M_0. Thus Equation (1) can be written in a more simplified form as follows (Dai et al., 2015; Ju et al., 2016a):

$$MR = \frac{M_t}{M_0} \quad (2)$$

The drying rate of wolfberries during drying experiments can be given by Equation (3) (Zhang et al., 2012; Xiao et al., 2012).

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \quad (3)$$

where, M_{t1} and M_{t2} is moisture content in dry basis of wolfberries at time t_1 and t_2, respectively.

Drying curves of wolfberries were fitted with the Weibull model Equation (4) (Bai et al., 2013b; Zhang et al., 2015b; Corzo et al., 2008).

$$MR = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \quad (4)$$

where, t is the drying time; α is the shape parameter of the Weibull model, and β is the scale parameter of the model.

2.4.2 Moisture effective diffusion coefficient

Fick's second law of diffusion has been used to describe the drying process during the falling rate period. However, the drying process of PVD probably includes the period of rising drying rate. Weibull model can be used to estimate the moisture diffusion coefficient during the drying process without considering the characteristics of moisture migration (Dai et al., 2015). Equation (5) is the calculation formula of D_{cal}.

$$D_{cal} = \frac{r^2}{\beta} \tag{5}$$

where, D_{cal} is the calculated moisture diffusivity (m^2/s); r is the volume equivalent radius of Goji berry samples, with a value of 5.91×10^{-3} m.

The relationship between the calculated moisture diffusion coefficient (D_{cal}) and the moisture effective diffusion coefficient (D_{eff}) is expressed as follows (Zhang et al., 2015a; Fang et al., 2016; Ju et al., 2016b):

$$D_{eff} = \frac{D_{cal}}{R_g} \tag{6}$$

where, R_g is the physical dimension constant.

2.4.3 Activation energy

The relationship of moisture effective coefficient and drying activation energy can be described by Arrhenius equation, as shown in Equation (7) (Bai et al., 2013a; Xiao et al., 2010a; 2010c).

$$D_{eff} = D_0 \exp\left[-\frac{E_a}{R(T+273.15)}\right] \tag{7}$$

where, D_{eff} is the moisture effective diffusion coefficient during drying, m^2/s; D_0 is the constant diffusivity basis, m^2/s; E_a is the activation energy, kJ/mol; R is the universal gas constant with 8.314 J/(mol·K) as its value; T is the drying air temperature, °C.

Equation (7) can be transfigured into Equation (8) by taking the natural logarithm of both sides.

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R(T+273.15)} \tag{8}$$

Equation (6) is introduced into Equation (8) can obtain Equation (9).

$$\ln D_{cal} = \ln R_g + \ln D_0 - \frac{E_a}{R(T+273.15)} \tag{9}$$

The logarithm form of calculated moisture diffusion coefficient lnD_{cal} and the reciprocal of the temperature (1/(T+273.15)) showed a linear relationship and the slope $-Ea/R$ can be gained by linear regression. Then Ea can be calculated by putting $-Ea/R$ into Equation (9), as is shown in Equation (10).

$$E_a = -kR \tag{10}$$

3 Results and discussion

3.1 Effects of different vacuum holding time on drying kinetics

The effects of different vacuum holding time (5, 10, 15, 20 and 25 min) on the drying kinetics of wolfberries with 60°C and 4 min as its constant drying temperature and normal atmosphere holding time, respectively, were shown in Figures 2 and 3. Figure 2 illustrated that moisture ratio decreased with increasing drying time under different vacuum holding time. The drying time needed for moisture content of wolfberries decreased to 13.4%-13.6% was 480, 494, 374, 440, and 486 min for the vacuum holding time of 5, 10, 15, 20, 25 min, respectively. Obviously, drying time was the shortest under 15 min vacuum holding time which was shortened by 22.08%, 24.3%, 15% and 23.05% compared to vacuum holding time of 5, 10, 20 and 25 min, respectively. Therefore, vacuum holding time had significant influence on drying time and the 15 min was the optimized vacuum holding time.

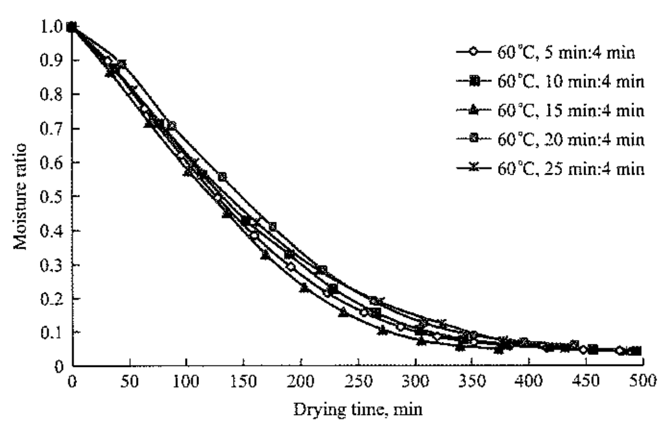


Figure 2 Moisture ratio curves vs drying time of Goji berry under different vacuum holding time

The drying rate curves of Goji berry under drying conditions of vacuum holding time of PVD were shown in Figure 3. It was observed that the PVD process of Goji berries can be divided into three stages: an accelerating period, a constant rate period, and a decelerating period.

Similar result was reported by Zhan and Liao (2014) for onion. During the acceleration period, which was short, heat was absorbed by material to increase its temperature to enhance moisture transfer gradually and at the meantime the samples' texture became soft due to the rising temperature. For this period, drying rate increased gradually and moisture loss came to the highest point. During the decelerating period, moisture loss decreased slowly and a short constant drying rate process appeared. This phenomenon occurred maybe due to the fact that the internal moisture diffusion rate is faster than moisture evaporation from material surface to environment outside so that drying rate is kept stable. Deceleration drying period is governed by internal moisture transfer so that drying rate decreased gradually. From Figure 3, it can be also found that drying rate was fastest under 15 min vacuum holding time.

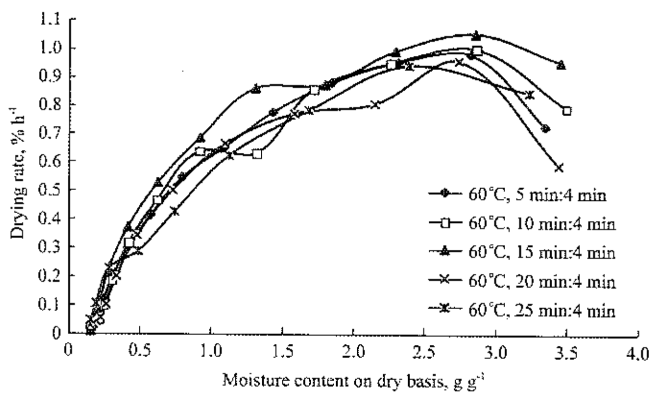


Figure 3 Drying rate curves of Goji berry under different vacuum holding time

3.2 Effects of different normal atmosphere holding time on drying kinetics

The effects of different normal atmosphere holding time (2, 4, 6, 8, and 10 min) on the PVD drying kinetics of wolfberries with 60°C and 4 min as the constant drying temperature and vacuum holding time, respectively, were shown in Figures 4 and 5. Figure 4 illustrated that moisture ratio decreased with increasing drying time under different normal atmosphere holding time. The drying time needed for moisture content of wolfberries reaching final moisture content was 424, 544, 440, 473 and 470 min for the normal atmosphere holding time of 2, 4, 6, 8, 10 min, respectively. The variation of moisture ration was decreased successively at the same time.

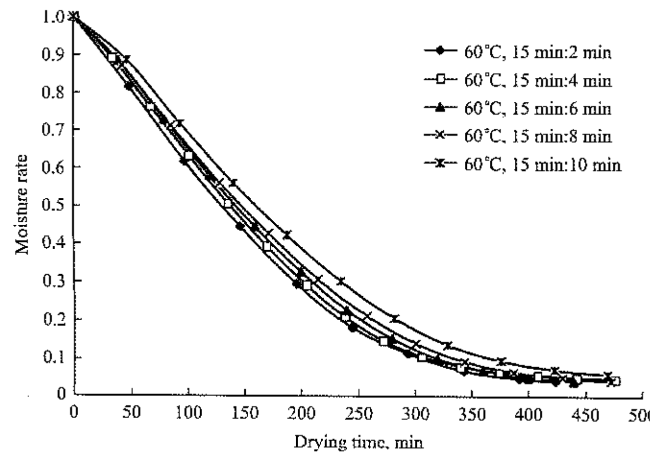


Figure 4 Moisture ratio curves vs drying time of Goji berry under different normal atmosphere holding time

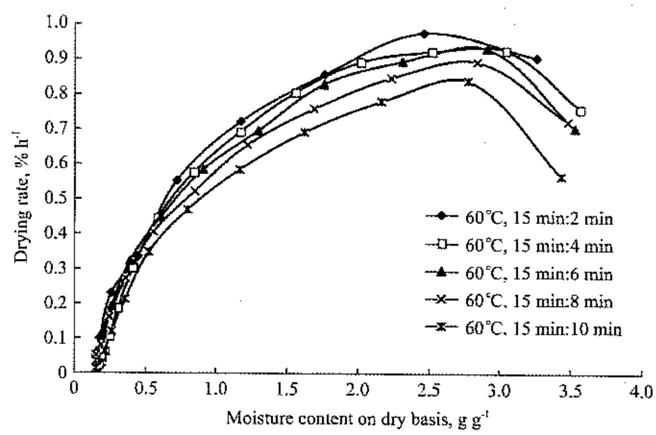


Figure 5 Drying rate curves of Goji berry under different normal atmosphere holding time

Figure 5 illustrated that vacuum pulse drying rate under different normal atmosphere had two stages: an accelerating period and a decelerating period which was comparatively longer than the accelerating period. This result was highlighted also by Gu et al. (2014) for green radish. This is probably due to the fact that the free water is relatively easier to remove in soft wolfberries during initial drying process, while for the deceleration drying period, non-free water was the main moisture content which is relatively harder to lose. In addition, from Figure 5, it was also found that when the normal atmosphere holding time was 2 min, the drying rate was fastest and the drying time was shortest.

3.3 Effects of different drying temperatures on drying kinetics

The effects of different drying temperatures (50°C, 55°C, 60°C, 65°C, and 70°C) on the drying kinetics of wolfberries with 15 and 2 min as the constant vacuum holding time and normal atmosphere holding time, respectively were shown in Figures 6 and 7. Figure 6 showed that water diffusion increased with increasing temperature, which meant high drying rate and efficiency. This is in agreement with the results observed by Limpaiboon (2011) for pumpkin; Ihns et al. (2011) for apricot; and Mariem et al. (2014) for tomato. Besides, combining quality property of Goji berry itself and low temperature of vacuum pulse drying, the drying temperature 60°C was selected as optimal drying temperature to ensure relatively fast drying, as well as good quality, nutrition and pharmacological value.

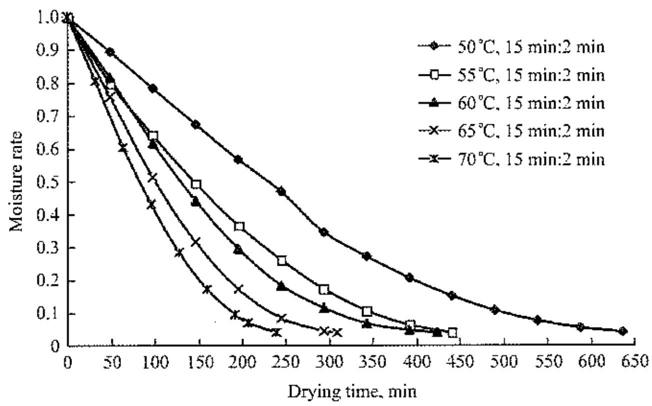


Figure 6 Moisture ratio curves vs drying time of Goji berry under different drying temperatures

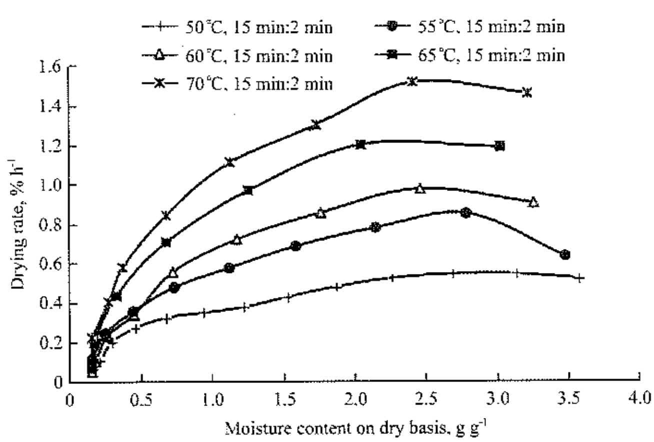


Figure 7 Drying rate curves of Goji berry under different drying temperatures

Figure 7 illustrated that temperature influenced drying of wolfberries significantly. Acceleration and deceleration period were obvious at drying temperatures of 70°C and 55°C, although the acceleration period was short. While when the samples were dried at 60°C and 65°C, the acceleration stage was not apparent and the whole drying process was in the deceleration process. When dried at 50°C, the drying rate was slowest and the whole drying process was basically a constant speed process. Therefore, by comprehensive analysis, 60°C was selected as suitable drying temperature.

3.4 Calculation of moisture effective diffusion coefficient and activation energy

The curves of ln(MR) versus time under different vacuum holding time, normal atmosphere holding time and drying temperatures are shown in Figures 8, 9, and 10, respectively. By linear regression, the calculated moisture diffusion coefficient of the Goji berry was calculated as shown in Table 2. Table 2 illustrated that the moisture diffusion coefficient increased obviously with increasing drying temperature. In addition, drying temperature had a more significant effect on D_{cal} than the vacuum holding and normal atmosphere holding time as both of which had little influence on D_{cal}.

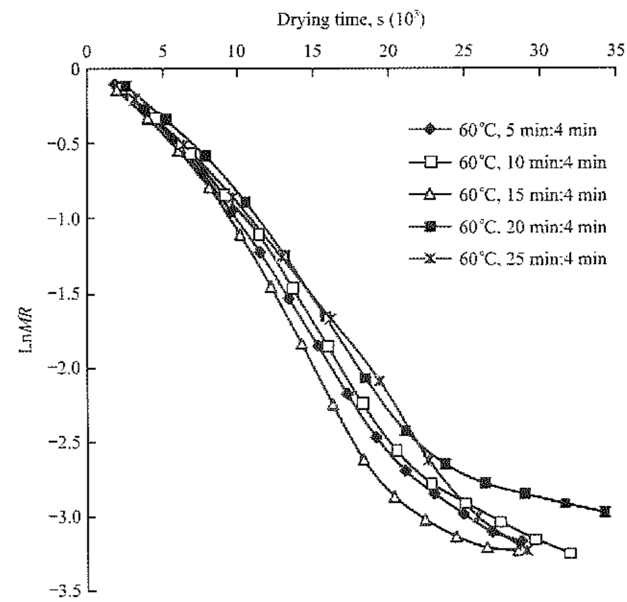


Figure 8 Curves of lnMR vs drying time under different vacuum holding time

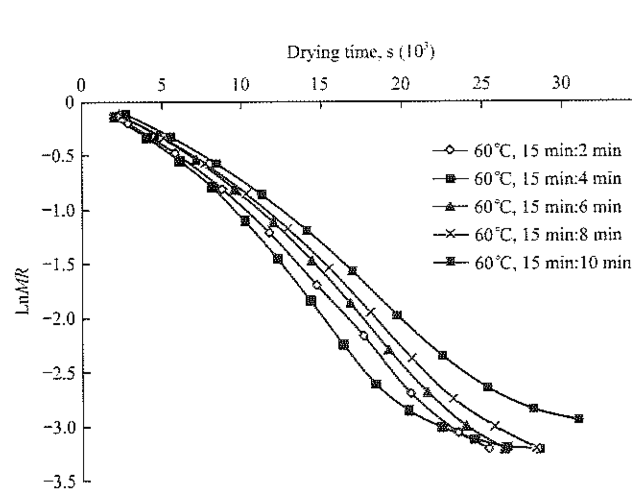


Figure 9 Curves of lnMR vs drying time under different normal atmosphere holding time

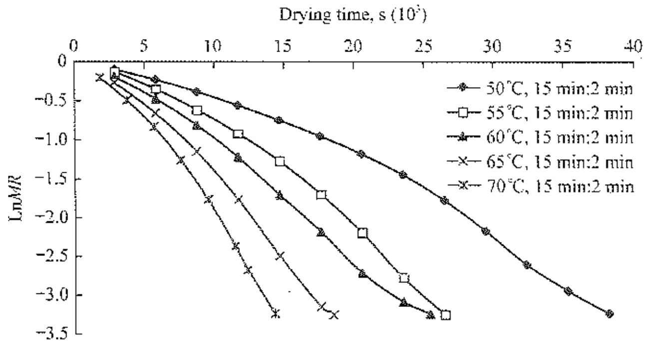


Figure 10 Curves of lnMR vs drying time under different drying temperatures

Table 2 Calculated moisture diffusion coefficient (D_{cal}) of Goji berry subjected to different drying condition

No.	Drying condition	Linear regression fitting equation	D_{cal} ($\times10^{-9}$ m²/s)	R^2
1	60°C, 5 min:4 min	LnMR=$-(t/8967)^{1.065}$	3.8952	0.9804
2	60°C, 10 min:4 min	LnMR=$-(t/9084)^{1.009}$	3.8450	0.9724
3	60°C, 15 min:4 min	LnMR=$-(t/8106)^{1.023}$	4.3089	0.9655
4	60°C, 20 min:4 min	LnMR=$-(t/9664)^{0.9509}$	3.6142	0.9540
5	60°C, 25 min:4 min	LnMR=$-(t/10540)^{1.195}$	3.3139	0.9950
6	60°C, 15 min:2 min	LnMR=$-(t/9739)^{1.265}$	3.5864	0.9950
7	60°C, 15 min:6 min	LnMR=$-(t/10640)^{1.341}$	3.2827	0.9953
8	60°C, 15 min:8 min	LnMR=$-(t/10930)^{1.282}$	3.1956	0.9933
9	60°C, 15 min:10 min	LnMR=$-(t/11680)^{1.190}$	2.9904	0.9858
10	50°C, 15 min:2 min	LnMR=$-(t/17930)^{1.562}$	1.9480	0.9968
11	55°C, 15 min:2 min	LnMR=$-(t/12360)^{1.549}$	2.8259	0.9988
12	65°C, 15 min:2 min	LnMR=$-(t/7741)^{1.375}$	4.5121	0.9982
13	70°C, 15 min:2 min	LnMR=$-(t/6431)^{1.470}$	5.4312	0.9990

The activation energy value of wolfberries subjected to pulsed vacuum drying by linear regression equation was determined to be 46.54 kJ/mol, which means that removing one kg water content from Goji berry using PVD needs at least 2585.6 kJ energy to trigger moisture transfer.

In order to compare the activation energy of Goji berry and other agricultural products, the drying activation energies of many bioproducts are listed in Table 3. From Table 3, it was found that the activation energy of Goji berry is higher than the activation energy of squash seed, apricot, corn kernel and apple slice, but lower than the activation energy of zizyphus jujube mill. This result indicated that the energy required for removal of the equivalent water from Goji berry was more than that of squash seed, apricot, corn kernel and apple slice and less than that of zizyphus jujube mill. The drying activation energy of the material is closely related to the shape, size and constituent of the material (Xiao et al., 2010a; Wang et al., 2015). The ratio of volume and surface area of squash seed and corn kernel are smaller than that of Goji berry, so they are easier to be dried. The sugar content of zizyphus jujube mill is higher than Goji berry, and sugar has a strong adsorption to water. Therefore, the activation energy of zizyphus jujube mill is relatively higher.

Table 3 Activation energies of Goji berry and other related products

Products	Ea, kJ/mol	References
Goji berry	46.54	Present work
Squash seed	31.94-34.49	Chayjan et al. (2013)
Apricot	29.35-33.78	Mirzaee et al. (2009)
Corn kernel	10.39-15.56	Voc'a et al. (2007)
Apple slice	22.66-30.92	Meisami et al. (2010)
Zizyphus jujube mill	74.2	Motevali et al. (2012)

4 Conclusion

To evaluate the feasibility of using PVD to dry Goji berry, the effects of normal atmosphere holding time (2, 4, 6, 8, 10 min), vacuum holding time (5, 10, 15, 20, 25 min), and drying temperatures (50°C, 55°C, 60°C, 65°C, 70°C) on the PVD drying kinetics of Goji berry were investigated. It was found that all three parameters had significant effect on the drying process of Goji berry. The D_{cal} values of Goji berry dried by PVD at various conditions ranged from 1.95×10^{-9} to 5.43×10^{-9} m²/s, calculated using the Weibull model. The drying activation energy (E_a) of Goji berry dried by PVD was 46.54 kJ/mol, which indicated that removing one kg water content from Goji berry using PVD needs at least 2585.6 kJ energy to trigger moisture transfer. The findings of current work contribute to a better understanding of the drying characteristics of Goji berry under PVD and indicate it is a promising drying technology for Goji berry.

Acknowledgements

This research is supported by the National Natural Science Foundation of China (No.31760471, 31501548), the National Key Research and Development Program of China (No. 2017YFD0400905) and the Chinese Transformation Fund of Agricultural Scientific and Technological Achievements (No.2014GB2G410112).

[References]

[1] AOAC. 1990. Official methods of analysis (15th edition). Association of Official Analytical Chemists, Washington, DC, USA.

[2] Bai, J. W., D. W. Sun, H. W. Xiao, A. S. Mujumdar, and Z. J. Gao. 2013a. Novel high-humidity hot air impingement blanching (HHAIB) pretreatment enhances drying kinetics and color attributes of seedless grapes. *Innovative Food Science and Emerging Technologies*, 20(5): 230–237.

[3] Bai, J. W., J. L. Wang, H. W. Xiao, H. Y. Ju, Y. H. Liu, and Z. J. Gao. 2013b. Weibull distribution for modeling drying of grapes and its application. *Transactions of the Chinese Society of Agricultural Engineering*, 29(16): 278–285. (in Chinese with English abstract)

[4] Borah, A., K. Hazarika, and S. M. Khayer. 2015. Drying kinetics of whole and sliced turmeric rhizomes (*Curcuma longa* L.) in a solar conduction dryer. *Information Processing in Agriculture*, 2(2): 85–92.

[5] Chayjan, R. A., K. Salari, Q. Abedi, and A. A. Sabziparvar. 2013. Modeling moisture diffusivity, activation energy and specific energy consumption of squash seeds in a semi fluidized and fluidized bed drying. *Journal of Food Science and Technology*, 50(4): 667–677.

[6] Chua, K.J., and S.K. Chou. 2004. On the experimental study of a pressure regulatory system for bioproducts dehydration. *Journal of Food Engineering*, 62(2): 151–158.

[7] Corzo, O., N. Bracho, and A. Pereira. 2008. Weibull distribution for modeling air drying of coroba slices. *LWT - Food Science and Technology*, 41(10): 2023–2028.

[8] Dai, J. W., J. Q. Rao, D. Wang, L. Xie, H. W. Xiao, Y. H. Liu, and Z. J. Gao. 2015. Process-based drying temperature and humidity integration control enhances drying kinetics of apricot halves. *Drying Technology*, 33(3): 365–376.

[9] Deng, L. Z., X. H. Yang, A. S. Mujumdar, J. H. Zhao, D. Wang, Q. Zhang, J. Wang, Z. J. Gao, and H. W. Xiao. 2017. Red pepper (*Capsicum annuum* L.) drying: effects of different drying methods on drying kinetics, physicochemical properties, antioxidant capacity, and microstructure. *Drying Technology*. (Accessed on August 2, 2017)

[10] Duan, X., X. Yang, G. Ren, Y. Pang, L. Liu, and Y. Liu. 2016. Technical aspects in freeze-drying of foods. *Drying Technology*, 34(11): 1271–1285.

[11] Fang, X. M., X. Zhang, J. Wang, Q. Zhang, H. W. Xiao, Y. Liu, H. Ju, S. Liang, and Z. J. Gao. 2016. Vacuum pulsed drying characteristics and quality of lotus pollen. *Transactions of the Chinese Society of Agricultural Engineering*, 32(10): 287–295 (in Chinese with English abstract).

[12] Gu, W. R., Y. Li, and S. G. Lou. 2014. Study on kinetics modeling of thin-layer vacuum drying of green radish. *Packaging and Food Machinery*, 32(5): 18–21.

[13] Haddad, J., F. Juhel, and N. Louka. 2004. A study of dehydration of fish using successive pressure drops (DDS) and controlled instantaneous pressure drop (DIC). *Drying Technology*, 22(3): 457–478.

[14] Hashemi, G., D. Mowla, and M. Kazemeini. 2009. Moisture diffusivity and shrinkage of broad beans during bulk drying in an inert medium fluidized bed dryer assisted by dielectric heating. *Journal of Food Engineering*, 92(3): 331–338.

[15] Ihns, R., L.M. Diamante, G. P. Savage, and L. Vanhanen. 2011. Effect of temperature on the drying characteristics, colour, antioxidant and beta-carotene contents of two apricot varieties. International *Journal of Food Science & Technology*, 46(2): 275–283.

[16] Ju, H. Y., H. EI-Mashad, X. M. Fang, Z. L. Pan, H. W. Xiao, Y. H. Liu, and Z. J. Gao. 2016a. Drying characteristics and modeling of yam slices under different relative humidity conditions. *Drying Technology*, 34(3): 296–306.

[17] Ju, H. Y., Q. Zhang, A. S. Mujumdar, X. M. Fang, H. W. Xiao, and Z. J. Gao. 2016b. Hot airdrying kinetics of yam slices under step change in relative humidity. *International Journal of Food Engineering*, 12(8): 783–792.

[18] Ju, H. Y., Q. Zhang, X. Guo, H.W. Xiao, X. M. Fang, Y. Liu, H. Zhao, and Z. J. Gao. 2016c. Control method of relative humidity of carrot hot air drying based on detecting material's temperature. *Transactions of the Chinese Society of Agricultural Engineering*, 32(4): 269–276 (in Chinese with English abstract).

[19] Limpaiboon, K. 2011. Effects of temperature and slice thickness on drying kinetics of pumpkin slices. *Walailak Journal of Science & Technology*, 8(2): 159–166.

[20] Lin, D. B, H. He, H. Ji, J. Willis, L. Willard, Y. Jiang, D. M. Medeiros, L. Wark, J. Han, Y. Z. Liu, and B. Lu. 2014. Wolfberries potentiate mitophagy and enhance mitochondrial biogenesis leading to prevention of hepatic steatosis in obese mice: The role of AMP - activated protein kinase α2 subunit. *Molecular Nutrition & Food Research*, *58*(5): 1005–1015.

[21] Li, W. Q., Z. B. Zhang, and J. J. Li. 2006. Plant epicuticular wax drought resistance as well as its molecular biology. *Journal of Plant Physiology and Molecular Biology*, 32(5): 505–512.

[22] Li, Y.C., Y. Bi, Y. Wang, L. Yuan, and Y. Yin. 2011. Effects of film packaging on major storage characters of fresh wolfberry fruit during room and low temperature storage. *Science and Technology of Food Industry*, 32(2): 302–304.

[23] Maache, Z., S. Rezzoug, and K. Allaf. 2001. Kinetics of drying and hydration of the scleroglucan polymer. *Drying Technology*, 19(8): 1961–1974.

[24] Mariem, S. B., S. B. Mabrouk, S. B. Mariem, and S. B. Mabrouk. 2014. Drying characteristics of tomato slices and

mathematical modeling. *International Journal of Energy Engineering*, 4(2A): 17–24.

[25] Meisami-Asl, E., S. Rafiee, and A. Keyhani. 2010. Drying of apple slices (var. Golab) and effect on moisture diffusivity and activation energy. *Plant Omics*, 3(3): 97–102.

[26] Mirzaee, E., S. Rafiee, and A. Keyhani. 2009. Determining of moisture diffusivity and activation energy in drying of apricots. *Research in Agricultural Engineering*, 55(3): 114–120.

[27] Motevali, A., A. Abbaszadeh, and S. Minaei. 2012. Effective moisture diffusivity, activation energy and energy consumption in thin-layer drying of jujube (*Zizyphus jujube* Mill). *Journal of Agricultural Science & Technology*, 14(3): 523–532.

[28] Thorat, I. D., D. Mohapatra, R. F. Sutar, S. S. Kapdi, and D. D. Jagtap. 2012. Mathematical modeling and experimental study on thin-layer vacuum drying of ginger (*Zingiber Officinale* R.) slices. *Food and Bioprocess Technology*, 5(4): 1379–1383.

[29] Voc′a, N., T. Krička, A. Matin, V. Jannusic, and Z. Jukic. 2007. Activation energy of water release rate from corn kernel during convective drying. *Agriculturae Conspectus Scientificus*, 72(3): 199–204.

[30] Wang, D., J. W. Dai, H. Y. Ju, L. Xie, H. W. Xiao, Y. H. Liu, and Z. J. Gao. 2015. Drying kinetics of American ginseng slices in thin-layer air impingement dryer. *International Journal of Food Engineering*, 11(5): 701–711.

[31] Wang, J., X. H. Yang, A. S. Mujumdar, D. Wang, J. H. Zhao, X. M. Fang, Q. Zhang, L. Xie, Z. J. Gao, and H. W. Xiao. 2017a. Effects of various blanching methods on weight loss, enzymes inactivation, phytochemical contents, antioxidant capacity, ultrastructure and drying kinetics of red bell pepper (*Capsicum annuum* L.). *LWT-Food Science and Technology*, 77(4): 337–347

[32] Wang, J., X. M. Fang, A. S. Mujumdar, J. Y. Qian, Q. Zhang, X. H. Yang, Y. H. Liu, Z. J. Gao, and H. W. Xiao. 2017b. Effect of high-humidity hot air impingement blanching (HHAIB) pretreatment on drying characteristic and quality attributes of red pepper (*Capsicum annuum* L.). *Food Chemistry*, 220(8): 145–152.

[33] Wu, Z. H., W.L. Li, L. J. Zhao, J. F. Shi, and Q. Liu. 2015. Drying characteristics and product quality of Lycium barbarum under stages-varying temperatures drying process. *Transactions of the Chinese Society of Agricultural Engineering*, 31(11): 287–293 (in Chinese with English abstract).

[34] Xiao, H. W., C. L. Pang, L. H. Wang, J. W. Bai, W.X. Yang, and Z. J. Gao. 2010a. Drying kinetics and quality of Monukka seedless grapes dried in an air-impingement jet dryer. *Biosystems Engineering*, 105(2): 233–240.

[35] Xiao, H. W., H. Lin, X. D. Yao, Z. L. Du, Z. Lou, and Z. J. Gao. 2009. Effects of different pretreatments on drying kinetics and quality of sweet potato bars undergoing air impingement drying. *International Journal of Food Engineering*, 5(5): 64–67

[36] Xiao, H. W., J. W. Bai, D. W. Sun, and Z. J. Gao. 2014. The application of superheated steam impingement blanching (SSIB) in agricultural products processing-a review.*Journal of Food Engineering*, 132(1): 39–47.

[37] Xiao, H. W., J. W. Bai, L. Xie, D. W. Sun, and Z. J. Gao. 2015. Thin-layer air impingement drying enhances drying rate of American ginseng (*Panax quinquefolium* L.) slices with quality attributes considered. *Food and Bioproducts Processing*, 94(2): 581–591.

[38] Xiao, H. W., S. X. Zhang, J.W. Bai, X. M. Fang, Z. J. Zhang, and Z. J. Gao. 2010b. Air impingement drying characteristics of apricots. *Transactions of the Chinese Society of Agricultural Engineering*, 26(7): 318–323 (in Chinese with English abstract).

[39] Xiao, H. W., X. D. Yao, H. Lin, W. X. Yang, J. S. Meng, and Z. J. Gao. 2012. Effect of SSB (superheated steam blanching) time and drying temperature on hot air impingement drying kinetics and quality attributes of yam slices. *Journal of Food Process Engineering*, 35(3): 370–390.

[40] Xiao, H. W., Z. Pan, L. Z. Deng, H. M. El-Mashad, X. H. Yang, A. S. Mujumdar, Z. J. Gao, and Q. Zhang. 2017. Recent developments and trends in thermal blanching-a comprehensive review. *Information Processing in Agriculture*, 4(2): 101–127.

[41] Xiao, H. W., Z. J. Gao, H. Lin, and W. X. Yang. 2010c. Air impingement drying characteristics and quality of carrot cubes. *Journal of Food Process Engineering*, 33(5): 899–918.

[42] Xie, L., A. S. Mujumdar, X. M. Fang, J. Wang, J. W. Dai, Z. L. Du, H. W. Xiao, Y. Liu, and Z. J. Gao. 2017a. Far-infrared radiation heating assisted pulsed vacuum drying (FIR-PVD) of Wolfberry: effects on drying kinetics and quality attributes. *Food and Bioproducts Processing*, 102(2): 320–331.

[43] Xie, L., A. S. Mujumdar, Q. Zhang, J. Wang, S. Liu, L. Z. Deng, D. Wang, H. W. Xiao, Y. H. Liu, and Z. J. Gao. 2017b. Effects of pulsed vacuum drying on infrared radiation heating (PVD-FIR) and electronic panel contact heating (PVD-EPC) on drying kinetics, colour and volatile compounds of wolfberry. *Drying Technology*, 35(11): 1312–1326.

[44] Xie, Y., Z. J. Gao, Y. Liu, and H. W. Xiao. 2017c. Pulsed vacuum drying of rhizoma dioscoreae slices. *LWT-Food Science and Technology*, 80(7):237–249.

[45] Zhan, D., and C. H. Liao. 2014. Study on the dynamics of onion vacuum drying. *Contemporary Chemical Industry*, 12(6): 2535–2538.

[46] Zhang, M., J. Tang, A.S. Mujumdar, and S. Wang. 2006.

Trends in microwave-related drying of fruits and vegetables. *Trends in Food Science & Technology*, 17(10): 524–534.

[47] Zhang, Q., H.W. Xiao, X.H. Yang, J.W. Bai, Z. Lou, and Z. J. Gao. 2012. Effects of pretreatment on air impingement drying characteristics and product color for line pepper. *Transactions of the Chinese Society of Agricultural Engineering*, 28(1): 276–281. (in Chinese with English abstract)

[48] Zhang, W. P., H. W. Xiao, Z. J. Gao, Z. A. Zheng, H. Y. Ju, P. Zhang, and X. M. Fang. 2015a. Improving quality of Poria cocos using infrared radiation combined with air impingement drying. *Transactions of the Chinese Society of Agricultural Engineering*, 31(10): 269–276. (in Chinese with English abstract)

[49] Zhang, W. P., Z. J. Gao, H. W. Xiao, Z. A. Zheng, H. Y. Ju, and L. Xie. 2015b. Drying characteristics of poria cocos with different drying methods based on Weibull distribution. *Transactions of the Chinese Society of Agricultural Engineering*, 31(5): 317–324. (in Chinese with English abstract)

[50] Zhang, X. D., J. M. Cheng, and L. Liu. 2010. Optimization of procedure parameters in freeze drying of lycium barbarum polysaccharide. *Journal of Nanjing TCM University*, 26(1): 50–52.

[51] Zhao, Q., L. Y. Zhang, and Z. M. Qiu. 2013. Study on microwave-vacuum drying of lycium barbarum polysaccharide extracts and analysis of its quality. *Science and Technology of Food Industry*, 34(23): 266–270.

[52] Zheng, S., M. B. Li, and S. Mu. 2012. Study and experiment on Chinese wolfberry drying dynamic characteristics in the condition of hot air convection. *Journal of Food Industry*, 33(9): 143–146.

[53] Zielinska, M., and M. Markowski. 2016. The influence of microwave-assisted drying techniques on the rehydration behavior of blueberries (*Vaccinium corymbosum* L.). *Food Chemistry*, 196(4): 1188–1196.

[54] Zielinska, M., P. Sadowski, and W. Błaszczak. 2016. Combined hot air convective drying and microwave-vacuum drying of blueberries (*Vaccinium corymbosum* L.): drying kinetics and quality characteristics. *Drying Technology*, 34(6): 665–684.