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Research Article

Optimization of Microwave Vacuum Drying and Pretreatment Methods for *Polygonum cuspidatum*

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This study was conducted to optimize the drying process of *Polygonum cuspidatum* slices using an orthogonal experimental design. The combined effects of pretreatment methods, vacuum pressure and temperature of inner material, drying kinetics, color value, and retention of the indicator compounds were investigated. Seven mathematical models on thin-layer drying were used to study and analyze the drying kinetics. Pretreatment method with blanching for 30 s at 100°C increased the intensity of the red color of *P. cuspidatum* slices compared with other pretreatment methods and fresh *P. cuspidatum* slices. *P. cuspidatum* slices dried at 60°C retained more indicator compounds. Furthermore, microwave pretreatment methods, followed by microwave vacuum for 200 mbar at 50°C, resulted in high concentration of indicator compounds, with short drying time and less energy. This optimized condition for microwave vacuum drying and pretreatment methods would be useful for processing *P. cuspidatum*. The Newton, Page, and Wang and Singh models slightly fitted the microwave vacuum drying system. The logarithmic, Henderson and Pabis, two-term, and Midilli et al. models can be used to scale up the microwave vacuum drying system to a commercial scale. The two-term and Midilli et al. models were the best fitting mathematical models for the no-pretreatment case at 600 mbar and 60°C.

1. Introduction

Polygonum cuspidatum is a well-known Chinese herb and is officially listed in the Chinese Pharmacopoeia. This herb has been traditionally used for the treatment of various inflammatory diseases, including hepatitis, tumors, and diarrhea, in Eastern Asian countries, such as China, Korea, and Japan [1]. The phytochemistry of the root of this plant has been well studied. Currently, over 67 compounds from this plant have been isolated and identified [2]. The four kinds of indicator compounds are polydatin, emodin, physcion, and resveratrol [3]. To retain indicator compounds, the roots must be dried. Furthermore, the degree of retention of the indicator compounds was determined by drying conditions.

P. cuspidatum are usually sun-dried. However, this process takes a long time, because it is dependent on the weather. Moreover, the plant can easily become moldy because reaching a low safe moisture content to prevent the growth of molds is difficult, and the retention of indicator compounds is low. Microwave vacuum drying is a promising, rapid, and efficient dehydration method, which yields improved product appearance and quality compared to conventionally dried products [4–12]. In the literature, microwave power and vacuum levels are key factors. As moisture decreases with drying, an increasing number of burnt spots can be found in the last stage of drying process [13]. Li et al. used temperature control to avoid burning [14]. Pretreatment of material by blanching and microwaving can influence product quality. The efficiency of the blanching process is usually based on the inactivation of heat-resistant enzymes, such as peroxidase and polyphenol oxidase. Microwave irradiation has been successfully used in the pretreatment of various types of biomass, including agricultural residues, woody biomass, grass, energy plants, and industrial residuals [15]. Pretreatment methods, vacuum pressure, and temperature of inner materials were shown to be factors influencing the indicator compounds and drying time.

The aims of this paper are as follows:

(1) Design and build a microwave vacuum drying system and test the system.

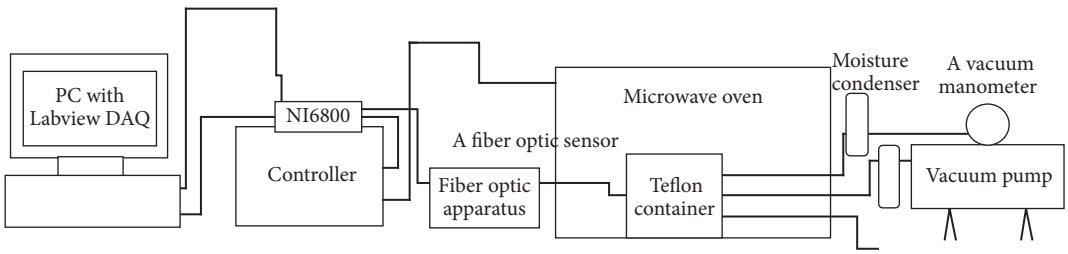

Figure 1: Schematic diagram of the microwave vacuum drying system.

(2) Analyze the effect of pretreatment methods, vacuum pressure, and temperature of inner material on indicator compounds and drying kinetics.

(3) Optimize conditions for pretreatment and microwave vacuum drying of *P. cuspidatum*.

(4) Develop mathematical models for the microwave vacuum drying of carrot slices to help in the scaling up of this drying technology.

2. Materials and Methods

2.1. Sample Preparation. Raw and sun-dried *P. cuspidatum* were purchased from farmers (Liu Jianhui, Liu Jiandong) in Jiangxi Province. Raw *P. cuspidatum* was washed, vacuum-packed, and sent to Jiangnan University. The samples were kept in the fridge at 4°C for 3 days. Before they were processed, each group was washed with tap water for 5 min and sliced to 5 mm thickness with a radius of 21.85–24.15 mm. The initial moisture content was determined by drying the samples for 24 h in a hot air oven at 80°C. Samples were dried to a final moisture content of less than 0.11 (dry basis, kg water/kg dry solid). Sample (25 g) was used for each drying experiment. Nine groups were tested and dried. All experiments were performed in triplicate.

2.2. Microwave Vacuum Drying System. A microwave vacuum drying system for drying *P. cuspidatum* was designed by our team and built in our laboratory (Figure 1). The system consisted of a microwave drying unit, a power and temperature control unit, a moisture condenser, a vacuum pump, a vacuum manometer, and a PC-based data acquisition unit. The microwave unit consisted of a reequipped microwave oven. The power and temperature control unit consisted of a fiber optic apparatus, a fiber optic sensor, and the power supply for the microwave oven. The PC-based data acquisition unit was an NI6800 with analog and digital inputs and outputs to record the temperature of inner material and to control the microwave oven power. A 2450 MHz microwave oven (media, MM720KG1-PW) and a hot air generator (Kada, 850) were modified for the experiments as the microwave dryer. The schematic diagram of the system is shown in Figure 1.

Samples were placed in a closed Teflon container, which was a cylinder with 110 mm in height and 120 mm in diameter. A porous basket was also fixed at 30 mm over the bottom of the container. The container was supported with an electronic balance (Lightever, LBA5200) to measure the weight of the samples.

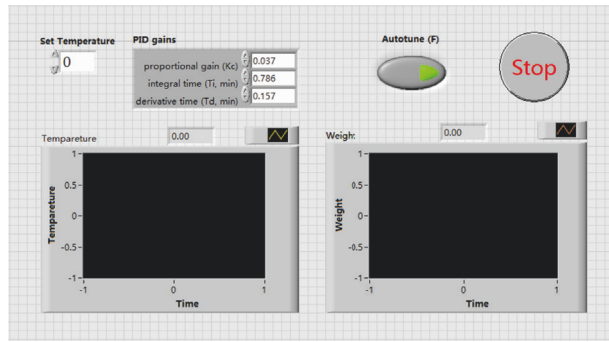

Figure 2: LabVIEW program.

One fiber optic sensor (Optsensor, ThermAigle-RD HQ-28) was inserted in the center of one of the samples for temperature measurement. The temperature of the center of sample and power control of magnetron was integrated in the DAQ board with a self-developed LabVIEW program, which used Proportion Integral Derivative (PID) control method (Figure 2). The recorded temperature is shown in Figure 3. Temperature was successfully maintained with the appropriate power levels. The maximum deviation in surface temperature was ±3°C, and standard deviations were less than 2°C. All the data were recorded at a time interval of 1 s.

2.3. Orthogonal Experiment Design. Three factors were studied: pretreatment method, temperature of the inner material, and vacuum (Table 1). Each pretreatment method changed the structure of the *P. cuspidatum* in a distinct way. By considering the cost of processing, samples were pretreated in three ways as follows: blanching for 30 s at 100°C, microwaving at 700 W for 10 s, and no pretreatment. The temperature of the inner material had a significant influence on the indicator components. When the temperature of the inner material was higher than 90°C, less indicator compounds were retained and toxic chemicals were produced. Below 40°C, the drying time was too long and the energy consumption was more than that of other drying methods. Therefore, the temperature of the inner material should be controlled in the range of 50°C–80°C. The use of a high vacuum lowered the drying temperature of the inner material. More thermosensitive compounds were retained under a high-temperature vacuum. Three pressures were used: 200, 400, and 600 mbar.

Table 1: Orthogonal experiment design.

Expt. number	Pretreatment methods	Vacuum pressure (mbar)	Temperature of inner materials (°C)
(1)	1 (blanching for 30 s at 100°C)	1 (200)	1 (50)
(2)	1	2 (400)	2 (60)
(3)	1	3 (600)	3 (70)
(4)	2 (microwave 700 w for 10 s)	1	2
(5)	2	2	3
(6)	2	3	1
(7)	3 (no pretreatment)	1	3
(8)	3	2	1
(9)	3	3	2

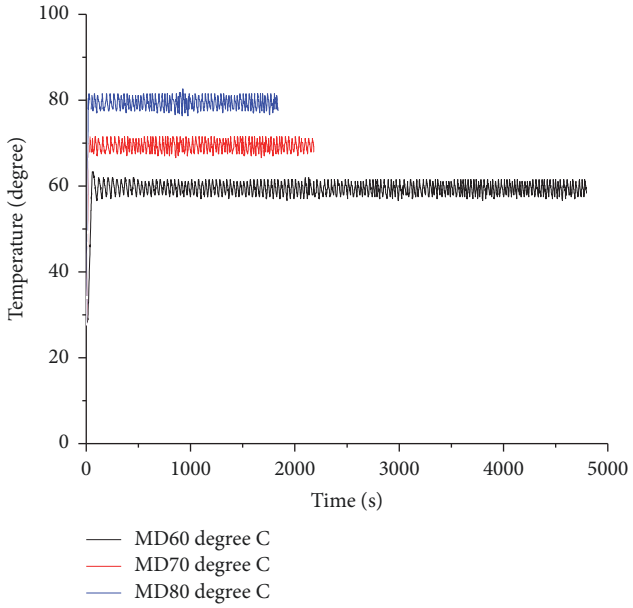

Figure 3: Recorded temperature of the microwave vacuum drying system.

2.4. Mathematical Models. The data on the drying of *P. cuspidatum* slices in microwave vacuum dryer were used to study the drying kinetics and to analyze the fit of mathematical models on thin-layer drying, including Newton, Page, logarithmic, Wang and Singh, Henderson and Pabis, two-term, and Midilli et al. models (Table 2). In Table 2, the MR in (i)–(vii) is the moisture ratio, which is defined in

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e}, \tag{1}$$

where M_t, M_o, and M_e are the moisture content (d.b.) at time t, initial moisture content (d.b.), and equilibrium moisture content (d.b.), respectively. k is the drying rate constant (min^{-1}); n, a, b, and c are the drying coefficients (unitless) that have different values depending on the equation and the drying curve; and t is time (min).

When the difference between the moisture content at time t and the equilibrium moisture content is negligible, (1) is reduced to

$$\mathrm{MR} = \frac{M_t}{M_o}. \tag{2}$$

2.5. Color Measurement. Color change is one of the quality criteria for dried products. Color parameters (L^*, a^*, b^*) were measured directly on the surface of fresh, dried, and rehydrated *P. cuspidatum* slices by using a chroma meter with $d/0$ diffuse illumination/0° viewing system (Model CR-300X, Minolta Co., Ltd., Japan). The CIE 1976 (L^*, a^*, b^*) color space was used to estimate the color values of *P. cuspidatum* slice samples. Color values, expressed as L^* (whiteness or brightness/darkness), a^* (redness/greenness), and b^* (yellowness/blueness), were determined for a sample in all drying conditions. The total color difference (ΔE) was calculated based on color values of fresh ($L_f{}^*$, $a_f{}^*$, and $b_f{}^*$) and dried *P. cuspidatum* slices ($L_d{}^*$, $a_d{}^*$, and $b_d{}^*$) based on

$$\Delta E = \sqrt{\left(L_f{}^* - L_d{}^*\right)^2 + \left(a_f{}^* - a_d{}^*\right)^2 + \left(b_f{}^* - b_d{}^*\right)^2}. \tag{3}$$

2.6. Chemicals. Polydatin (3,4′,5-trihydro-hydroxystil-bene-3-b-mono-D-glucoside), emodin (6-ethyl-1,3,8-trihydroxyanthraquinone), physcion(1,8-dihydroxy-3-methoxy-6-methylanthraquinone emodin 3-methyl ether), and resveratrol (3,4′,5-trihydrohydroxystilbene) were provided by the National Institute for the Control of Pharmaceutical and Biological Products (China). For standard solutions, polydatin, emodin, physcion, and resveratrol were dissolved in 50% ethanol and used to prepare standard solutions containing 239.7, 83.68, 10.78, and 62.96 μg/mL, respectively, which were diluted with the same solvent to obtain solutions with different concentrations.

2.7. High Performance Liquid Chromatography (HPLC) Analysis. Samples (200 mg) were ground to powders and were refluxed with 25 ml ethanol (50 : 50, v/v) for 30 minutes. The weight loss was made up with ethanol (50 : 50 v/v). The solution obtained was filtered through a 0.45 μm micropore membrane. Ten μl solution was injected into the HPLC instrument for analysis (Palo Alto, CA, USA). Samples were separated on an Agilent ZORBAX SB-C18 column (250 mm × 4.6 mm, 5 μm particles) (Agilent, USA) together with a C18 guard column. The mobile phase was a gradient prepared from acetonitrile (component A) and 0.1% formic

Table 2: Mathematical models of the kinetics of fluidized bed drying.

Model name	Model equation	Reference	Equation number
Newton	$MR = e^{-kt}$	[16]	(i)
Page	$MR = e^{-kt^n}$	[17]	(ii)
Logarithmic	$MR = ae^{-kt} + c$	[18]	(iii)
Wang and Singh	$MR = 1 + at + bt^2$	[19]	(iv)
Henderson and Pabis	$MR = ae^{-kt}$	[20]	(v)
Two-term	$MR = ae^{k_0 t} + be^{k_1 t}$	[21]	(vi)
Midilli et al.	$MR = ae^{-kt^n} + bt$	[22]	(vii)

Table 3: Color values of *P. cuspidatum* slices in all drying conditions.

Samples	Color values			
	L^*	a^*	b^*	ΔE
Fresh	62.78	8.25	36.63	-
(1)	51.78	9.34	34.12	11.33
(2)	48.59	9.97	33.90	14.55
(3)	49.3	8.57	34.19	13.70
(4)	51.57	7.05	34.35	11.50
(5)	56.82	7.23	41.05	7.49
(6)	51.94	7.98	36.49	10.84
(7)	55.48	7.04	38.85	7.73
(8)	54.79	7.77	37.48	8.05
(9)	56.25	7.69	41.24	8.01

acid (component B) prepared in water. The elution program was 0–15 min, 15% (A) to 20% (A), and 15–60 min, 20% (A) to 80% (A), and the total acquisition time was 65 min. The mobile phase flow rate was 1.0 mL/min, and the column temperature was set at 25°C [23].

2.8. Correlation Coefficients and Error Analysis. Statistical parameters, such as root mean square error (RMSE) (see (4)), chi-square (χ^2) (see (5)), and correlation coefficient (R^2) (see (6)), were used to estimate the quality of fit of drying models to the observed values.

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right]^{1/2}, \quad (4)$$

where $\mathrm{MR}_{\mathrm{exp},i}$ is the experimental moisture ratio at time t, $\mathrm{MR}_{\mathrm{pre},i}$ is the predicted moisture ratio at time t, and N is the observation number.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{exp},i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N - n}, \quad (5)$$

where n is the constant number in drying models.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2}{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{exp},i} - \overline{\mathrm{MR}}_{\mathrm{exp}}\right)^2}, \quad (6)$$

where $\overline{\mathrm{MR}}_{\mathrm{exp}}$ is the mean experimentally measured value of MR.

In addition to the parameters mentioned above, the reduced sum square error (SSE) (see (7)) was also used as a criterion to analyze the closeness of fit.

$$\mathrm{SSE} = \frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2. \quad (7)$$

2.9. Statistical Analysis. The statistical analysis of variance of the experiment results was conducted using the SPSS17.0 (SAS Institute Inc., Cary, NC, USA) with a confidence level ($p \leq 0.05$) of 95%. The mathematical models of the drying of carrot slices in microwave vacuum drying were fitted and analyzed by using SPSS.

3. Results and Discussion

3.1. Color Values. The results of color parameters of dried *P. cuspidatum* slices in microwave vacuum drying system are presented in Table 3. The L^* values of all the dried *P. cuspidatum* slices decreased in comparison with the fresh *P. cuspidatum* slices. However, b^* values almost stayed the same in all drying conditions, which shows the yellowness of *P. cuspidatum* slices, and ranged from 33.90 to 41.24. The a^* values varied with different pretreatment methods. Pretreatment method with blanching for 30 s at 100°C made *P. cuspidatum* slices redder than other pretreatment methods and fresh *P. cuspidatum* slices. The total color difference (ΔE) of the dried *P. cuspidatum* slices from all the drying conditions was between 7.49 and 14.55.

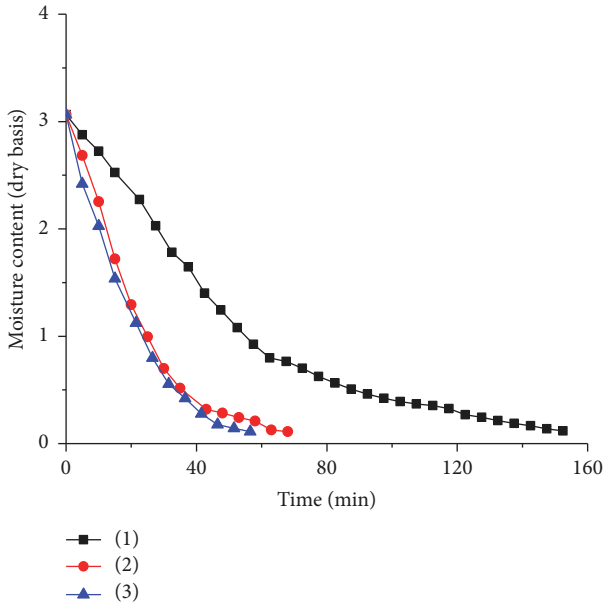

Figure 4: Drying curves of *P. cuspidatum* slices at (1) blanching for 30 s at 100°C, vacuum pressure at 200 mbar and 50°C; (2) blanching for 30 s at 100°C, vacuum pressure at 400 mbar and 60°C; and (3) blanching for 30 s at 100°C, vacuum pressure at 600 mbar and 70°C.

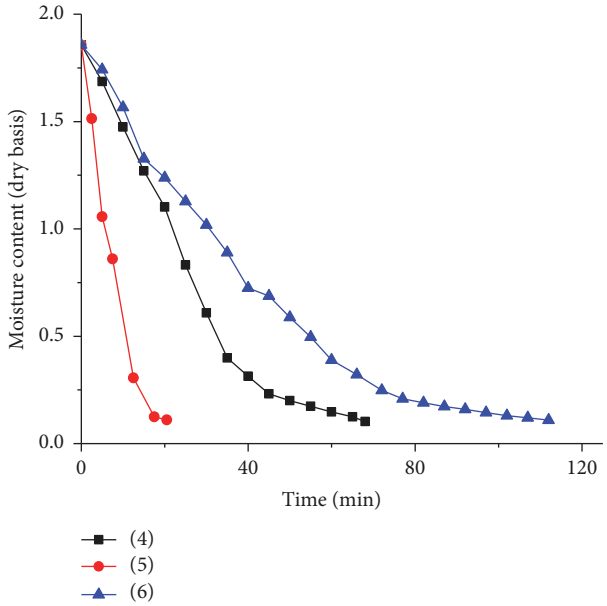

Figure 5: Drying curves of *P. cuspidatum* slices at (4) blanching for 30 s at 100°C, vacuum pressure at 200 mbar and 60°C; (5) blanching for 30 s at 100°C, vacuum pressure at 400 mbar and 70°C; and (6) blanching for 30 s at 100°C, vacuum pressure at 600 mbar and 50°C.

3.2. Drying Curves. The pretreatment methods of the nine groups were various; hence, the initial moisture content (dry basis) of each sample was different. The lowest moisture content was found in the pretreated material microwaved at 700 w for 10 s before the drying process (1.86, dry basis), whereas the dried material blanched for 30 s at 100°C had the highest moisture content (3.06, dry basis). Figure 4 shows the change of moisture content for groups (1) to (3). The drying curve for group (2) was similar to that for group (3). The moisture content of group (1) slowly decreased over time. Thus, a low temperature of the inner material and low vacuum pressure required more time for drying to occur. This phenomenon was due to the fact that, at a low temperature, the pressure of water vapor inside the material was low; thus, the water was not easily transferred. Similar observations were reported by Li et al. [14].

Figure 5 shows the drying curves for groups (4) to (6), which were pretreated with microwave at 700 w for 10 s. As the initial moisture was the least, the drying time for group (5) (22 minutes) was the shortest. The use of a high temperature and a high vacuum pressure to the inner material resulted in fast drying. The drying time for group (6) (600 mbar and 50°C) was 1.6 times longer than that for group (4) (600 mbar and 60°C). Thus, the influence of temperature of the inner material on the drying time was more significant than that of vacuum pressure.

Figure 6 shows the drying curves of groups without pretreatments. The initial moisture was 2.33 (dry basis). Vacuum pressure had little influence on drying time; hence, the drying time of group (8) at 50°C was almost 2 times more than that for group (7) at 70°C without considering the vacuum pressure. Furthermore, atmospheric pressure for

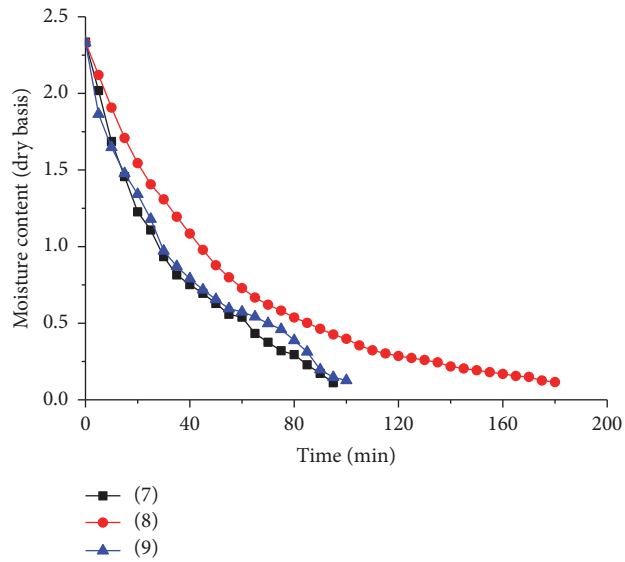

Figure 6: Drying curves of *P. cuspidatum* slices at (7) vacuum pressure at 200 mbar and 70°C, (8) vacuum pressure at 400 mbar and 50°C, and (9) vacuum pressure at 600 mbar and 60°C.

group (7) was 200 mbar lower than that for group (8). The temperature of the root had more significant influence on the drying time for microwave vacuum drying.

To compare the influence of pretreatment on the drying time, the groups with the same temperature should be considered. The lengths of drying times of groups with a temperature of 50°C were in the following order: the length of drying time of group (8) was greater than that of groups (1) and (6). In addition, the initial moisture of group (8) with a

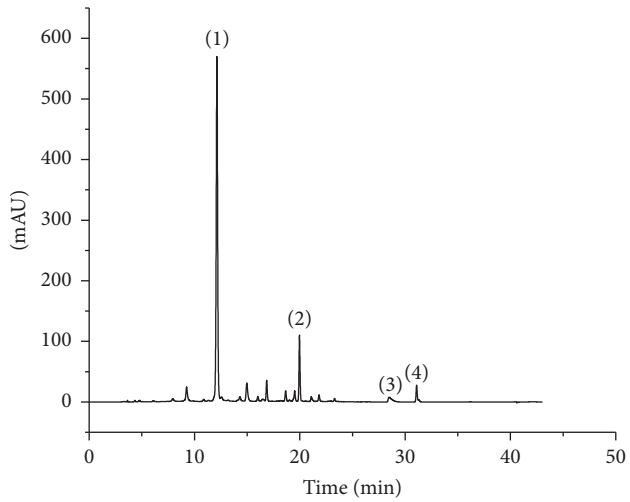

Figure 7: HPLC chromatograms of compound retained in sample (1) (peak (1), polydatin; peak (2), resveratrol; peak (3), emodin; and peak (4), physcion).

higher vacuum pressure was less than that of group (1) with lower vacuum pressure. Thus, pretreatment methods with blanching for 30 s at 100°C made dry process faster than no pretreatment. The lengths of drying times of groups with a temperature of 70°C were in the following order: the length of drying time of group (7) was greater than that of groups (3) and (5). In addition, the vacuum pressure of group (3) was lower than that for group (5). Thus, pretreatment with microwave for 10 s made dry process faster than blanching for 30 s.

3.3. Mathematical Models and Statistical Analysis. The drying curves of *P. cuspidatum* slices were fitted into the mathematical models (see (i)–(vii)). The statistical values were calculated to estimate the accuracy of closeness of fit and are shown in Tables 4–6. The best fitting model was determined according to the lowest χ^2, RMSE, and SSE and the highest R^2 values. The R^2 values ranged from 0.2090 to 1.0000 and the SSE values ranged from 0.0065 to 0.0997, respectively (Tables 4–6). The R^2 in Tables 4 and 6 is low. Thus, Newton, Page, and Wang and Singh model were not suitable under all the drying conditions.

The two-term and Midilli et al. models were the best fitting mathematical models for the no-pretreatment case at 600 mbar and 60°C. Moreover, the lowest χ^2 values were 0.0001 and 0.0002. The logarithmic, Henderson and Pabis, two-term, and Midilli et al. models can be used to scale up the microwave vacuum drying system to a commercial scale.

3.4. Effect of Microwave Vacuum Drying and Pretreatment Methods on Concentrations of Indicator Compounds. The concentrations of indicator compounds in sample 1 were analyzed by HPLC (Figure 7). The results of nine groups of experiments are listed in Table 7. The highest concentrations of polydatin were found in samples pretreated by blanching for 30 s and microwave vacuum drying at 400 mbar and 60°C. Emodin and physcion were the highest when samples were pretreated with blanching for 30 s and microwave vacuum drying at 200 mbar and 50°C. Furthermore, resveratrol concentrations were the highest when samples were pretreated with microwave at 700 W for 10 s and dried with microwave vacuum at 600 mbar and 50°C.

3.4.1. Factors Affecting the Retention of Polydatin. The variance of the concentrations of polydatin for each of the factors was analyzed in Table 7. Pretreatment had a significant influence on the retention of polydatin at a confidence level of 0.05, whereas vacuum pressure and temperature of root material had a significant influence on retention at a confidence level of 0.01. The concentrations of polydatin were the highest in groups (1), (2), and (3) (Table 2), which were pretreated with blanching for 30 s. This effect was probably due to the inhibition of the hydrolysis of the polydatin. As the temperature of the root increased, retention decreased, which may be due to the decomposition of polydatin. Moreover, as the temperature of the inner material increased, the moisture content decreased and less polydatin was retained because polydatin is soluble in water. When the vacuum pressure was higher, the temperature of inner material should be lower [24]. Thus, with a low temperature of inner material, less polydatin was retained.

3.4.2. Factors Affecting the Retention of Emodin and Physcion. The effect of the factors on the retention of emodin is in the following order. The effect of temperature of inner material was greater than that in pretreatment methods and use of vacuum pressure (Table 8). Vacuum pressure and pretreatment had no significant influence, whereas the temperature of inner material had a significant influence at a confidence level of 0.1. A high temperature of the root may decrease the retention of emodin. In addition, a high thermal process may affect the stability of bioactive compounds in food, including vitamins and trace elements, as proposed by Hirun et al. [25].

The effect of the different factors on the retention of physcion is discussed in Table 8. Pretreatment and vacuum pressure had no significant influence, whereas the temperature of inner material had a significant influence at a confidence level of 0.1. This finding was the same as that obtained for emodin, thus suggesting the use of low temperature.

3.4.3. Factors Affecting the Retention of Resveratrol. The effect on the factors on the retention of resveratrol is in the following order: the temperature of the root was greater than that in pretreatment and vacuum pressure use (Table 8). The three factors had no significant influence at a confidence level of 0.1. Table 2 shows the least retention of resveratrol in the no-pretreatment case, followed by microwave vacuum drying with a vacuum pressure of 0.02 Mpa and a temperature of 70°C. A high temperature led to chemical changes in the resveratrol. The highest retention was 0.397 mg/g, which was 13 times more than the highest retention (0.029 mg/g) obtained by Zhang et al. [23]. Drying at 50°C caused most of the retention in the groups, but drying time with low temperature of the inner material was long.

Table 4: Statistical results of mathematical model for *P. cuspidatum* for groups (1), (2), and (3).

Expt. number	Statistics/coefficient	Models						
		Newton	Page	Logarithmic	Wang and Sing	Henderson and Pabis	Two-term	Midilli et al.
(1)	R^2	0.209	0.319	0.993	0.334	0.992	0.992	0.998
	SSE	0.00653125	0.009969	0.031031	0.010438	0.031	0.031	0.031188
	RMSE	0.080816149	0.099844	0.176157	0.102164	0.176068	0.176068	0.1766
	χ^2	0.648780935	0.577014	0.006232	0.564585	0.006624	0.007097	0.002238
(2)	R^2	0.211	0.302	0.983	0.295	0.982	0.984	0.997
	SSE	0.015071	0.021571	0.070214	0.021071	0.070143	0.070286	0.071214
	RMSE	0.122766	0.146872	0.26498	0.14516	0.264845	0.265115	0.26686
	χ^2	0.821399	0.786975	0.021068	0.795255	0.020394	0.021737	0.004037
(3)	R^2	0.23	0.343	0.997	0.337	0.993	0.998	0.998
	SSE	0.017692	0.026385	0.076692	0.025923	0.076385	0.076769	0.076769
	RMSE	0.133012	0.162433	0.276934	0.161006	0.276378	0.277073	0.277073
	χ^2	0.755287	0.70324	0.003333	0.70912	0.00756	0.00291	0.002067

Table 5: Statistical results of mathematical model for *P. cuspidatum* for groups (4), (5), and (6).

Expt. number	Statistics/coefficient	Models						
		Newton	Page	Logarithmic	Wang and Sing	Henderson and Pabis	Two-term	Midilli et al.
(4)	R^2	0.653	0.771	0.983	0.69	0.979	0.985	0.996
	SSE	0.0653	0.036714	0.04681	0.032857	0.046619	0.046905	0.047429
	RMSE	0.255539	0.19161	0.216355	0.181265	0.215914	0.216575	0.217781
	χ^2	0.120337	0.087957	0.006901	0.118796	0.008169	0.006536	0.001526
(5)	R^2	0.588	0.751	0.989	0.678	0.989	0.99	0.997
	SSE	0.025565	0.0751	0.0989	0.0678	0.0989	0.099	0.0997
	RMSE	0.159891	0.274044	0.314484	0.260384	0.314484	0.314643	0.315753
	χ^2	0.241822	0.129542	0.006555	0.167694	0.005932	0.006765	0.002055
(6)	R^2	0.41	0.727	0.995	0.699	0.991	0.995	0.997
	SSE	0.018636	0.031609	0.043261	0.030391	0.043087	0.043261	0.043348
	RMSE	0.136515	0.177788	0.207992	0.174331	0.207574	0.207992	0.208201
	χ^2	0.3664	0.091569	0.001927	0.111174	0.003075	0.001801	0.001044

Table 6: Statistical results of mathematical model for *P. cuspidatum* for groups (7), (8), and (9).

Expt. number	Statistics/coefficient	Models						
		Newton	Page	Logarithmic	Wang and Sing	Henderson and Pabis	Two-term	Midilli et al.
(7)	R^2	0.491	0.513	0.988	0.507	0.983	0.994	0.993
	SSE	0.018885	0.023318	0.044909	0.023045	0.044682	0.045182	0.045136
	RMSE	0.137421	0.152703	0.211918	0.151807	0.211381	0.21256	0.212453
	χ^2	0.344994	0.181661	0.004813	0.183733	0.006275	0.002431	0.002721
(8)	R^2	0.521	0.573	0.989	0.551	0.98	0.994	0.909
	SSE	0.013711	0.022038	0.038038	0.021192	0.037692	0.038231	0.034962
	RMSE	0.117092	0.148454	0.195035	0.145576	0.194145	0.195527	0.18698
	χ^2	0.544095	0.144854	0.003781	0.152392	0.006815	0.002187	0.033678
(9)	R^2	0.657	0.617	0.999	0.573	0.997	1	1
	SSE	0.031286	0.016237	0.026289	0.015079	0.026237	0.026316	0.026316
	RMSE	0.176878	0.127424	0.16214	0.122796	0.161978	0.162221	0.162221
	χ^2	0.214399	0.145253	0.000242	0.161685	0.001093	0.000129	0.000178

Table 7: Indicator compounds retained in samples with drying condition.

Number	Polydatin (mg/g)	Emodin (mg/g)	Physcion (mg/g)	Resveratrol (mg/g)
(1)	18.828	18.589	0.128	0.379
(2)	20.656	13.664	0.011	0.228
(3)	17.806	10.186	0.004	0.285
(4)	12.619	14.154	0.027	0.272
(5)	12.037	6.397	0.004	0.068
(6)	13.931	17.397	0.055	0.397
(7)	11.795	5.49	0.026	0.112
(8)	15.013	14.714	0.111	0.377
(9)	12.405	7.513	0.008	0.188

Table 8: Variance analysis of the retention of polydatin.

Indicator compounds	R^2	Source of variation	Sum of squares	Degree of freedom	Mean square	F value	Sig.
Polydatin	0.991	Pretreatment	88.853	2	44.427	89.450	0.011
		Vacuum pressure	9.291	2	4.646	9.354	0.097
		Temperature of inner material	15.266	2	7.633	15.369	0.061
Emodin	0.939	Pretreatment	27.766	2	13.883	2.273	0.306
		Vacuum pressure	1.646	2	0.823	0.135	0.881
		Temperature of inner material	157.277	2	78.639	12.873	0.072
Physcion	0.944	Pretreatment	0.001	2	0.000	0.535	0.652
		Vacuum pressure	0.002	2	0.001	1.421	0.413
		Temperature of inner material	0.016	2	0.008	14.791	0.063
Resveratrol	0.865	Pretreatment	0.008	2	0.004	0.543	0.648
		Air pressure	0.006	2	0.003	0.428	0.700
		Temperature of inner material	0.082	2	0.041	5.418	0.156

4. Conclusion

Pretreatment method with blanching for 30 s at 100°C intensified the red color of *P. cuspidatum* slices compared with other pretreatment methods and fresh *P. cuspidatum* slices. The logarithmic, Henderson and Pabis, two-term, and Midilli et al. models can be used to scale up the microwave vacuum drying system to a commercial scale. The temperature of the root had a significant influence on the retention of polydatin, emodin, and physcion at a confidence level of 0.1. The temperature of the root, pretreatment, and vacuum pressure had no significant influence on the retention of resveratrol. In addition, low temperature of inner material retained all the indicator compounds of *P. cuspidatum*. However, low root temperature required a long drying time. The order of drying time with pretreatment was as follows. The drying time of no-pretreatment case was greater than that of blanching for 30 s and microwaving at 700 w for 10 s. Furthermore, the temperature of the root had more significant influence on drying time than vacuum pressure. In conclusion, pretreatment with microwave at 700 w for 10 s, with a low temperature and low vacuum pressure, would retain more indicator compounds and require less drying time.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] H. Chen, T. Tuck, X. Ji et al., "Quality assessment of Japanese knotweed (Fallopia japonica) grown on Prince Edward Island as a source of resveratrol," *Journal of Agricultural and Food Chemistry*, vol. 61, no. 26, pp. 6383–6392, 2013.

[2] W. Peng, R. Qin, X. Li, and H. Zhou, "Botany, phytochemistry, pharmacology, and potential application of *Polygonum cuspidatum* Sieb.et Zucc.: a review," *Journal of Ethnopharmacology*, vol. 148, no. 3, pp. 729–745, 2013.

[3] P. Ma, K. Luo, Y. Peng et al., "Quality control of polygonum cuspidatum by uplc-pda and related statistical analysis," *Journal of Liquid Chromatography & Related Technologies*, vol. 36, no. 20, pp. 2844–2854, 2013.

[4] A. Figiel, "Drying kinetics and quality of vacuum-microwave dehydrated garlic cloves and slices," *Journal of Food Engineering*, vol. 94, no. 1, pp. 98–104, 2009.

[5] Á. Calín-Sánchez, A. Figiel, A. Wojdyło, M. Szarycz, and Á. A. Carbonell-Barrachina, "Drying of Garlic Slices Using Convective Pre-drying and Vacuum-Microwave Finishing Drying:

Kinetics, Energy Consumption, and Quality Studies," *Food and Bioprocess Technology*, vol. 7, no. 2, pp. 398–408, 2014.

[6] S. Ferenczi, B. Czukor, and Z. Cserhalmi, "Evaluation of microwave vacuum drying combined with hot-air drying and compared with freeze- and hot-air drying by the quality of the dried apple product," *Periodica Polytechnica Chemical Engineering*, vol. 58, no. 2, pp. 111–116, 2014.

[7] A. Figiel and A. Michalska, "Overall quality of fruits and vegetables products affected by the drying processes with the assistance of vacuum-microwaves," *International Journal of Molecular Sciences*, vol. 18, no. 1, article no. 71, 2017.

[8] S. Ambros, S. A. W. Bauer, L. Shylkina, P. Foerst, and U. Kulozik, "Microwave-Vacuum Drying of Lactic Acid Bacteria: Influence of Process Parameters on Survival and Acidification Activity," *Food and Bioprocess Technology*, vol. 9, no. 11, pp. 1901–1911, 2016.

[9] J. de Bruijn, F. Rivas, Y. Rodriguez et al., "Effect of Vacuum Microwave Drying on the Quality and Storage Stability of Strawberries," *Journal of Food Processing and Preservation*, vol. 40, no. 5, pp. 1104–1115, 2016.

[10] M. Zielinska, P. Sadowski, and W. Błaszczak, "Combined hot air convective drying and microwave-vacuum drying of blueberries (Vaccinium corymbosum L.): Drying kinetics and quality characteristics," *Drying Technology*, vol. 34, no. 6, pp. 665–684, 2016.

[11] Y. Tian, S. Wu, Y. Zhao, Q. Zhang, J. Huang, and B. Zheng, "Drying Characteristics and Processing Parameters for Microwave-Vacuum Drying of Kiwifruit (Actinidia deliciosa) Slices," *Journal of Food Processing and Preservation*, vol. 39, no. 6, pp. 2620–2629, 2015.

[12] D. Wray and H. S. Ramaswamy, "Quality Attributes of Microwave Vacuum Finish-Dried Fresh and Microwave-Osmotic Pretreated Cranberries," *Journal of Food Processing and Preservation*, vol. 39, no. 6, pp. 3067–3079, 2015.

[13] N. Therdthai and W. Zhou, "Characterization of microwave vacuum drying and hot air drying of mint leaves (Mentha cordifolia Opiz ex Fresen)," *Journal of Food Engineering*, vol. 91, no. 3, pp. 482–489, 2009.

[14] Z. Li, G. S. V. Raghavan, and V. Orsat, "Temperature and power control in microwave drying," *Journal of Food Engineering*, vol. 97, no. 4, pp. 478–483, 2010.

[15] J. Xu, *Chapter 9 - Microwave Pretreatment*, A. P. N. B. Larroche, Ed., Pretreatment of Biomass, Elsevier, Amsterdam, p. 157-172, 2015.

[16] P. C. Corrêa, F. M. Botelho, G. H. H. Oliveira, A. L. D. Goneli, O. Resende, and S. de Carvalho Campos, "Mathematical modeling of the drying process of corn ears," *Acta Scientiarum—Agronomy*, vol. 33, no. 4, pp. 575–581, 2011.

[17] Q. Shi, Y. Zheng, and Y. Zhao, "Mathematical modeling on thin-layer heat pump drying of yacon (*Smallanthus sonchifolius*) slices," *Energy Conversion and Management*, vol. 71, pp. 208–216, 2013.

[18] M. Özdemir and Y. Onur Devres, "The thin layer drying characteristics of hazelnuts during roasting," *Journal of Food Process Engineering*, vol. 42, no. 4, pp. 225–233, 1999.

[19] C. Chen and P.-C. Wu, "Thin-layer drying model for rough rice with high moisture content," *Journal of Agricultural Engineering Research*, vol. 80, no. 1, pp. 45–52, 2001.

[20] A. Midilli, H. Kucuk, and Z. Yapar, "A new model for single-layer drying," *Drying Technology*, vol. 20, no. 7, pp. 1503–1513, 2002.

[21] S. M. Henderson, "Progress in developing the thin layer drying equation," *Transactions of the ASAE*, vol. 17, no. 6, pp. 1167–1172, 1974.

[22] H. O. Menges and C. Ertekin, "Mathematical modeling of thin layer drying of Golden apples," *Journal of Food Engineering*, vol. 77, no. 1, pp. 119–125, 2006.

[23] W. Zhang, Y. Jia, Q. Huang, Q. Li, and K. Bi, "Simultaneous determination of five major compounds in Polygonum cuspidatum by HPLC," *Chromatographia*, vol. 66, no. 9-10, pp. 685–689, 2007.

[24] N. Hamidi and T. Tsuruta, "Improvement of freezing quality of food by pre-dehydration with microwave-vacuum drying," *Journal of Thermal Science and Technology*, vol. 3, no. 1, pp. 86–93, 2008.

[25] S. Hirun, N. Utama-ang, and P. D. Roach, "Turmeric (Curcuma longa L.) drying: an optimization approach using microwave-vacuum drying," *Journal of Food Science and Technology*, vol. 51, no. 9, pp. 2127–2133, 2014.