

Article

Drying Characteristics of Moutan Cortex by Rotary Wheel Microwave Vacuum Drying and Its Influence on Quality

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Abstract: To enhance the quality of Moutan Cortex for medicinal purposes, this study was conducted to analyze the impact of rotary microwave vacuum drying on its drying characteristics and overall quality. Experimental variables including drying temperature, rotor speed, and vacuum were examined to evaluate their effects on the microstructure, effective components, and drying properties of Moutan Cortex. The back propagation (BP) neural network was optimized by the northern eagle algorithm (NGO) to predict the moisture ratio throughout the drying process. Results indicated that increasing the drying temperature, vacuum level, and rotation speed led to an acceleration in the drying rate of Moutan Cortex, thereby reducing the drying time. The quality and color of dried products after microwave vacuum drying were superior to those achieved through natural drying. Notably, at the drying temperature of 50 °C, the Moutan Cortex demonstrated the highest total phenol content (451.33 mg/g) and antioxidant capacity (78.95%). With an increase in drying temperature, vacuum, and rotational speed, the polysaccharide showed an upward trend, and the highest value (681.37 mg/g) was obtained at 50 Hz. The highest total flavonoid content (1.08 mg/g) was observed at vacuum of −70 kPa. Optimal conditions for preserving the internal organization and maximizing the contents of gallic acid, paeoni-florin, benzoylpaeoniflorin, and paeonol were identified at a drying temperature of 45 °C, vacuum level of −65 kPa, and rotation rate of 35 Hz. Overall, the study concluded that the microwave vacuum drying of Moutan Cortex can significantly improve its medicinal value, offering valuable insights for the industrial processing of Moutan Cortex.

Keywords: drying characteristics; microstructure; microwave vacuum drying; Moutan Cortex; quality



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1. Introduction

Moutan Cortex (MC) originates from the root bark of Moutan *Paeonia suffruticosa* Andr. of the buttercup family [1]. This plant extract is known for its abundance of beneficial compounds such as gallic acid, paeoniflorin, paeonol, flavonoids, and benzoic acid. Its properties include clearing heat and cooling blood, promoting blood circulation and removing blood stasis, and relieving deficiency heat [2].

Fresh MC has a high water content and is susceptible to mold during transport and storage, leading to the loss of active ingredients. Drying is a widely employed initial treatment process for MC. However, traditional drying techniques such as shade and natural drying are associated with drawbacks like extended drying periods, weather vulnerability, and low-quality dried medical materials [3]. In recent years, drying methods based on modern drying principles and techniques have been gradually applied to the post-harvest processing of Chinese medicinal materials, and have shown the advantages of high efficiency, controllable conditions, and stable product quality. Modern drying techniques such as far-infrared drying, vacuum drying, and freeze-drying have made significant

progress in the research field of medicinal plants. Far-infrared drying has demonstrated the ability to reduce drying time and preserve the quality of the material significantly, although it is associated with challenges such as uneven heating and a poor rehydration ratio [4]. Vacuum drying can better protect the active ingredients of heat-sensitive substances, but, due to the high investment in equipment, the production scale is small [5]. Freeze-drying is effective in preventing wrinkles and shrinkage in the dried product, while maintaining the bioavailability and flavor, but it is characterized by lengthy drying times and high operational expenses [6].

Microwave drying harnesses electromagnetic waves to directly interact with the material, inducing molecular friction that generates heat energy. This internal heating mechanism facilitates rapid heat generation within the material, leading to the evaporation and removal of moisture. The advantages of microwave drying over traditional drying include excellent drying efficiency and good quality dried products [7]. By combining the benefits of vacuum and microwave drying, microwave vacuum drying has the ability to increase the rate of microwave drying while reducing non-uniformity in drying and the low boiling point of water in a vacuum setting [8]. This innovative technique has found widespread application in various industries, including the processing of medicinal materials and food products [9]. Nong [10] conducted a study on the impact of different microwave vacuum drying conditions on the drying characteristics of fresh ginger slices. The findings revealed that increasing the microwave power and reducing the thickness of ginger slices enhanced drying speed, efficiency, and reduced unit energy consumption. Shen et al. [11] observed that microwave vacuum drying improved the uniformity of the drying temperature and ensured a stable drying rate, which is conducive to the retention of dry product quality. In a study by Huang et al. [12] on stevia, it was demonstrated that microwave vacuuming could elevate the content of stevioside and stevioside A, enhancing the heat and mass transfer rate of the material. Traditional microwave vacuum drying is mainly continuous drying; however, prolonged microwave exposure can lead to uneven drying and trigger local high temperature, affecting the drying quality. In contrast, intermittent microwave drying has been proven to enhance heating efficiency, improve product quality, and prevent uneven drying and overheating during the process. Based on the numerical analysis of intermittent microwave drying of porous media of sweet potato slices, Man et al. [13] found that an intermittent microwave heat source can promote the drying process of sweet potato slices, improve the drying speed, and realize the drying optimization. Bhagya et al. [14] explored the effect of intermittent microwave convection drying on the quality attributes of persimmons, noting the minimal color changes and good quality of the samples after intermittent microwave drying. Rotary microwave drying is a form of microwave gap drying. It uses a controlled pendant rotor that holds the material and passes it sequentially through the top microwave source, thus realizing the intermittent action of the microwaves. Zang et al. [15] investigated the impact of rotational microwave vacuum drying on the physicochemical quality and drying characteristics of *Angelica sinensis*. Results indicated that rotary microwave vacuum drying greatly enhanced heat transfer and mass transfer efficiency. As the drying temperature and vacuum level increased, along with the reduction in slice thickness, the drying time shortened, and the drying rate accelerated. After microwave vacuum drying, a consistent and orderly honeycomb pore structure emerged within the material, effectively minimizing structural damage and producing the optimal color ($\Delta E = 6.77 \pm 2.01$).

In this research, rotary microwave vacuum drying technology was used to dry MC, and the effects of different factors on the drying characteristics of MC were discussed. A predictive model for the moisture ratio of MC was formulated using the northern eagle algorithm (NGO) optimized back propagation (BP) neural network. Then, the changes of quality, color difference, microstructure, and content of four natural active substances of dried MC products were analyzed.

2. Materials and Methods

2.1. Experimental Materials

Fresh MC was purchased from Longnan City, Gansu Province, China. MC with a uniform size (10 mm in diameter and 200 mm in length) and no damage to its appearance was selected as the experimental material. The average dry basis moisture content of fresh MC was $(51.24 \pm 0.5)\%$.

2.2. Chemicals and Instruments and Equipment

The chemicals used included paeonol (standard), gallic acid (standard), paeoniflorin (standard), benzoylpaeoniflorin (standard), ascorbic acid, 1,1-diphenyl-2-trinitrophenylhydrazine, phenol, catechin, and Folin–Ciocalteu’s phenol reagent, etc.

The instruments used included rotary microwave vacuum dryer [15], Figure 1, (HWZ-3B, Tianshui Shenghua Microwave Technology Co., Ltd., Tianshui, China), high performance liquid chromatograph (Agilent-1126-II, Agilent, Santa Clara, CA, USA), electronic balance (JM-A3003, Yuyao Jiming Weighing Calibration Equipment Co., Ltd., Ningbo, China), scanning electron microscopy (S-4800N, Hitachi, Tokyo, Japan), etc.

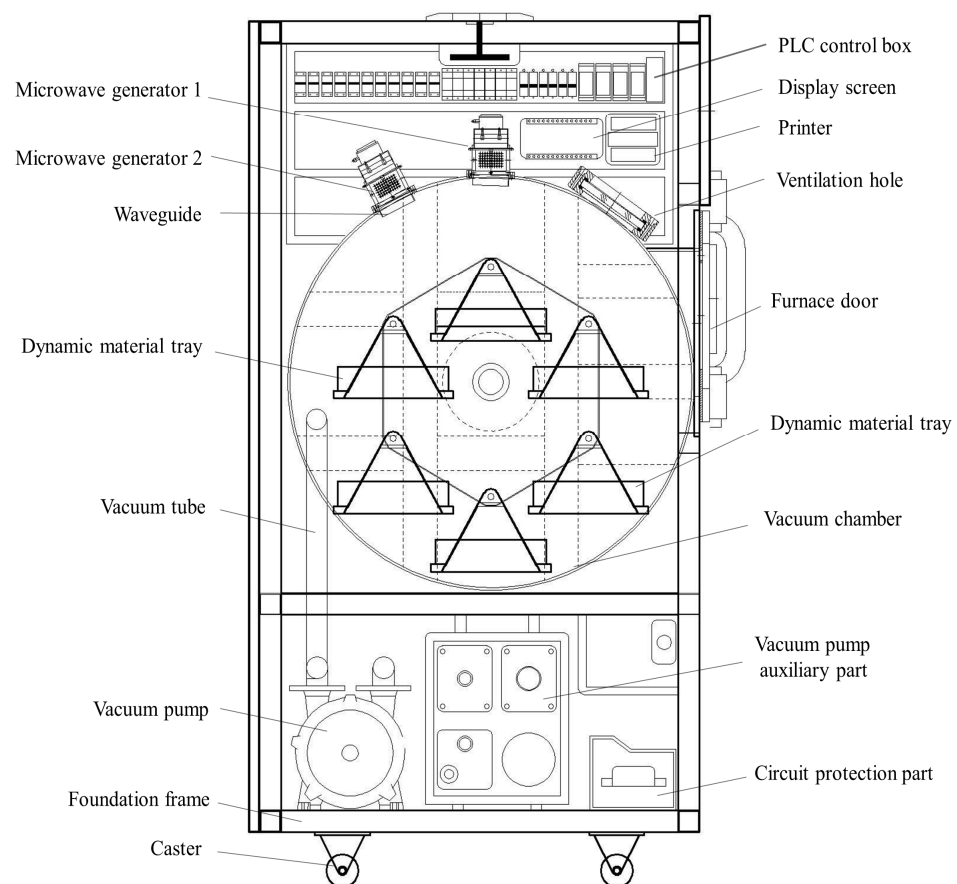


Figure 1. Rotary microwave vacuum schematic diagram.

2.3. Drying Methods

The drying experiment was carried out using an HWZ-3B (microwave frequency 2450 ± 50 MHz, microwave power 3 kW) rotary microwave vacuum dryer. The study focused on three experimental factors: drying temperature, rotating speed, and vacuum level. Drying temperatures of 40°C , 45°C , and 50°C were chosen, rotational speeds of 20 Hz, 35 Hz, and 50 Hz were selected (rotor speed = $2 \times \pi$ frequency), and vacuum levels were set at -60 kPa, -65 kPa, and -70 kPa. Before the test, uniform fresh MC samples were preheated, and (180 ± 0.5) g single layer was placed on the tray area. Weighing was

conducted every 4 min until the moisture content dropped below 13%. Each experiment was repeated thrice, and the mean value was taken as the experimental result. To assess the impact of microwave drying on the drying effect of MC, natural dried MC was utilized as the control group for comparison. The microwave vacuum single factor test of MC is shown in Table 1.

Table 1. Microwave vacuum single factor test of Moutan Cortex.

Experimental Number	Drying Temperature	The Rotor Speed	Vacuum Degree
1	45 °C	35 Hz	−60 kPa
2	45 °C	35 Hz	−65 kPa
3	45 °C	35 Hz	−70 kPa
4	45 °C	20 Hz	−65 kPa
5	45 °C	50 Hz	−65 kPa
6	40 °C	35 Hz	−65 kPa
7	50 °C	35 Hz	−65 kPa

2.4. Calculation of Drying Parameters

2.4.1. Dry Basis Moisture Content

The calculation formula is as follows [16]:

$$M_t = \frac{(X_a - X_0)}{X_0} \times 100\% \quad (1)$$

where X_0 is the dry weight of peony skin, g, and X_a is the mass of peony skin at time t , g.

2.4.2. Moisture Ratio

The calculation formula is as follows [16]:

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

where M_0 represents the starting moisture content of MC, measured in g/g, M_e represents the equilibrium moisture content of MC, measured in g/g, and M_t represents the dry base moisture content of MC at time t .

2.4.3. Drying Rate

The calculation formula is as follows [17]:

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \quad (3)$$

where DR represents the drying rate, g/s, and M_{t1} and M_{t2} are the dry basis water content of MC at the moments of t_1 and t_2 , respectively, g/g.

2.5. Moisture Content Prediction Based on NGO-BP Neural Network

A prediction model based on the NGO-BP neural network model was constructed to forecast the rate of water content during the drying process of MC. The Northern Goshawk Algorithm NGO was utilized to enhance the initial weights and thresholds of the BP neural network [18], with the network's architecture illustrated in Figure 2. The input layer comprises parameters such as temperature, rotational speed, vacuum, and initial moisture ratio. The hidden layer contains nodes ranging from 5 to 12, with 9 nodes ultimately selected. The number of panel points in the output layer is 1. The hidden layer and output layer use tansig function and purelin function as transfer functions, respectively. The maximum training iterations were set to 1000, with a learning rate of 0.01 and a minimum target error of 10^{-5} .

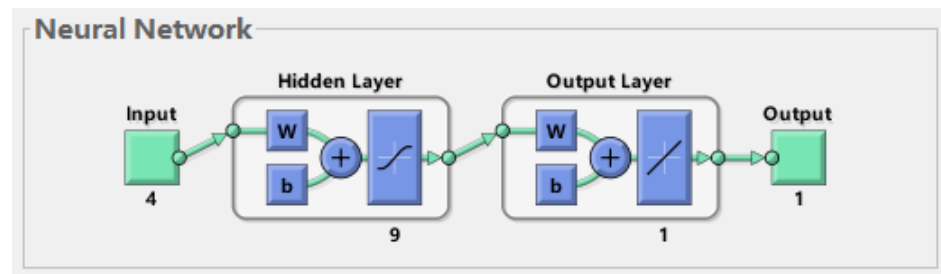


Figure 2. Topological structure of BP neural network.

In NGO, the population size is 50, the independent variable dimension is 55, and the maximum number of evolutions is 100. The performance evaluation indexes of the prediction effectiveness are mean absolute error, mean squared error, and root mean squared error [19]. The calculation formula is as follows:

$$MAE = \frac{1}{N} \left| \sum_{i=1}^N (x_{ti} - x_{oi}) \right| \quad (4)$$

$$MSE = \frac{1}{N} \sum_{i=1}^N (x_{ti} - x_{oi})^2 \quad (5)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_{ti} - x_{oi})^2} \quad (6)$$

where N denotes the total sample size; x_{ti} , x_{oi} denote the predicted and actual values of the i th data in the data set.

2.6. Quality Indicators

2.6.1. Color

The CR-410 colorimeter was used to determine the color difference ΔE of MC under different microwave drying conditions. The smaller the chromatism ΔE , the better the quality of dried MC products. The calculation formula is as follows [20]:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (7)$$

$$H^0 = \tan^{-1} \left(\frac{b^*}{a^*} \right) \quad (8)$$

$$Chroma = \sqrt{a^{*2} + b^{*2}} \quad (9)$$

where L^* , a^* , and b^* represent the color value of the dried product and L_0 , a_0 , and b_0 represent the color value, red-green value, and yellow-blue value of the fresh sample of MC.

2.6.2. Microstructure Analysis

Using scanning electron microscopy, the microstructure of dried MC was examined. The material was thinly sliced into 3×3 mm pieces and immediately submerged in a 2.5% glutaraldehyde solution for fixing, which stabilized the structure of the biological system. After 12 h, gold was sprayed and examined with a 5.0 KV accelerating voltage using a SEM (magnification of $\times 300$, S-4800N, Hitachi Corporation, Osaka, Japan).

2.6.3. Preparation of Sample Extracts

After passing through an 80-mesh sieve pore diameter and weighing 1.0 g, MC powder was added to a 25 mL solution of 80% anhydrous ethanol in a plugged conical flask. To determine total phenols, total flavonoids, polysaccharides, and antioxidant activity, the

mixture was centrifuged for 10 min (rotational speed: 5000 r/min) after it had been rotating oscillatingly for 48 h in the dark at 25 °C and 150 rpm. The supernatant was then extracted and diluted to 25 mL.

2.6.4. Polysaccharides Content

The sulfuric acid–phenol technique was used to ascertain the polysaccharide content of MC [21], calculated as

$$P_c = \frac{V_1 C_3}{V_t M} \quad (10)$$

where P_c stands for the polysaccharide content of the sample, C_3 for the mass concentration of sucrose, mg/mL, V_t for the aspirated sample volume, mL, and M for the weight of the dried MC sample, g.

2.6.5. Total Phenolic Content

We used the Foline–phenol reagent method [21] to measure the total phenol content of MC, calculated as

$$TPC = \frac{V_1 C_1}{V_f M} \quad (11)$$

where TPC stands for total phenol content, C_1 for gallic acid concentration, mg/mL, V_1 for extract volume, mL, V_f for aspirated sample volume, mL, and M for the weight of the dried MC sample, g.

2.6.6. Total Flavonoid Content

The total flavonoid content of MC was determined using the NaNO_2 – $\text{Al}(\text{NO}_2)_3$ – NaOH method [22] and calibrated with catechin as the standard, calculated as

$$TFC = \frac{V_1 C_2}{V_h M} \quad (12)$$

where TFC stands for total flavonoid content of the sample, V_1 for extract volume, mL, C_2 represents the concentration of catechin, mg/mL, V_h represents the volume of aspirated material, mL, and M the weight of the dried MC sample, g.

2.6.7. Antioxidant Activity DPPH

The DPPH technique [22] was used to determine the antioxidant capacity of MC, calculated as

$$\text{Antioxidant capacity} = \frac{A_c - A_d}{A_c} \quad (13)$$

where A_d is the absorbance value of the dried specimen liquor and A_c is the absorbance value of the reference substance.

2.6.8. Determination of Effective Constituent

Reference substance preparation involved precisely weighing 3 mg of gallic acid, paeoniflorin, benzoylpaeoniflorin, and paeonol using an electronic balance to create a reference material with a mass concentration of 1 mg/mL [16]. Then, the reference material was diluted, and the linear relationship was examined at various concentrations and gradients.

Sample preparation involved filtering MC powder through an 80-grit sieve, accurately weighing 0.5 g, and sonicating the mixture for 30 min at 200 W and 40 kHz in a 25 mL 80% anhydrous ethanol stoppered triangle flask. Following cooling, 25 mL of anhydrous ethanol was added at a constant volume. Before injection analysis, the mixture was centrifuged for 10 min, and the supernatant was filtered through a 0.22 µm filter membrane [21].

The chromatographic column used was Agilent-1126-II (4.6 × 250 mm, 5 µm); the mobile phase consisted of acetonitrile (B) and −0.01% phosphoric acid (D); the gradient elution was as follows: 0–5 min (10–20% B), 5–10 min (20–35% B), 10–15 min (35–60% B),

15–20 min (60–45% B), 20–24 min (45–10% B); the flow rate was 1.0 mL/min, the column temperature was 30 °C, the sample volume was 2 µL, and the detection wavelength was 234 nm.

3. Results

3.1. Drying Characteristics

When the vacuum reached −65 kPa and the rotation speed was set at 35 Hz, the drying characteristics of MC at different drying temperatures are shown in Figure 3a,b. During the initial drying phase, the majority of moisture within the material existed as free water, facilitating microwave penetration. As moisture content decreased, the drying rate diminished accordingly. Similar outcomes were observed in studies of stevia [11] and *Angelica sinensis* [14] after microwave vacuum treatment. This phenomenon can be attributed to the considerably lower attenuation coefficient of liquid media for microwave propagation compared to solid media [23]. When the microwave drying temperatures were 40 °C, 45 °C, and 50 °C, the durations required for the moisture content of MC to decrease below the safe moisture level were 40 min, 32 min, and 20 min; the drying times at 45 °C and 50 °C were 20% and 50% shorter than that at 40 °C. This phenomenon occurs due to the ease of water molecules to vaporize under vacuum conditions. Elevating the temperature enables water molecules to have more internal energy, accelerates evaporation, and reduces the amount of time needed to dry to a suitable moisture content. However, higher microwave power levels result in greater absorption of microwave energy by the material, leading to the disruption of intermolecular chemical bonds of bound water. This transformation of bound water into free water enhances heat and mass transfer efficiency. Yet, excessively high temperatures can induce browning, significantly compromising the quality of the dried products. Hence, it is essential to ensure that the drying temperature remains within an optimal range.

When the drying temperature was 45 °C and the rotation speed was 35 Hz, the drying characteristics of MC under different vacuum degrees are shown in Figure 3c,d. The vacuum levels were −60 kPa, −65 kPa, and −70 kPa, with the time needed for the water content rate of MC to reach the safe moisture level of 13% recorded at 44 min, 32 min, and 32 min, respectively. This may be attributed to the gradual rise in the internal temperature and humidity pressure gradient of the material with increasing vacuum levels, facilitating the continuous outward diffusion of water molecules. Additionally, the heightened overall pressure difference between the inside and outside of the material accelerates the vaporization rate of water on the surface, thereby expediting the drying process [24]. However, minimal variations were observed in the drying rate and moisture content curves of the material under different vacuum levels, suggesting that the vacuum degree had a limited influence on the drying characteristics of the material during microwave-vacuum drying.

At a vacuum level of −65 kPa and a drying temperature of 45 °C, the drying characteristics of MC at different rotor speeds is illustrated in Figure 3e,f. The rotation speeds of the rotary wheel were 20 Hz, 35 Hz, and 50 Hz, and the times for the moisture content of MC to drop under the secure moisture content were 36 min, 32 min and 28 min, respectively. The drying times of 35 Hz and 50 Hz were reduced by 11% and 22% compared with 20 Hz. The increased rotation speed of the rotary wheel allowed the sample to pass through the microwave source more frequently per unit time, enhancing sample uniformity. Additionally, the material absorbed more microwave energy at higher rotation speeds, leading to accelerated drying rates and reduced energy consumption.

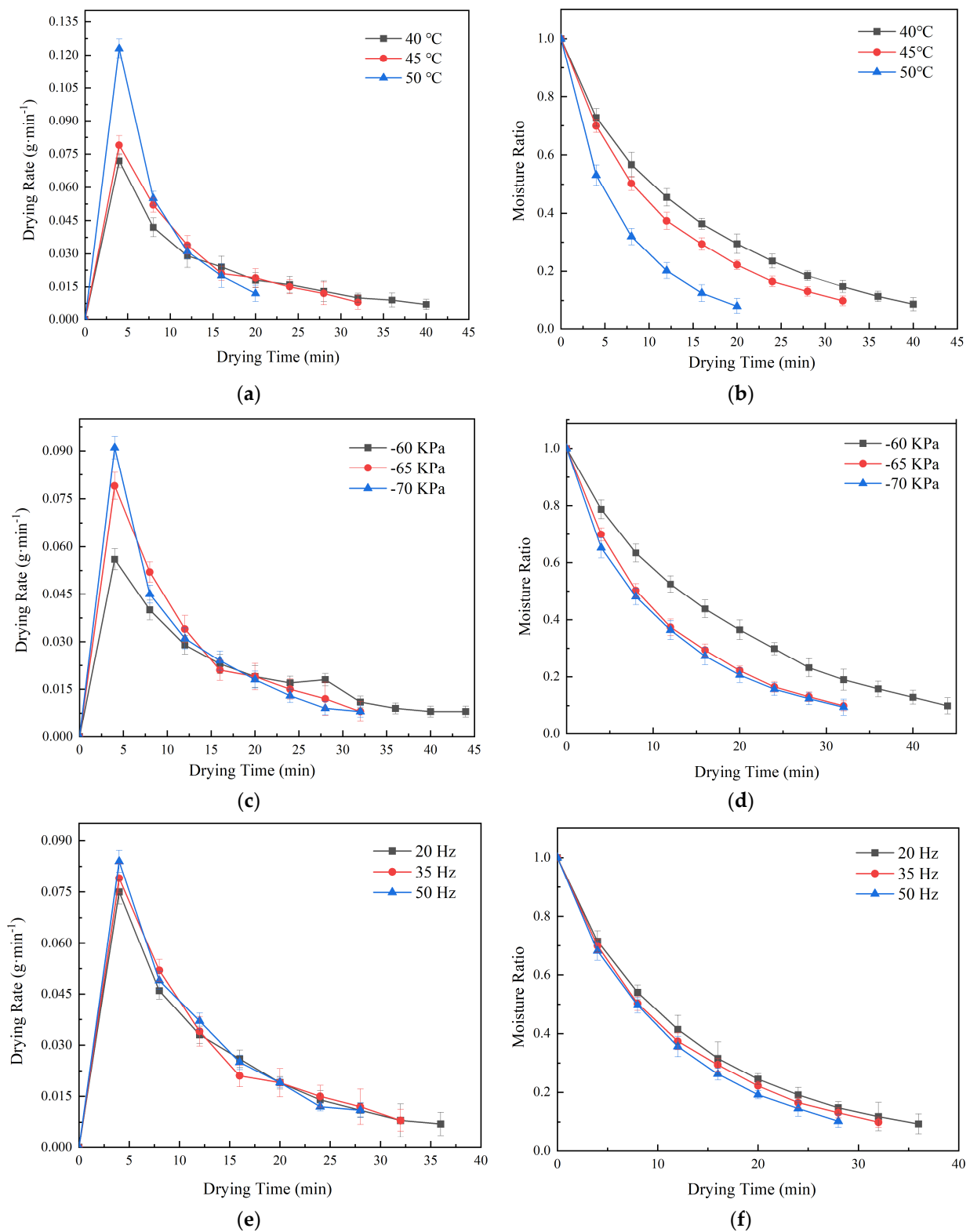


Figure 3. The MC's drying rate curve (a) and moisture ratio curve (b) at various temperatures (-65 kPa, 35 Hz), as well as its drying rate curve (c) and moisture ratio curve (d) at various vacuum levels 45 °C, 35 Hz), and its drying rate curve (e) and moisture ratio curve (f) at various revolution speeds (45 °C, -65 kPa).

3.2. Moisture Content Prediction Based on NGO-BP Model

Based on the experimental data from the microwave drying of MC, the NGO-BP neural network model of water ratio in the microwave drying process was trained and tested. Figure 4a demonstrates the stability of the prediction model after 10 iterations of training. After verification, the BP neural network model has the best verification performance in the fourth representative, and the MSE is 0.18525. The fitness curve illustrates the efficiency and capability of the NGO-BP neural network, as depicted in Figure 4b, showcasing rapid convergence and high accuracy after approximately 40 evolutions. The mean absolute error (MAE) was utilized as a criterion for evaluating the prediction results of the model [25], and the optimized MAE prediction values of the BP neural network and NGO-BP neural network were 0.01393 and 0.01346, which indicated that the NGO-BP neural network model could obtain a better prediction of the water ratio. The predicted and experimental values for the test dataset are shown in Figure 4c, where the experimental values and the moisture ratios predicted by NGO-BP are in good agreement and the model is well fitted. The prediction error is shown in Figure 4d, and the prediction error of NGO-BP neural network is more gentle and relatively stable. Consequently, the model based on the NGO-BP neural network proved to be effective in forecasting the changes in moisture content during the microwave drying process of MC.

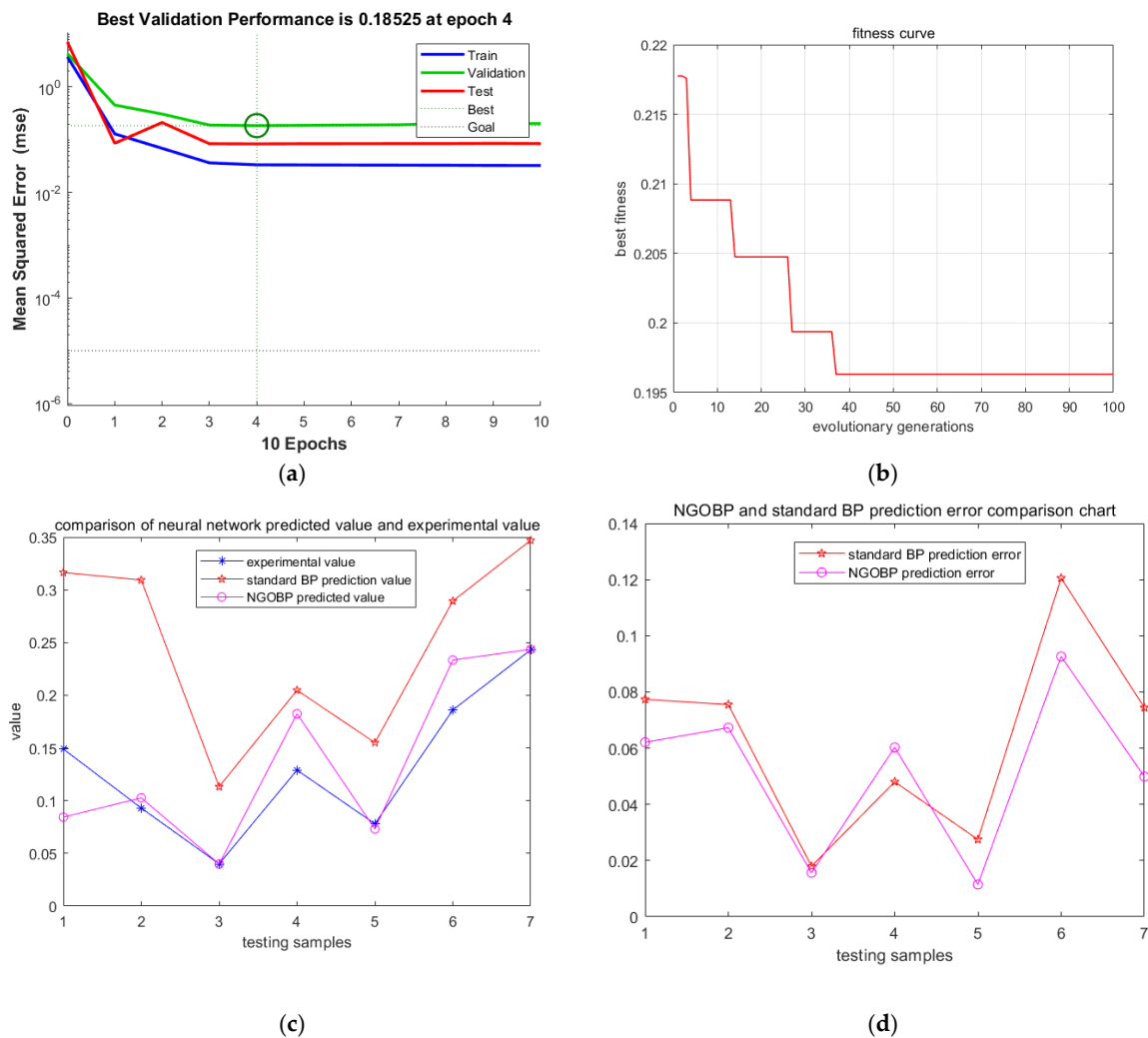


Figure 4. Prediction results of SSA-optimized BP neural network model: (a) mean square error curve; (b) fitness curve; (c) comparison of predicted and experimental values; (d) error. BP, back-propagation; NGO.

3.3. Influence of Quality

3.3.1. Effect on Polysaccharide Content

The effects of different microwave vacuum drying conditions on the polysaccharide content of MC are shown in Figure 5a. We observed a gradual increase in polysaccharide content with rising drying temperature, vacuum, and rotor speed. Specifically, when the vacuum was -65 kPa, the rotation speed was 50 Hz, and the temperature was 45 °C, the polysaccharide content peaked at 681.37 mg/g. Analyzing the influence of different temperatures on the polysaccharide content revealed a positive correlation with temperature increments. This enhancement could be attributed to the increase of temperature, leading the cellulose in the materials to further degrade into soluble polysaccharides and fibrous oligosaccharides [26]. The polysaccharide content gradually increases due to the easier extraction and obtainment of the polysaccharide produced through cellulose degradation. With the increase of rotor speed, the polysaccharide content exhibited an ascending tendency. This phenomenon can be explained by the fact that the lower the rotational speed, the slower the speed of the MC approaching the microwave source during the drying process, and the enzymatic and non-enzymatic browning reactions were accelerated, leading to a decline in the polysaccharide content of the dried product [27]. Conversely, at higher rotor speeds, the material passes through the microwave source more frequently per unit time, absorbing more microwave energy. This elevated energy absorption stimulates the breakdown of carbohydrates within the material, leading to the generation of a multitude of chemical compounds such as cellulose are produced, and thus increasing the polysaccharide content [28].

3.3.2. Effect on Total Phenolic Content (TPC)

The variation in total phenolic content in dried MC products is shown in Figure 5b, showing that the difference between the total phenol values obtained by different rotational speeds is not significant. Conversely, a more pronounced relationship was observed between the vacuum level, temperature, and the total phenolic content. At a vacuum level of -65 kPa, rotational speed of 50 Hz, and temperature of 50 °C, the total phenol content reached the highest value of 451.33 mg/g. By observing the variation of total phenolic content, it was found that an appropriate increase in temperature was beneficial to the retention of polyphenols in the sample [29]. This beneficial effect could be attributed to the high temperature environment's effect on the non-extractable phenolic components [30]. Phenolic compounds related to polymer polyphenols and macromolecules can be depolymerized or dissociated into free polyphenols with increasing temperatures, thereby increasing the content of polyphenols [31], aligning with the outcomes of a raspberry study conducted by Wu et al. [32]. As the vacuum degree grows, the tendency in total phenol content declined. The vacuum degree was -70 kPa, and the content had the lowest value (370.65 mg/g). This may be due to the breakdown of the tissue structure with increasing vacuum levels, which leads to the release of a significant amount of phenolic compounds. These compounds are then degraded by phenol oxidase, consequently inhibiting the polyphenol content [33].

3.3.3. Influence on Total Flavonoid Content (TFC)

Flavonoids are a class of substances whose basic parent nucleus is 2-phenylchromenone, which has a variety of effects such as antioxidant, free radical scavenging, resisting inflammation and antibiosis. The change of total flavonoids content in dried MC is shown in Figure 5c. It can be observed that, as the temperature rises, the content of total flavonoids increases at first, then reduces. This may be because flavonoids can be divided into flavonoids and flavonoid glycosides, according to the presence or absence of linked glycosyl groups [34]. At low drying temperatures, the enzyme activity is inhibited, leading to a reduction in the hydrolysis of flavonoid glycosides. As the temperature rises, the enzyme activity is also enhanced, facilitating the hydrolysis of flavonoid glycosides and thereby increasing the flavonoid content. However, at high temperatures, there is a risk of hydrolysis, oxidation, and degradation of flavonoids, resulting in a decrease in their

content [35]. With the increase of vacuum degree, their content trend is on the rise. Specifically, when the vacuum reaches -70 kPa, the total flavonoid content has a maximum value of 1.08 mg/g. The rise in total flavonoid content may be attributed to the escalation in vacuum levels during the drying process, leading to the intensified extrusion of the material structure and heightened damage, consequently releasing more flavonoids and resulting in increased content. As the rotational speed increases, there is a downward trend in the total flavonoid content. This decline may be attributed to the greater number of times the material passes through the microwave source at higher speeds, leading to increased damage from electromagnetic waves to the internal tissue structure of the sample. Consequently, the reduction of internal polar molecules exacerbates the damage and degradation of flavonoids. This suggests that an increase in rotational speed is not conducive to the preservation of flavonoids.

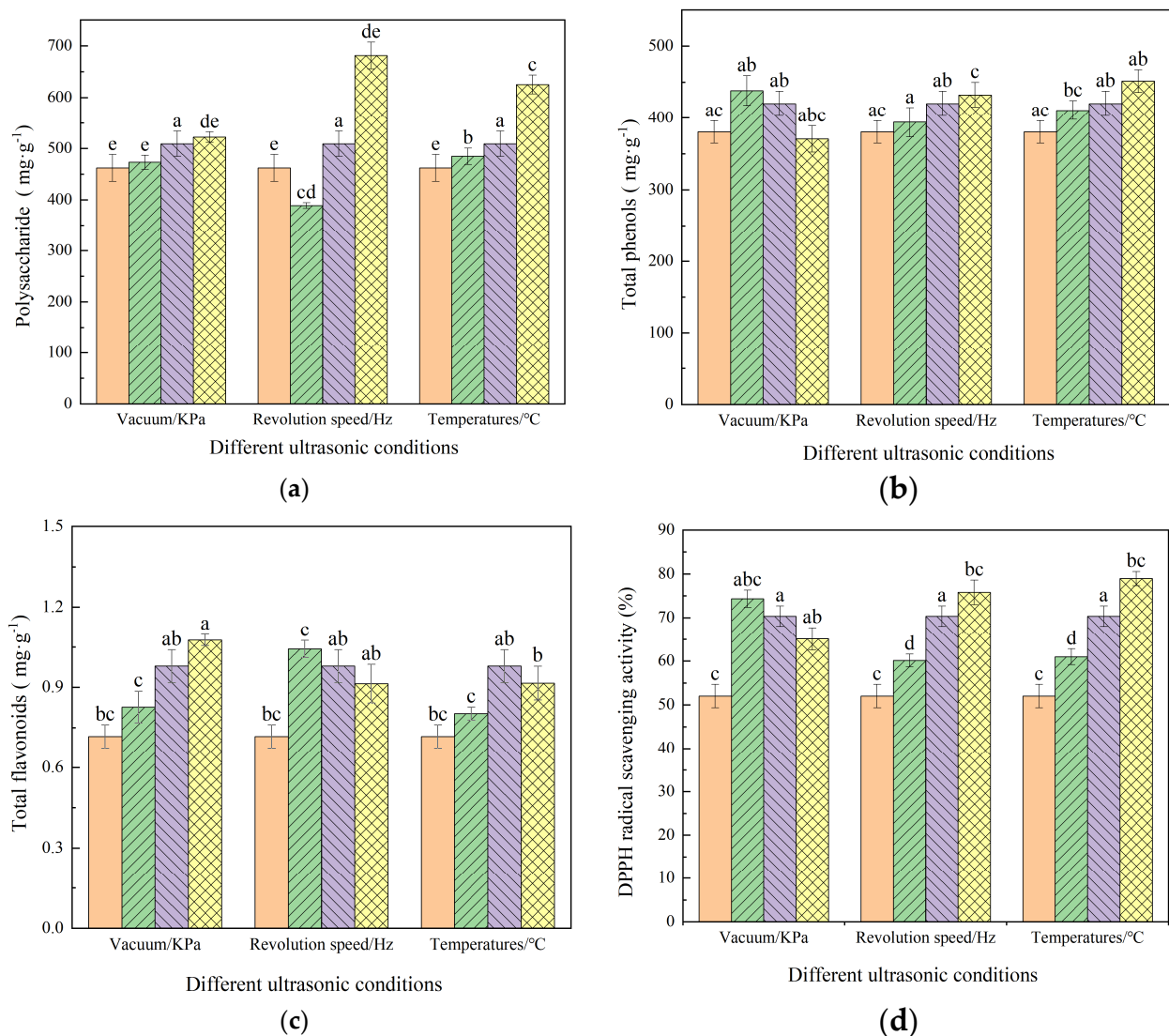


Figure 5. The effects of different microwave vacuum conditions on (a) polysaccharide content; (b) total flavonoids content; (c) total phenolic content; and (d) DPPH radical scavenging activity. Different drying conditions: natural drying (orange), -60 kPa (green), -65 kPa (purple), -70 kPa (yellow); natural drying (orange), 20 Hz (green), 35 Hz (purple), 50 Hz (yellow); natural drying (orange), 40 °C (green), 45 °C (purple), 50 °C (yellow). The vertical bars indicate the standard deviation from the mean. The letters reveal significant differences ($p < 0.05$) according to the Duncan test.

3.3.4. Effect on Antioxidant Capacity (DPPH)

Antioxidant capacity is commonly expressed as inhibition rates, and the DPPH scavenging capacity can be regarded as an evaluation index of the overall antioxidant property; the larger the scavenging capacity, the stronger the antioxidant property of the material. The ability of antioxidants, such as phenolic compounds, to suppress the oxidation chain reaction by providing hydrogen donors or free radical acceptors is referred to as antioxidant capacity. The variation in the antioxidant properties of MC samples are shown in Figure 5d, revealing higher antioxidant activity in MC post-microwave vacuum drying compared to natural drying. With the increase of rotational speed and temperature, the material's oxidation resistance shows an increasing tendency. The change pattern is roughly the same as that of phenolic substances, indicating that heightened polyphenol content results in more potent antioxidant activity. The supreme radical scavenging rate (78.95%) was observed in the sample dried at 50 °C, while the minimum radical scavenging rate was observed in the sample dried at 45 °C. This may be due to the degradation of antioxidant components caused by a long drying time under low temperature conditions. Gulcin et al. [36] also obtained similar results. Some studies have shown that there is a positive correlation between antioxidant capacity and total phenolic content in various plants, such as raspberry [37], wolfberry [38], and Codonopsis [39].

3.4. Content of Natural Active Ingredients

Paeonol, gallic acid, paeoniflorin, and benzoylpaeoniflorin are the prominent natural active ingredients in MC, known for their antioxidant, hypolipidemic, anti-atherosclerotic, antibacterial, anti-inflammatory properties, their enhancement of immune system regulation, etc. The contents of these main components under varying drying conditions are detailed in Table 2. The results of ANOVA showed that the differences in the contents of effective active substances caused by different drying conditions were significant ($p < 0.05$). In comparison to hot air drying, microwave vacuum drying could shorten the drying time, inhibit the activity of enzymes, reduce the oxidative loss of phenolic substances in Mudanpi, which alleviate the oxidation degree of phenolic compounds, and their effective active substance content was 12.08% higher with microwave vacuum drying than with hot air drying. The paeoniflorin contents corresponding to drying temperatures of 45 and 50 °C, recorded as 3.069 mg/g and 3.065 mg/g, respectively, exhibited respective increases of 14.13% and 13.98% compared to 40 °C (2.689 mg/g). This elevation highlights that the appropriate increase of temperature could inhibit the degradation of salvinorin substances. Because phenolics are a heat-sensitive component with oxidization resistance, the suitable temperature prevents the loss of phenolic compounds because of solute transfer and oxidative degradation during long-term dehydration. Secondly, the vacuum degree had a significant effect ($p < 0.05$) on the natural active components of MC. When the vacuum degree was −65 kPa (temperature 45 °C, the rotor speed 35 Hz), the gallic acid, paeoniflorin, benzoylpaeoniflorin, and paeonol in the sample were 3.196 mg/g, 3.069 mg/g, 0.914 mg/g, and 2.577 mg/g, respectively. Compared with −60 kPa, they were increased by 32.61%, 30.32%, 16.28%, and 8.55%, respectively. The incremental rise in rotational speed from 20 Hz to 50 Hz demonstrated a tendency for the content of gallic acid, paeoniflorin, benzoylpaeoniflorin, and paeonol to increase and then decrease, and their content was the highest at 35 Hz.

This was probably due to the fact that as the rotor speed increases, the frequency of the material passing through the microwave source increases, and the microwave heating time increases, so that the active ingredients inside the material easily oxidize under the action of catalytic enzymes such as polyphenol oxidase, resulting in a decrease in the content of natural active substances in the sample [40].

Table 2. The content of effective components in Cortex Moutan under different vacuum microwave conditions (mg/g).

Drying Conditions	Gallic Acid	Paeoniflorin	Benzoylpaeoniflorin	Paeonol
Natural drying	2.192 ± 0.291 ^{bc}	2.192 ± 0.049 ^{bc}	0.852 ± 0.089 ^{ab}	1.583 ± 0.018 ^c
40 °C–35 Hz–65 KPa	3.051 ± 0.192 ^{ab}	2.689 ± 0.107 ^{ab}	0.846 ± 0.037 ^{ab}	2.468 ± 0.034 ^{ab}
45 °C–35 Hz–65 KPa	3.196 ± 0.098 ^a	3.069 ± 0.095 ^a	0.914 ± 0.077 ^a	2.577 ± 0.019 ^a
50 °C–35 Hz–65 KPa	3.100 ± 0.154 ^{ab}	3.056 ± 0.114 ^a	0.735 ± 0.045 ^b	2.100 ± 0.026 ^b
45 °C–20 Hz–65 KPa	2.554 ± 0.149 ^a	2.616 ± 0.124 ^{ab}	0.809 ± 0.041 ^{ab}	2.531 ± 0.015 ^a
45 °C–50 Hz–65 KPa	2.009 ± 0.079 ^{bc}	3.069 ± 0.139 ^a	0.897 ± 0.038 ^{ab}	2.424 ± 0.033 ^{ab}
45 °C–35 Hz–60 KPa	2.410 ± 0.031 ^a	2.355 ± 0.131 ^b	0.786 ± 0.034 ^b	2.374 ± 0.025 ^b
45 °C–35 Hz–70 Kpa	2.375 ± 0.105 ^a	2.466 ± 0.079 ^b	0.857 ± 0.029 ^{ab}	2.038 ± 0.014 ^{bc}

Note: Data are expressed as means ± standard deviation of triplicate samples. The letters in the same column reveal significant differences ($p < 0.05$) according to the Duncan test.

3.5. Color Difference Analysis

Color intensity is a key parameter for evaluating the quality of Chinese medicinal materials, with ΔE serving as a critical indicator of color changes in dehydrated products. The quality of the dried product improves with minimal browning and a lower ΔE . As outlined in Table 3, ΔE increases with increasing drying temperature. The ΔE corresponding to 45 °C and 50 °C increases by 9.7% and 21.83%, respectively, compared with 40 °C. Higher drying temperatures elevate the likelihood of oxidation reactions, leading to increased browning reactions. When the rotational speed is heightened to 50 Hz, the ΔE value reaches its peak at 12.00 ± 0.39 , while the L^* value decreases to 72.03 ± 0.37 . This is because the higher the rotational speed, the shorter the intermittent ratio of the MC to the microwave source. The Maillard reaction and caramelization reaction are aggravated, and the phenols, glycosides, and other substances are degraded, so that the ΔE value increases and the browning is serious. Furthermore, with an increase in vacuum level and rotor speed, the trend of ΔE exhibits a fluctuation, initially decreasing and then increasing. This shift suggests that the color of the dried MC products is close to that of the fresh samples under the conditions of −65 kPa and 35 Hz. Taken together, the appropriate increase of vacuum degree and rotation speed were beneficial to the color quality and the retention of medicinal components of MC. It was investigated how the microwave drying conditions affected the MC's color. At 45 °C microwave temperature, 35 Hz rotation speed, and 65 kPa vacuum degree, the MC demonstrated an improved ΔE value and superior color quality.

Table 3. Color of MC under different microwave drying conditions.

Different Microwave Drying Conditions	L^*	a^*	b^*	ΔE	H^0	C
Fresh Sample	55.08 ± 1.12 ^c	5.5 ± 0.25 ^a	16.3 ± 0.56 ^a	/	−5.56 ± 0.34 ^a	17.20 ± 0.63 ^a
−65 kPa 40 °C	76.33 ± 1.08 ^a	2.31 ± 0.07 ^c	10.31 ± 0.12 ^c	7.10 ± 1.06 ^c	0.25 ± 0.41 ^c	10.57 ± 0.64 ^{bc}
35 Hz 45 °C	75.46 ± 0.39 ^a	2.42 ± 0.15 ^c	10.49 ± 0.38 ^{bc}	7.79 ± 0.43 ^c	0.40 ± 0.53 ^{bc}	10.77 ± 0.31 ^c
50 °C	74.74 ± 0.57 ^b	2.63 ± 0.16 ^{bc}	10.87 ± 0.38 ^{bc}	8.55 ± 0.57 ^c	0.65 ± 0.39 ^{bc}	11.18 ± 0.59 ^b
−65 kPa 20 Hz	72.49 ± 1.49 ^b	2.21 ± 0.38 ^c	11.10 ± 0.42 ^{abc}	10.19 ± 1.46 ^b	−0.32 ± 0.52 ^{abc}	11.32 ± 0.42 ^{ab}
35 Hz 45 °C	75.46 ± 0.39 ^a	2.42 ± 0.15 ^c	10.49 ± 0.38 ^{bc}	7.79 ± 0.43 ^c	0.40 ± 0.53 ^{bc}	10.77 ± 0.31 ^c
50 Hz	72.03 ± 0.37 ^b	2.45 ± 0.03 ^c	11.46 ± 0.37 ^{bc}	12.00 ± 0.39 ^a	0.03 ± 0.47 ^{abc}	11.72 ± 0.25 ^{bc}
45 °C −60 kPa	73.98 ± 1.22 ^b	2.34 ± 0.15 ^c	10.84 ± 0.32 ^{bc}	10.25 ± 1.21 ^b	0.08 ± 0.37 ^{ab}	11.09 ± 0.77 ^{bc}
35 Hz −65 kPa	75.46 ± 0.39 ^a	2.42 ± 0.15 ^c	10.49 ± 0.38 ^{bc}	7.79 ± 0.43 ^c	0.40 ± 0.53 ^{bc}	10.77 ± 0.31 ^c
−70 kPa	72.12 ± 1.30 ^b	3.00 ± 0.34 ^b	11.55 ± 0.86 ^{bc}	11.97 ± 1.27 ^a	1.17 ± 0.67 ^{abc}	11.93 ± 0.95 ^a

Note: Data are expressed as means ± standard deviation of triplicate samples. The letters in the same column reveal significant differences ($p < 0.05$) according to the Duncan test.

3.6. Microstructural Analysis

The macroscopic properties of materials are intricately linked to their microstructure, with organizational variations during the drying process significantly affecting moisture

diffusion characteristics. Figure 6 shows the microstructure of MC under different drying conditions. Following natural drying, the microstructure of the MC is denser, and the internal microporous channels have collapsed and ruptured. This may be because the sample was left to dry for an extended period, causing the surface hardening phenomenon and strong local stress to occur. This phenomenon makes the material moisture diffusion resistance increase, and is, thus, not conducive to the evaporation of water overflow.

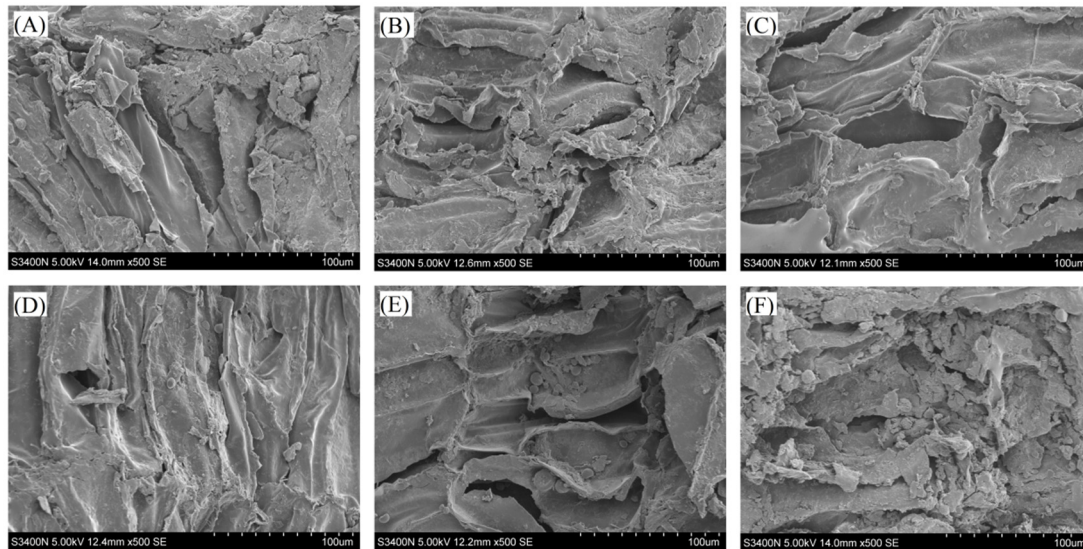


Figure 6. Microstructure of MC under different vacuum microwave drying conditions. (A) Natural drying; (B) 40 °C, 65 kPa, 35 Hz; (C) 45 °C, 65 kPa, 35 Hz; (D) 45 °C, 65 kPa, 50 Hz (E) 45 °C, 60 kPa, 35 Hz; (F) 45 °C, 70 kPa, 35 Hz.

In contrast, following microwave vacuum treatment, an enhanced honeycomb pore structure with an increase in the number of microporous channels and an increase in pore diameter was observed, compared to natural drying. Similar trends were noted by Zang et al. in their study on *Angelica sinensis* slices. With the increase of temperature, it can be seen that some of the tissue structure of the sectioned surface of MC became loose when the drying temperature was 45 °C, and the aperture of the microporous channels became larger and the number of honeycomb pores increased. However, at 50 °C, it was observed that the cells were fragmented, and the sample formed a high-density, disordered, and irregular tissue structure, and the contraction was serious, which may be due to the high temperature caused by the rapid loss of internal moisture and rapid expansion pressure of the sample, and the tissue structure was damaged. This may be due to the rapid loss of internal moisture and the rapid decline in expansion pressure caused by the elevated temperature, the organizational structure was damaged, which conforms with the assay results of drying characteristics. This indicates that raising the temperature suitably can positively facilitate the transfer of moisture within the material. Under −65 kPa vacuum conditions, the sample exhibited enhanced internal structure integrity, orderly pore alignment, signifying that a higher vacuum level contributes to safeguarding microstructure integrity and promoting efficient internal moisture migration, reducing heat and mass transfer resistance.

4. Conclusions

In this study, Moutan Cortex (MC) underwent rotary microwave vacuum drying, and the impacts of different drying temperatures, vacuum, and rotation speeds on the microwave vacuum drying properties and MC quality were investigated. The experimental findings revealed that increasing the drying temperature, the vacuum, and rotational speed led to accelerated drying rates and reduced drying times for MC. This indicates

that microwave vacuum drying helps to improve the heat and mass transfer efficiency during the sample drying process. The NGO-BP neural network model exhibited commendable stability and predictability, indicating that the NGO-BP neural network model holds reference value for predicting the moisture ratio of MC dried by rotary microwave vacuum drying. Compared with natural drying, the contents of effective active components such as paeonol, gallic acid, polysaccharide, total phenol, total flavonoids, and antioxidant activity in MC were significantly increased after microwave vacuum treatment. It is worth noting that the increase of temperature and rotor speed caused the loss of effective active ingredients in dried products to a certain extent, indicating that the combination of appropriate temperature and rotor speed can better improve the nutritional value and sensory quality of the samples. Additionally, after microwave vacuum treatment, the sample exhibited a brighter color, accompanied by the formation of a honeycomb-like pore structure inside the material, promoting structural uniformity and integrity. This study serves as a theoretical foundation for further exploring the intrinsic value of peony bark and optimizing its industrial processing techniques.

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