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Effect of Ultrasonic Pretreatment on Radio Frequency Vacuum Drying Characteristics and Quality of *Codonopsis pilosula* Slices

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Abstract: In this paper, the effects of ultrasonic pretreatment on the drying kinetics, bioactive components (polysaccharides, total phenols, total flavonoids and antioxidant), qualitative characteristics (color index, lobetyolin and syringin) and microstructure of *Codonopsis pilosula* during radio frequency vacuum drying (RFVD) were studied. The average drying rate curve showed that the whole drying process could be divided into three stages: accelerating period, constant drying rate period and falling drying rate period. Deff values ranged from 6.61425 to 9.46745 $\times$ 10^{-8}. Analysis of the drying rate constants revealed that different conditions of pretreatment were effective in increasing the drying rate. Ultrasonic pretreatment has a positive effect on the retention of polysaccharide content; low frequency favors retention of total phenols, flavonoids and syringin; and with the increase in ultrasonic time and ultrasonic power, the antioxidant capacity was higher than that without ultrasonic treatment. Ultrasonic pretreatment significantly improved color and microstructure. In summary, the pretreatment condition of ultrasonic frequency 20 kHz and power 60 W for 30 min is suitable, which provides a certain reference for the application of ultrasonic pretreatment technology in RFVD of *Codonopsis pilosula* slices.

Keywords: *Codonopsis pilosula*; radio frequency; ultrasonic pretreatment; drying kinetics; quality

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1. Introduction

Radix Codonopsis is the dried root of *Codonopsis pilosula* (Franch.) Nannf, *Codonopsis pilosula* Nannf. var. modesta (Nannf.), L.T. Shen or Codonopsis tangshen Oliv [1]. It is one of the herbal resources with greatest development value and is also a raw material for health food [2]. It is rich in *Codonopsis pilosula* polysaccharides, *Codonopsis pilosula* saponins, trace alkaloids and trace elements such as amino acids, which are indispensable to the human body, given their multiple functions such as protecting nerves, regulating blood glucose and enhancing immunity. *Codonopsis pilosula* has attracted increasing attention [3,4]. Fresh after harvesting, *Codonopsis pilosula* contains a large amount of moisture, which will cause mildew, insects and browning during storage, thus affecting the overall quality of *Codonopsis pilosula* [5]. Whether from an environmental point of view or economic point of view, post-harvest losses are a major problem. Dehydration not only effectively reduces water and enzyme activity and inhibits the growth of microorganisms, but also reduces transportation and storage costs [6].

The traditional drying method of *Codonopsis pilosula* is mostly sun-drying, which results in the loss of medicinal components and uncontrollable hygiene conditions over a long period of time [7]. In recent years, many scholars have gradually applied modern drying technology to the original processing of *Codonopsis pilosula*. Related studies have found that the application of microwave technology to the drying of *Codonopsis* shortened the drying process while increasing the content of polysaccharides, but local overheating caused the degradation of thermosensitive component syringin [8]. The active substance content of Codonopsis samples dried by hot air is stable at low temperature. Too high a

temperature will cause loss, however, and the hot air-drying process temperature is difficult to accurately control [9]. Infrared drying has a positive effect on the retention of Lobetyolin, Atractylenolide III and Syringin in dried Codonopsis products, but the energy consumption is relatively large [10]. Therefore, more suitable drying methods need to be explored to improve the quality of dried Codonopsis products.

Radio frequency (RF) drying involves heating dielectric materials with electromagnetic waves between 1 MHz and 300 MHz. Ion conduction and dipole rotation can occur inside the materials. The bulk materials can be quickly and effectively heated to the target temperature in an alternating electromagnetic field [11]. Compared with the traditional heating method, the energy in RF heating can penetrate into the interior of the material, which gives rise to a volume heating effect and can significantly reduce the quality damage caused by uneven heating inside and outside the material in the traditional drying process. It has a greater penetration depth than infrared heating or microwave heating. Compared with microwave heating, it also has a simpler and more uniform field pattern [12]. Research has shown that the use of RF in the thermal processing of hazelnuts is more conducive to achieving a more efficient drying process and retaining more of the active ingredients of hazelnuts compared to hot air drying [13]. Xu et al. found that the microstructure of Wolfberry was more regular due to the special heating characteristics of RF vacuum mediums [14]. When applied to the drying of food crops such as soybeans [15], corn [16], and rice [17], seed moisture can be quickly dried to ensure stable storage and that pests can be effectively controlled.

In order to improve the quality of dried products after drying, the materials usually need to be pretreated before the drying process, so as to achieve the purpose of enzyme inactivation, color protection, energy consumption reduction and product quality enhancement. Acting as a kind of mechanical wave, ultrasound can change the microstructure and processing characteristics of food through the mechanical effect, cavitation effect and thermal effect produced by the interaction with the medium, thus effectively preserving the physical and sensory characteristics of the final product. Therefore it has been widely used as a pretreatment method in the field of food processing [18]. It was found that the application of ultrasound to the convection drying process of apples reduced the loss of total polyphenol and flavonoid content [19]. Ultrasonic pretreatment of sweet potatoes before hot air drying has a significant indigenous effect on their phytochemical properties and microstructure, and low-temperature ultrasonic pretreatment preserves the biological activity and quality of dried sweet potatoes [20]. By investigating the effect of combined ultrasound and microwave vacuum drying on the drying characteristics and physicochemical properties of Tremella fuciformis, it was found that the application of ultrasound was beneficial in accelerating the drying process. With the increase in acoustic energy density, the drying time was shortened, and the cavitation effect and mechanical effect were enhanced [21]. The study of low frequency ultrasound pretreatment of carrot mid-wave infrared radiation drying process revealed that low frequency ultrasound can improve the drying rate of carrot slices, and maintain their color [22].

Ultrasonic pretreatment has been applied to the drying process of a variety of materials, but research on its effect on Codonopsis has not been reported. In this study, ultrasound was used to pretreat *Codonopsis pilosula* before RFVD. The effects of ultrasonic treatment time, ultrasonic power and ultrasonic frequency on water migration in *Codonopsis pilosula* slices were discussed. The effects of pretreatment on the microstructure of dried *Codonopsis pilosula* slices were observed and analyzed by scanning electron microscopy. The influence of ultrasonic pretreatment on the drying process was investigated in combination with the changes of RFVD characteristics, quality index components and active ingredient content after pretreatment, which provided some theoretical support for the production and processing of *Codonopsis pilosula*.

2. Materials and Methods

2.1. Test Materials

Fresh *Codonopsis pilosula* used in this experiment was procured from Min County Guiqi Ginseng Growers Cooperative (Dingxi, China). The average moisture content of fresh *Codonopsis pilosula* determined by the AOAC official method at 105 °C for 24 h was 72.5% [23].

2.2. Test Equipment

The high-frequency vacuum medium heating test device used in this experiment was developed by Hebei Huashi Jiyuan High-frequency Equipment Co., Ltd. (Langfang, China). The structural schematic diagram is shown in Figure 1. The equipment mainly includes a control system, RF heating system and vacuum system. The high frequency oscillation power is 3 KW, the rated power is 27.12 MHz, and the adjustable range of upper and lower plates (600 mm × 400 mm) is 20 mm ~ 300 mm to provide RF energy for specific applications. Parameters such as pole plate spacing and vacuum level are entered on the control panel, and the pole plate spacing is adjusted by the lifting system while the air pressure value in the vacuum chamber is regulated by the solid-state relay of the vacuum pump. The temperature, weight and vacuum of the material are measured by fiber optic temperature sensors, load cells and pressure sensors respectively and sent to the control panel in real time.

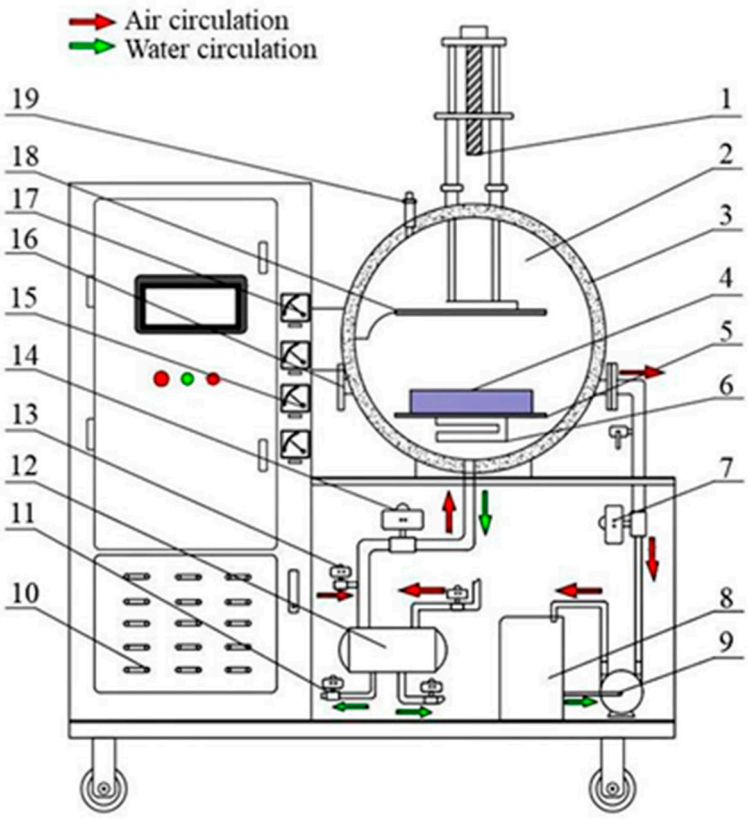


Figure 1. Schematic diagram of RF vacuum drying equipment structure: 1. ball screws; 2. vacuum vessel; 3. view port; 4. sample; 5. bottom electrode; 6. load cell; 7. vacuum valve; 8. cooling box; 9. vacuum pump; 10. ventlight; 11. drain valve; 12. water tank; 13. air inlet valve; 14. isolating valve; 15. ammeter; 16. fiber optic sensors; 17. volt meter; 18. top electrode; 19. pressure sensor.

2.3. Test Method

Considering the sensory characteristics of Codonopsis including freshness, coarseness and uniformity, color, mechanical damage and disease symptoms, the Codonopsis material used in this study was first screened. On the basis of preliminary experiments, a drying

temperature of 55 °C, slice thickness of 4 mm, plate spacing of 90 mm, and vacuum of 0.025 MPa were selected. Before drying, the equipment was adjusted to the preset temperature for preheating, and the samples were cleaned with tap water. The ultrasonic time (20 min, 30 min, 40 min), ultrasonic power (40 W, 60 W, 80 W) and ultrasonic frequency (20 kHz, 40 kHz, 60 kHz) were selected as the experimental variables. After pretreatment, the water was absorbed by the absorbent paper. In order to keep the thickness of each sample uniform, the slicer was used to slice the fresh sample, and then the vernier caliper was used to accurately measure the thickness. The allowable error range was 4 ± 0.05 mm. Fresh Codonopsis slices (300 ± 0.5 g) were evenly spread on the material plate and put into the drying equipment cavity. During the drying process, samples were weighed every 20 min. The moisture content of Codonopsis slices at sampling time was calculated according to the mass loss, and the test was stopped when the safe moisture content was below 10% [1]. The process involved in this experiment is shown in Figure 2.

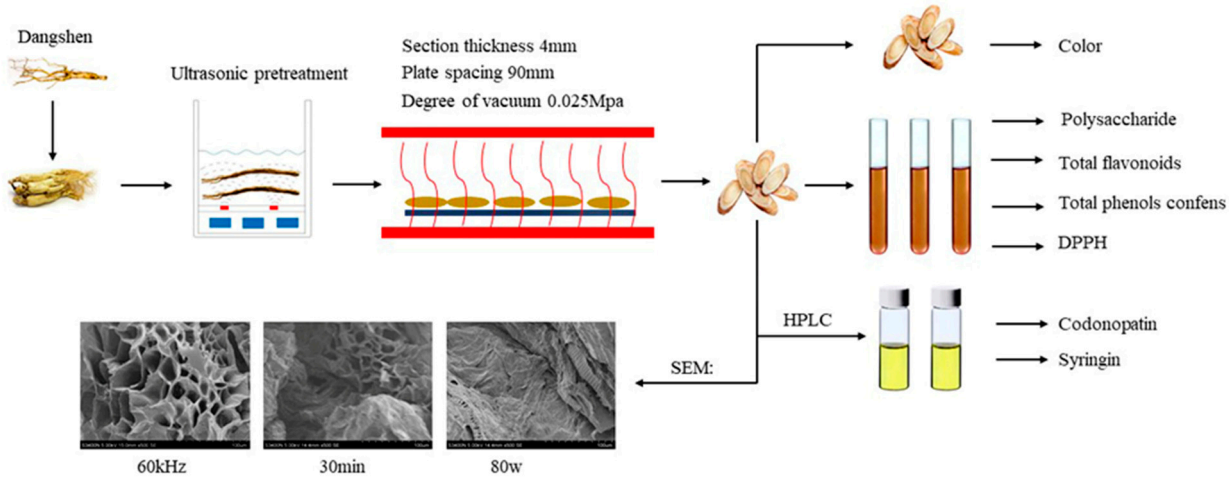


Figure 2. Diagram of RF vacuum drying and quality inspection of Codonopsis Radix under different ultrasonic pretreatment conditions.

2.4. Determination of Test Indicators

2.4.1. Dry Base Moisture Content Determination

This is given by:

$$X = \frac{M_t - M_d}{M_d} \quad (1)$$

where X represents dry basis moisture content, %; M_t represents the weight of Codonopsis at time t, g; and M_d represents the dry weight of Codonopsis, g.

2.4.2. Determination of Drying Rate

This is given by:

$$DR = \frac{M_{t_2} - M_{t_1}}{t_2 - t_1} \quad (2)$$

where DR represents the drying rate, g/s; M_{t2}, M_{t1} represents the weight of the sliced Codonopsis at the moment of t_2 and t_1, g; and $t_2 - t_1$ represents the time interval between the two weighings, min.

2.4.3. Determination of Moisture Ratio

This is given by:

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (3)$$

where M_t represents the dry basis moisture content of Codonopsis at moment t, %; M_i represents the initial moisture content of Codonopsis, %; and M_e represents the moisture content of Codonopsis dried to equilibrium, %.

Since the equilibrium water content of Codonopsis is small, a simplified formula is chosen here [24]:

$$\mathrm{MR} = \frac{M_t}{M_c} \tag{4}$$

2.4.4. Effective Moisture Diffusion Coefficient

This is given by:

$$ln\mathrm{MR} = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L_0^2}t\right) \tag{5}$$

where MR represents the moisture ratio; D_{eff} represents the effective moisture diffusion coefficient of the material, m^2/s; t represents the drying time, s; and L_0 indicates 1/2 of the thickness of the Codonopsis slices, mm.

2.4.5. Calculation of Drying Rate Constant

In order to better describe the relationship between moisture content and time in the drying process, scholars have summarized many empirical and semi-empirical mathematical models to describe this process through experimental exploration of a large number of agricultural products. These have included an exponential model, single diffusion model and Wibull equation model. In order to compare the drying rate of Codonopsis under different ultrasonic pretreatment conditions, the Page model was used to describe the change of moisture ratio with time in the drying process of apple samples:

$$\mathrm{MR} = exp(-kt^m) \tag{6}$$

where MR represents moisture ratio; t represents time, min; k represents the drying rate constant, $g/g{\cdot}min^{-1}$; and m denotes the dimensionless drying constant.

2.5. Determination of Color

The surface color of Codonopsis slices was measured by precision colorimeter (CS-210, Zhengzhou North-South Equipment Co., Ltd., Zhengzhou, China). The results were expressed as L^*, a^* and b^* values, and the total color difference (ΔE) was calculated according to Formula (7):

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

where ΔE represents the total color difference of the sample; L^*, a^*, b^* represent the brightness value, red-green value and yellow-blue value of fresh Codonopsis, respecitvely; and L_0^*, a_0^* and b_0^* represent the brightness value, red-green value and yellow-blue value of dried products of Codonopsis, respectively.

2.6. Determination of Polysaccharide

2.6.1. Drawing of Standard Curve

This was carried out according to the phenol-sulfuric acid method [25], with sucrose concentration ($mg{\cdot}g^{-1}$) as ordinate X and absorbance as abscissa Y. The standard curve is $Y = 0.00835X - 0.163 (R^2 = 0.99355)$.

2.6.2. Determination of Polysaccharide Content in Codonopsis Slices

The preparation of the extract was based on the research methods of Wan et al. with slight modifications [26]. After 2500 μL was taken, the drug was added according to the method in Section 2.6.1 to determine the absorbance and to calculate the sucrose mass

concentration. The polysaccharide content in Codonopsis Radix samples was calculated according to Equation (8):

$$\text{polysaccharides content} = \frac{V_2 C_1}{V_1 M} \quad (8)$$

where C_1 represents the content of sucrose in the sample determination tube obtained on the standard curve, μg; V_1 represents the volume of sample extract at titration, mL; V_2 represents the total volume of sample extract, mL; and M represents sample quality, g.

2.7. Determination of Total Phenolic Content (TPC)

2.7.1. Drawing of Standard Curves

This was carried out according to the Folin–Ciocalteu reagent method [27]. The mass concentration of gallic acid ($mg \cdot g^{-1}$) was used as ordinate Y, and the absorbance was used as abscissa X. The standard curve is Y = 0.0498X + 0.5051(R^2 = 0.9905).

2.7.2. Determination of TPC in Codonopsis Slices

The preparation of extract was based on the research methods of Wan et al. with slight modifications [26]. Taking a volume of 2500 μL, the drugs were added according to the method in Section 2.7.1, to determine absorbance and to calculate gallic acid concentration. According to Equation (9), the calculation of TPC in Codonopsis was:

$$\text{TPC} = \frac{V_2 C_2}{V_1 M} \quad (9)$$

where C_2 is the content of gallic acid in the sample determination tube obtained on the standard curve, μg; V_1 represents the volume of sample extract used in titration, mL; V_2 represents the total volume of sample extract, mL; and M represents sample quality, g.

2.8. Determination of Total Flavonoid Content (TFC)

2.8.1. Drawing of Standard Curve

This was carried out according to the $NaNO_2$-$Al(NO_2)_3$-NaOH method [28], with catechin concentration ($mg \cdot g^{-1}$) as ordinate X and absorbance as abscissa Y. The standard curve is Y = 0.0053X + 0.037(R^2 = 0.9984).

2.8.2. Determination of TFC in Codonopsis Slices

The preparation of extract based on the research methods of Wan et al. with slight modifications [26]. After absorbing 2500 μL, the drug was added according to the method in Section 2.8.1; the absorbance was measured and the mass concentration of catechin was calculated. Calculation of TFC was according to Equation (10):

$$\text{TFC} = \frac{V_2 C_3}{V_1 M} \quad (10)$$

where C_3 represents the amount of catechin in the sample determination tube found from the standard curve, μg; V_1 represents the volume of sample extract used in titration, mL; V_2 represents the total volume of sample extract, mL; and M represents sample quality, g.

2.9. Determination of Antioxidant Capacity

The preparation of the extract was based on the research methods of Wan et al. with slight modifications [26]. The total antioxidant capacity of the organic active substances was determined by the DPPH method [29], and 70% anhydrous ethanol was used as a blank control while 500 μmol/L 90% ascorbic acid in methanol was used as a positive control.

$$\text{I} = \frac{A_{reference} - A_{sample}}{A_{reference}} \times 100 \quad (11)$$

where A_{sample} is the absorbance value of the sample solution; and $A_{reference}$ is the absorbance value without the sample solution.

2.10. Determination of Active Ingredients

2.10.1. Chromatographic Conditions

Chromatographic column: I Merk RP-C 18 (250 mm × 4.6 mm, 5 μm), mobile phase: acetonitrile (B) −1% acetic acid solution (D), gradient elution program: 0 ~ 4 min (15% ~ 40% B), 4 ~ 8 min (40% ~ 65% B), 8 ~ 10 min (65% ~ 85% B), 10 ~ 12 min (85% ~ 15% B), 12 ~16 min (15% ~ 15% B); flow rate: 1.0 mL/min; column temperature: 25 °C; detection wavelength: 268 nm; injection volume: 10 μL.

2.10.2. Preparation of Reference Substance

An amount (3 mg each) of lobetyolin and syringin were weighed separately, dissolved and diluted with the appropriate amount of methanol to prepare the reference substance with mass concentration of 0.333 mg/mL. The mixed reference stock solutions with concentrations of 0.1332 mg/mL, 0.5328 mg/mL, 0.05328 mg/mL, 0.02131 mg/mL, 0.0085 mg/mL and 0.0034 mg/mL were then prepared by stepwise dilution. The linear relationship of detection mass concentration (C) was investigated by peak area (Y). The regression equation of lobetyolin reference substance was $Y_1 = 1527.7C + 12.027(R^2 = 0.9931)$, and the regression equation of syringin reference substance was $Y_2 = 8271.3C + 75.835(R^2 = 0.9989)$.

2.10.3. Preparation of Test Samples

An amount (1.0 g) of sample powder was weighed in a 50 mL stoppered centrifuge tube, 25 mL of methanol solution was added, sonicated in an ultrasonic cleaner (power: 100 W; frequency: 40 kHz; time: 25 min), and centrifuged after sonication (setting parameters: 4000 r/min, 4 °C) for 10 min. The supernatant was filtered through a 0.22 μm filter membrane and fed into the sample for analysis.

2.11. Microstructure

The dried products obtained under different drying conditions were made into 2 × 2 mm. Sample was oriented for observation, and fixed on the SEM sample table with conductive tape for observation under scanning electron microscope after spraying with gold. The magnification was ×500, and the representative field of vision selected for microscopic photography.

2.12. Data Analysis

Each group of tests was repeated three times and the average value was taken. The obtained data were calculated by Excel for moisture ratio and drying rate. The curve and histogram were drawn by Origin 8.0. SPSS 24.0 was used for analysis of variance (ANOVA). Tukey 's multiple-range test was used to analyze the significance of the mean difference, and the significance level was 0.05.

3. Results and Analysis

3.1. Analysis of Drying Characteristics

When the ultrasonic frequency was 40 kHz and the ultrasonic power was 60 W, the effects of different ultrasonic time on the moisture ratio and drying rate of RFVD of Codonopsis slices are shown in Figure 3a,b. When the ultrasonic time was 20 min, 30 min and 40 min, the effective time required for the drying of Codonopsis slices to below the safe moisture content was 260 min, 220 min and 240 min, respectively. Compared with 20 min and 40 min, the effective drying time in the 30 min experiment was shortened by 15.38% and 8.3%, respectively. This may be due to the fact that during the ultrasonic pretreatment process, heat is generated by the friction between the molecules of the material. With the increase in ultrasonic time, the temperature of the ultrasonic medium increases continuously. The increasing loss factor with the increase in temperature will lead to the

material absorbing more RF energy in the RF field. Longer sonication time decreases the water activity of the Codonopsis samples, which leads to a lower polarization effect of water molecules and increases the time required for the RFVD process of Codonopsis slices. In addition, the possible reason for the increase in drying rate may be that the cavitation phenomenon caused by ultrasonic pretreatment results in the change of microstructure and the decrease in moisture diffusion boundary layer, which leads to the increase in moisture transferred from the internal part of Codonopsis [30].

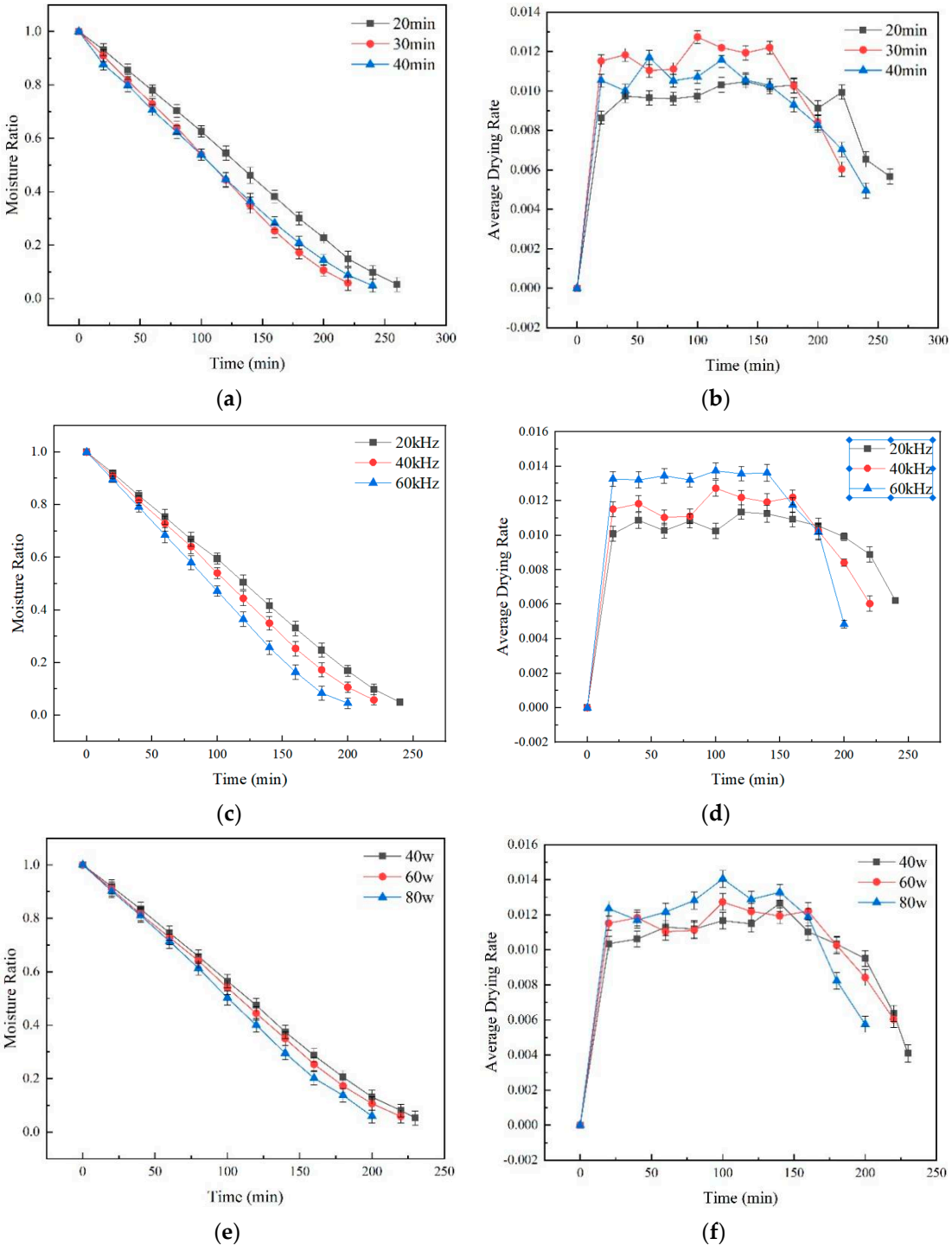


Figure 3. Drying curve (**a**) and drying rate curve (**b**) of Codonopsis pilosula with different ultrasonic time; drying curve (**c**) and drying rate curve (**d**) of Codonopsis pilosula with different ultrasonic frequency; drying curve (**e**) and drying rate curve (**f**) of Codonopsis pilosula with different ultrasonic power.

The effects of different ultrasonic frequencies on the moisture ratio and drying rate of RFVD of Codonopsis slices at ultrasonic time of 30 min and ultrasonic power of 60 W are shown in Figure 3c,d. With the increase in ultrasonic frequency, the time required for drying to below safe moisture content was shorter: 240 min, 220 min and 200 min, respectively. This may be because ultrasound is directly coupled to the material to be dried at high strength. It passes through the solid medium, causing a series of rapid alternating compression and expansion, and then producing strong pressure and shear stress inside the Codonopsis slices. The force involved in this mechanical mechanism may be higher than the surface tension, which maintains the water within the capillaries of the material, resulting in the formation of microchannels that make the removal of water easier and increase the evaporation rate of surface water [31]. In addition, high intensity acoustic waves can cause a cavitation effect on water molecules in the solid matrix, which is beneficial to remove the strongly attached water in *Codonopsis pilosula*. In the drying process, the water diffusion resistance of the material is affected by the acoustic energy, which increases the mass transfer effect and shortens the drying time. Similar results were obtained in apple [32] and pineapple [33].

When the ultrasonic time was 30 min and the ultrasonic frequency was 40 kHz, the effects of different ultrasonic power on the moisture ratio and drying rate of RFVD of Codonopsis slices were measured, as shown in Figure 3e,f. As the power increases, the time required for drying to below the safe water rate is less, 230 min, 220 min and 200 min, respectively. This may be because the ultrasonic intensity of 0.33 (W/mL) at an ultrasonic power of 40 W was not sufficient to have a significant effect on the internal water fluidity of Codonopsis, and its strengthening effect was limited. The higher the power is, the more ultrasonic energy is generated, causing stronger cavitation and mechanical effects. The bubbles near the cell wall surface collapsed asymmetrically, resulting in micro-jets, which increased the medium temperature. This intermittent-form of energy is partly absorbed by the medium and dissipated in the form of heat, leading to an increase in temperature and making the loss factor of the material increase. In addition, high intensity ultrasound can cause continuous damage to the cell membrane of tissue cells. The increased degree of damage accelerates the rate of mass transfer between the cell and the extracellular environment and shortens the drying time. The use of ultrasound has a beneficial effect on the quality of the obtained dry products, both in the drying process of materials and as a preliminary treatment before water removal [34].

By analyzing the average drying rate curves of *Codonopsis pilosula* under different ultrasonic pretreatment conditions, it was found that the whole drying process could be divided into three stages. Stage I is the speed-up period: in this stage, because the material is heated inside and outside at the same time, the moisture is transferred from the inside to the surface where its evaporation occurs, and the surface temperature of the material is lower than the central temperature, which improves the drying rate. Stage II is a constant drying rate period, during which the internal moisture migration rate is approximately equal to the surface moisture evaporation rate, and the process time is relatively long in this experiment. Stage III is the falling drying rate period, during which the moisture in the material mainly exists in the form of bound water from drying duringthe late stage. The dielectric loss factor decreases slowly with the decrease in moisture content, and since the absorbed RF energy is less, the drying rate decreases gradually. Overall, the RF vacuum drying process limits the temperature rise of the sample and reduces severe thermal deterioration of the product quality.

3.2. Effective Moisture Diffusion Coefficient

In order to study the effect on the water migration ability of Codonopsis pilosula, the effective water diffusion coefficient was calculated. After fitting the linear relationship of InMR-t, the effective moisture diffusion coefficient of Codonopsis Radix was calculated according to the slope, as shown in Table 1. It can be seen that the Deff value is between $6.61425 \sim 9.46745 \times 10^{-8}$. The Deff values of this study are consistent with the findings of

Zogzas, where the Deff values of agricultural products are between 10^{-8} and 10^{-12} [35]. With the increase in ultrasonic frequency and power, Deff showed an upward trend, indicating that the increase in frequency and power in the process of ultrasonic pretreatment was helpful in improving the migration ability of water in the Codonopsis pilosula sample during the drying process. This was because the pretreatment produces mechanical, cavitation and thermal effects [36], which could change the medium structure, enhance the liquid turbulence, and reduce the mass transfer resistance in the solid–liquid system, thus effectively promoting the transfer and migration of water.

Table 1. Effect of different ultrasonic conditions on the effective moisture diffusion coefficient and drying rate constants.

Experimental Factor			Drying Rate Constant/g·10^{-4}/g Min^{-1}	Effective Moisture Diffusivity/m^2·Min·10^{-8}
Pretreatment Time/Min	Ultrasound Frequency/kHz	Ultrasound Power/W		
Without ultrasonic treatment			3.43256 ± 0.23 ^{ab}	6.87363 ± 1.12 ^{b}
20	40	60	3.54025 ± 1.34 ^{ab}	6.61425 ± 0.52 ^{b}
30	40	60	4.65612 ± 0.32 ^{ab}	7.78147 ± 0.85 ^{ab}
40	40	60	5.66589 ± 0.14 ^{a}	7.52208 ± 0.24 ^{ab}
30	20	60	3.74271 ± 0.39 ^{ab}	7.26271 ± 0.82 ^{ab}
30	60	60	5.63408 ± 1.34 ^{b}	9.46745 ± 0.32 ^{ab}
30	40	40	3.68494 ± 1.45 ^{a}	7.68416 ± 0.25 ^{b}
30	40	80	4.89157 ± 0.35 ^{ab}	8.23539 ± 0.39 ^{a}

Note: In the same column, the different lowercase letters reveal significant differences ($p < 0.05$).

3.3. Drying Rate Constant

In order to describe the effect of ultrasonic pretreatment on drying rate, the drying rate constants of Codonopsis under different ultrasonic pretreatment conditions were calculated, as shown in Table 1. When the ultrasonic frequency was 40 kHz and the power was 60 W, the longer the ultrasonic time, the greater was the drying rate constant (K = 3.54025 at 20 min; at 30 min, K = 4.65612; at 40 min, K = 5.66589), indicating that as time increases, the overall drying rate of Codonopsis is faster. The increase in ultrasonic power and ultrasonic frequency has a similar trend, similarly showing that the higher the power and frequency, the faster the overall drying rate. Compared with the drying rate constant (3.43256) without ultrasonic pretreatment, it can be found that pretreatment under different conditions can effectively improve the drying rate.

3.4. Analysis of Drying Quality

3.4.1. Color Difference Analysis

Color difference is an important index for evaluating the quality of dried products, and Table 2 shows the values of color difference parameters of dried Codonopsis products under different ultrasonic conditions. Compared with the control group, ultrasonic pretreatment did not significantly affect the L^* and b^* values of the dried Codonopsis sections, indicating that the brightness and yellow-blueness were close to those of the control group. The relatively large fluctuations in a^* values under different pretreatment groups may be due to the fact that changes in a^* can be linked to the formation of colored compounds [37]. Enzymatic and nonenzymatic browning reactions occur during processing. Brown pigments are formed from colorless polyphenols and lead to changes in optical properties [38]. Moreover, color changes are determined by natural non-ferrous compounds that can be oxidized during pretreatment, and the most important factors that accelerate their degradation are elevated temperatures and the presence of oxygen [39]. In the case of maximum power, the parameter of L^* changes most, which may be due to the generation of free radicals and acoustic chemicals caused by cavitation [40]. In the case of RFVD after ultrasonic pretreatment, the change of total chromatic aberration was observed to increase with the increase in ultrasonic

power. However, in all these cases, the values of Δ*E* were lower than for the drying process without ultrasonic pretreatment, although there was no significant variability in the total color difference. Thus, ultrasonic pretreatment can maintain the color of Codonopsis slices after RFVD. This may be because during the treatment process, the tissue is immersed in the medium, and the entry of air is limited, so the color is better preserved.

Table 2. Color Difference of Codonopsis Radix under Different Pretreatment Conditions.

Drying conditions	*L**	*a**	*b**	Δ*E*
Without ultrasonic treatment	71.38 ± 0.73^{a}	1.51 ± 0.76^{ab}	18.81 ± 2.09^{bc}	6.10 ± 2.76^{bcd}
20 min	73.83 ± 1.26^{ab}	1.56 ± 0.38^{bcd}	18.93 ± 0.69^{bc}	5.81 ± 0.99^{bcd}
30 min	73.03 ± 0.45^{a}	1.14 ± 0.82^{abcd}	18.22 ± 0.77^{bc}	3.58 ± 0.47^{cd}
40 min	73.72 ± 8.67^{ab}	1.43 ± 1.47^{abcd}	18.68 ± 2.54^{bc}	5.16 ± 4.35^{abc}
20 kHz	74.31 ± 7.38^{ab}	1.61 ± 1.53^{d}	18.9 ± 0.44^{bc}	5.57 ± 2.34^{ab}
60 kHz	73.95 ± 6.76^{ab}	1.53 ± 1.54^{bcd}	18.84 ± 3.51^{bc}	5.69 ± 3.28^{abcd}
40 W	74.16 ± 7.11^{a}	1.93 ± 0.17^{ab}	19.67 ± 1.16^{b}	5.77 ± 2.26^{bcd}
80 W	75.76 ± 5.33^{a}	1.78 ± 0.96^{a}	18.83 ± 3.25^{bc}	5.96 ± 4.10^{bcd}

Note: In the same column, the different lowercase letters reveal significant differences ($p < 0.05$).

3.4.2. Analysis of Polysaccharides, TPC, TFC and Antioxidant Capacity

The effects of different ultrasonic conditions on polysaccharide content are shown in Figure 4a. It can be seen intuitively that the polysaccharide content decreased with the increase in ultrasonic time, which were 39.567 mg/g, 37.086 mg/g and 35.906 mg/g, respectively. This may be because the temperature becomes higher as the ultrasonic time increases. Under high temperature, Maillard reaction occurred inside *Codonopsis pilosula*, and some products with large and medium molecular weights were generated, thereby degrading the polysaccharide content in *Codonopsis pilosula* slices. The polysaccharide content decreased with increasing frequency. This shows that high frequency is not conducive to the retention of polysaccharide content in the pretreatment process. This may be due to the huge pressure, temperature and shear generated by high intensity ultrasound, which breaks the structure of the polysaccharide (chitosan) side chains, leading to degradation of the polysaccharide into other substances. With the increase in ultrasonic power, the polysaccharide content demonstrated first an increasing then a decreasing trend. This may be due to the fact that as the ultrasonic power increases, there is a stronger mechanical and cavitation effect, which reduces the mass transfer resistance, promotes the diffusion of water, shortens the time required for drying, and reduces the oxidation time of the polysaccharides. However, when the ultrasound power is too high, the high intensity ultrasound generates extreme temperatures and pressures that cause more free radicals to be generated, thus intensifying a series of oxidative reactions that degrade the polysaccharide content [41]. Collectively, the polysaccharide content of *Codonopsis pilosula* after pretreatment was higher than that without ultrasonic treatment (34.074 mg/g). This shows that pretreatment has a positive effect on the retention of polysaccharide content.

The effect of different ultrasonic conditions on total phenol content are shown in Figure 4b. It can be seen from the figure that with the increase in ultrasonic time and power, the TPC first decreased and then increased. The contents were 1.278 mg/g, 1.109 mg/g and 1.278 mg/g at ultrasonic times of 20 min, 30min and 40 min, respectively, which were higher than those without ultrasonic treatment (1.071 mg/g), which increased by 19.37%, 3.6% and 19.40%, respectively. Under different ultrasonic power of 40W, 60W and 80W, the contents were 1.345 mg/g, 1.109 mg/g and 1.249 mg/g, respectively, which were increased by 25.71%, 3.6% and 16.66%, respectively, relative to those without ultrasound treatment. In this study, it was found that ultrasonic pretreatment was conducive to the increase in polysaccharide content in *Codonopsis pilosula* by RFVD, while soluble sugar could induce the accumulation of polyphenols and ultimately maintain the balance of flavanol polyphenolic acid content [42]. The influence of different ultrasonic frequencies on the total phenol

content was analyzed. It was found that with the increase in ultrasonic frequency, the total phenol content decreased from 1.478 mg/g to 0.898 mg/g. Compared with that without ultrasonic treatment (1.071 mg/g), the total phenol content decreased by 16.09% at 60 kHz, which was the lowest parameter under all conditions. This may be because the solution containing enzymes has a higher activity after exposure to ultrasound for a short time [41]. In the drying process, the activation of shikimic acid dehydrogenase can result in shikimic acid being oxidized to dehydroshikimic acid, and further generate gallic acid, which increases the content of phenolic compounds [43]. However, after high-frequency ultrasonic treatment, strong pressure, shear and temperature gradients were generated inside the material; flavanol-like polyphenols were then exposed to thermal conditions to undergo isomerization and autoxidation reactions, leading to their conversion to other substances. Taken together, the retention of TPC was not favored by high ultrasound frequency under different ultrasound conditions [44].

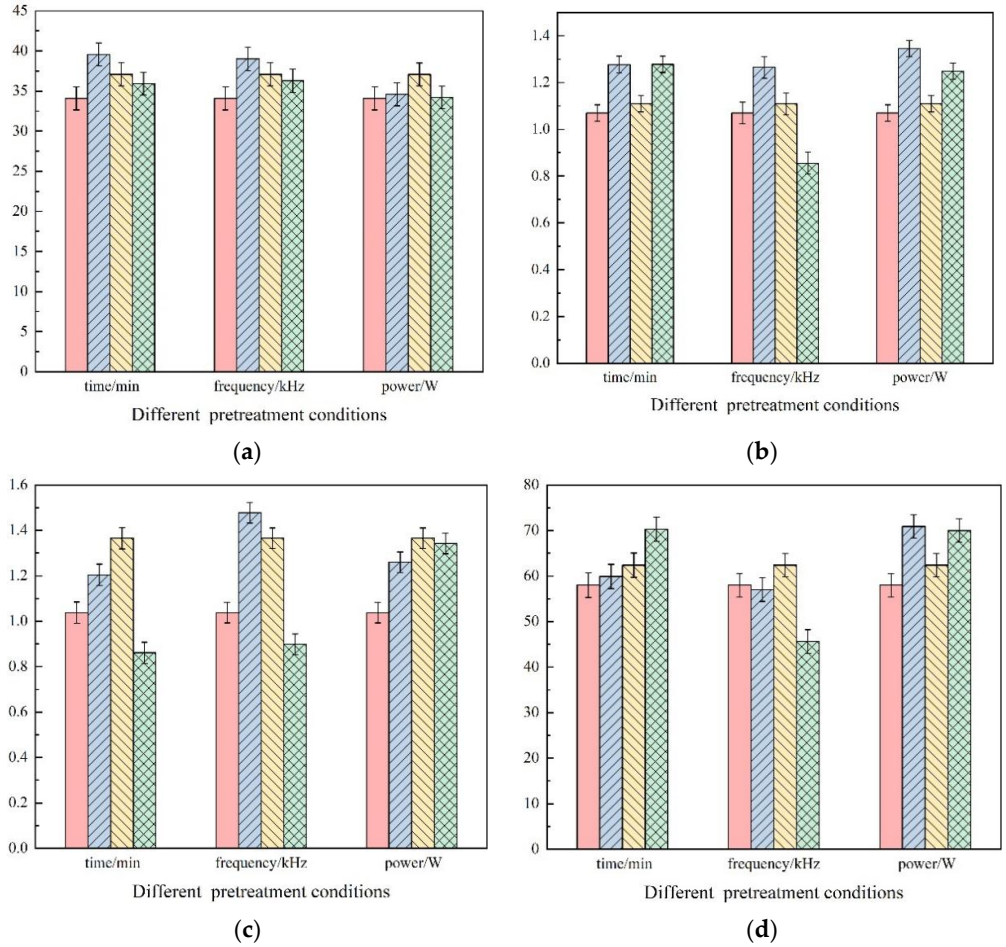


Figure 4. Effects of different ultrasonic conditions on (**a**) polysaccharides, (**b**) total phenols, (**c**) total flavonoids and (**d**) antioxidant capacity. Different drying conditions: radio frequency (▭), 20 min (▨), 30 min (▧), 40 min (▩); radio frequency (▭), 20 kHz (▨), 40 kHz (▧), 60 kHz (▩); radio frequency (▭), 40 W (▨), 60 W (▧), 80 W (▩). Note: The vertical axis of each figure indicates the mean value.

The effects of different sonication conditions on the total flavonoid content are shown in Figure 3c. It can be visualized from the graph that the TFC showed a trend of increasing and then decreasing with the increase in ultrasonic time and ultrasonic power. Under the different ultrasonic times of 20 min, 30min and 40 min, the contents were 1.205 mg/g, 1.365 mg/g and 0.861 mg/g, respectively. Compared with that without ultrasonic treatment (1.038 mg/g), 20 min and 30 min increased by 16.05% and 31.53%, respectively, while 40 min decreased by

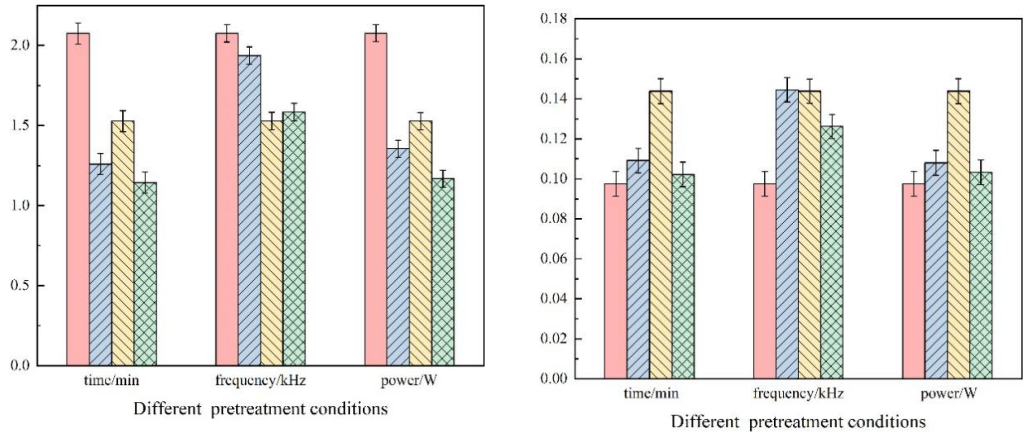
17.05%. This shows that too long an ultrasonic time was not conducive to the synthesis of flavonoids, since ultrasound action itself produces a thermal effect, and high temperature can destroy the structure and activity of related flavonoids synthase, resulting in the inability to synthesize certain flavonoids. Their contents were 1.259 mg/g, 1.365 mg/g and 1.343 mg/g at ultrasound powers of 40W, 60W and 80W, respectively, which were higher than those without ultrasound treatment (1.038 mg/g) by 21.37%, 31.53% and 29.39%, respectively. This may be due to the radio frequency having the ability of both radiation and penetration, which can break the covalent bond between polymers inside the cell, contributing to the release and extraction of flavonoids and other substances. This is in agreement with the results of Li et al. in a study of hawthorn juice [45]. Analysis of the effect of different ultrasound frequencies on the TFC revealed that the content tended to decrease with the increase in ultrasound frequency. The lowest level of 0.8080 mg/g was obtained with the ultrasound frequency of 60 kHz, which was 22.15% less relative to that obtained without ultrasound treatment. This indicates that low frequency was beneficial to the retention of total flavonoids after RFVD under different ultrasonic frequency pretreatment conditions.

The effects of different ultrasonic conditions on antioxidant capacity are shown in Figure 3d. It can be visualized from the figure that with the increase in ultrasonic time and ultrasonic power, the antioxidant capacity of *Codonopsis pilosula* was higher than that without ultrasonic treatment (57.98%). At ultrasonic times of 20 min, 30 min and 40 min, the antioxidant capacity was 59.90%, 62.39% and 70.29%, respectively, which was increased by 3.3%, 7.6% and 21.23%, respectively, compared with those without ultrasonic treatment. Moreover, under the same three different ultrasonic powers, the content of phenolic acids was 70.89%, 62.39% and 69.99%, respectively, which was increased by 22.27%, 7.6% and 20.71%, respectively, compared with that without ultrasonic treatment. This may be because phenolic acids are considered to be antioxidants, because they can not only provide hydrogen or electrons, but also stable free radical intermediates to prevent the oxidation of various components [46]. Dietary polyphenols can actively participate in nonenzymatic browning and contribute to new pigments and antioxidants. In this study, different ultrasonic time and ultrasonic power were beneficial to the retention of TPC, thus improving its antioxidant capacity. In addition, with the decrease in molecular weight, the intramolecular hydrogen bonds changed slightly, resulting in more free hydroxyl radicals and amino groups [47]. At the same mass concentration, lower molecular weight polysaccharides contained relatively more reducing sugars. At different ultrasonic frequencies, the antioxidant capacity was the strongest when the ultrasonic frequency was 40 kHz. This may be due to the fact that at low frequency, the Codonopsis RF vacuum drying process takes longer. Under the action of polyphenol oxidase and peroxidase, the oxidation reaction time was increased, resulting in the aggravation of the oxidation degree. When the frequency was too high, the degradation of antioxidant substances was caused by the ultrasonic and superheating effects.

3.4.3. Analysis of active components

The effects of different ultrasonic conditions on lobetyolin are shown in Figure 5a. It can be visualized from the figure that the content of lobetyolin (2.076 mg/g) under pure RF was higher than that under different ultrasonic conditions, suggesting that the ultrasonic pretreatment was not conducive to the retention of lobetyolin. This phenomenon may be due to the 'sponge effect' produced in the process of ultrasonic application, resulting in rapid compression and expansion of Codonopsis slice cells, forming thousands of rapidly moving microbubbles. The pressure changes result in changes in viscosity and surface tension, and the destruction of cell walls. There is also the formation of micro-channels and free radicals and the production of sonochemical substances. Moreover, the structure of lobetyolin contains alkyne bonds, which are prone to addition and oxidation after a series of reactions, thus reducing the content of lobetyolin. The analysis of the effects of different ultrasonic time on the content of lobetyolin showed that as ultrasonic times increased from 20 min, to 30 min and then 40 min, the content of lobetyolin was 1.259 mg/g, 1.527 mg/g

and 1.144 mg/g, respectively, which decreased by 39.33%, 26.43% and 44.91%, respectively, compared with that under the pure RF condition. This indicated that the content loss of lobetyolin was the smallest when the ultrasonic time was 30 min. Analysis of the effect of different ultrasound frequencies on lobetyolin revealed that the content of lobetyolin was 1.936 mg/g, 1.527 mg/g and 1.583% with increasing frequency (20 kHz, 40 kHz and 60 kHz, respectively), which decreased by 6.73%, 26.43% and 23.75%, respectively, relative to the content under pure RF conditions. This indicated that the content loss of lobetyolin was the smallest under low-frequency ultrasound conditions. The analysis of the effects of different ultrasonic power on lobetyolin showed that with the increase in ultrasonic power, the content of lobetyolin was 1.355 mg/g, 1.527 mg/g and 1.169 mg/g, for 20 kHz, 40 kHz and 60 kHz, respectively, which decreased by 34.71%, 26.43% and 43.70%, respectively, compared with that under the pure RF conditions. In conclusion, during the RFVD of Codonopsis slices, the loss of its lobetyolin content was minimized at an ultrasonic frequency of 20 kHz under different pretreatment conditions, and the greatest loss was observed at an ultrasonic time of 40 min.



(**a**) (**b**)

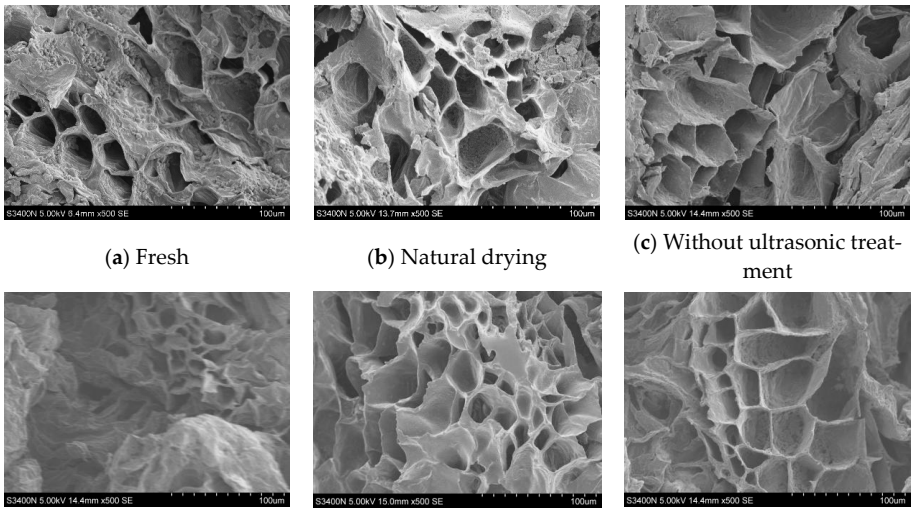
Figure 5. Effect of different ultrasonic conditions on active components: (**a**) lobetyolin, and (**b**) syringin. Different drying conditions: radio frequency (▭), 20 min (▨), 30 min (▨), 40 min (▨); radio frequency (▭), 20 kHz (▨), 40 kHz (▨), 60 kHz (▨); radio frequency (▭), 40 W (▨), 60 W (▨), 80 W (▨). Note: The vertical axis of each figure indicates the mean value.

The effects of different ultrasonic conditions on syringin are shown in Figure 5b. It can be seen from the figure that the content of syringin after ultrasonic treatment was higher than that under pure RF conditions (0.098 mg/g), indicating that ultrasonic treatment was beneficial to the retention of this component. This may be because when the ultrasonic wave is running, it has high frequency and strong sound, and it can destroy the mechanical structure of the material when propagating in the medium. It has a strong vibration and crushing effect, can break the object into small particles and play a solubilizing role. Moreover, the rapid compression and expansion of the internal structure caused by ultrasonic high frequency vibration produces a large number of micro bubbles. Strong kinetic energy and compression energy are produced when bubbles burst instantly. These energies reduce the close combination of water molecules and microtube wall, enhance the fluidity of water, shorten the time required for RFVD, and reduce the loss of the active ingredient. The analysis of the effect of different ultrasonic time on this component showed that with the increase in time (20 min, 30 min and 40 min), the content of syringin was 0.109 mg/g, 0.144 mg/g and 0.102 mg/g, respectively, which increased by 12%, 47.49% and 4.82%, respectively, compared with that without ultrasonic treatment. This indicated that the retention of syringin was the highest when the ultrasonic time was 30 min. By analyzing the effects of different ultrasonic frequencies on this component, it was found that with the increase in frequency (20 kHz, 40 kHz and 60 kHz), the content of syringin was 0.145 mg/g,

0.144 mg/g and 0.126 mg/g, respectively, which increased by 48.2%, 47.49% and 29.44%, respectively, compared with that without ultrasonic treatment. This indicated that the retention of syringin was the highest at 20 kHz. The analysis of the effect of different ultrasonic power on this component showed that with the increase in power (40 W, 60 W and 80 W), the contents of syringin was 0.108 mg/g, 0.144 mg/g and 0.103 mg/g, respectively, which increased by 10.77%, 47.49% and 5.95%, respectively, compared with that without ultrasonic treatment. This indicated that the retention of syringin was the highest at 60 W.

3.5. Microstructure

A scanning electron microscope was used to observe the microstructure of the dried product after natural drying, without ultrasonic treatment and several different pretreatments, as shown in Figure 6. As can be observed from Figure 6a, most of the cells in the fresh Codonopsis slice tissue showed integrity and a uniform size. Comparing Figure 6a to Figure 6c, it is found that the organization of the dried product heated by RF is regularly arranged, and deformation and expansion of fine channels as well as pores appear in some areas. This may be due to the fact that RF is dielectric heating, and RF waves can penetrate the surface of the Codonopsis slices and enter the interior to cause high-frequency oscillation of charged particles, thus achieving the overall heating effect. The high heating efficiency and the same direction of heat and mass transfer are conducive to the maintenance and formation of the sparse and porous morphology of Codonopsis slices during the drying process [48]. In addition, volumetric heating leads to increased internal pressure and faster evaporation at the beginning of drying, resulting in cell swelling during drying [49]. Figure 6d–f revealed that in the case of ultrasonic treatment, the stomata were more pronounced than in the untreated samples. In these ultrasonic treatments, bubble rupture causes cell structure rupture and mechanical damage, resulting in high pressure gradient and local high speed in the liquid layer nearby, leading to shear force breaking the polymer chain and damaging the cavity. Figure 6d shows the samples treated with 40 kHz low ultrasonic frequency. Compared with the dry products treated with 60 kHz (Figure 6e), the shrinkage is greater and the pores are smaller. This may be due to the cavitation effect, where the explosion of microbubbles impinges and damages the tissue, leading to the formation of microchannels in samples dried at a frequency of 60 kHz. By comparing Figure 6e with Figure 6f, it was found that the cells of dry products obtained under high power were distorted, and a large number of cells were damaged or fused to form a large space. The greatest changes in cell structure occurred during high temperature treatment. This may be because ultrasonic pretreatment expands the space between cells by repeatedly stretching and shrinking the material.



(**a**) Fresh (**b**) Natural drying (**c**) Without ultrasonic treatment

(**d**) 30 min 40 kHz 60W (**e**) 60 kHz 30 min 60 W (**f**) 80 W 30 min 40 kHz

Figure 6. Microstructure of Codonopsis Radix under different drying methods.

4. Conclusions

In this study, ultrasonic pretreatment was used for RF drying of *Codonopsis pilosula*, and the effects of different pretreatment conditions on drying kinetics, quality characteristics and microstructure were investigated.

The results showed that ultrasonic pretreatment had significant effects on the physicochemical properties and microstructure of the slices of *Codonopsis pilosula*. Under different ultrasonic time, when the ultrasonic frequency was 40 kHz and the power was 60 W for 30 min, the time needed for the sample to dry to the safe moisture content was the least. By observing the drying rate curve, it was concluded that the whole drying process could be divided into three periods: accelerating period, constant drying rate period and falling drying rate period. This is consistent with the results of Zhou et al. using radio frequency to study kiwifruit [50]. Deff values ranged from 6.61425 to 9.46745 $\times$ 10^{-8}, which were higher than those without ultrasonic pretreatment. Analysis of the drying rate constant found that pretreatment under different conditions can effectively increase the drying rate.

Cavitation and mechanical effects caused by ultrasound break the metabolic balance of carbohydrates in Codonopsis slices, and a large number of compounds with high molecular weight increase the polysaccharide content. The longer the sonication time was, the more unfavorable the retention of TFC. The antioxidant capacity was the strongest when ultrasonic frequency was 40 kHz. The analysis of active ingredients showed that ultrasonic pretreatment was not conducive to the retention of lobetyolin content, but had a positive effect on the retention of syringin content. In general, the application of ultra-pretreatment improved the quality characteristics of dried products. The same results were found in the studies of carrot [51,52], strawberry [53] and mulberry leaves [54].

Sensory analysis showed that total color difference rises with increasing ultrasonic power. However, the values of ΔE were lower than those in the drying process without ultrasonic pretreatment, and there was no significant difference in the microstructure of *Codonopsis pilosula*. Under different drying conditions analyzed, it was found that the volume heating of RF vacuum drying led to the increase in internal pressure at the beginning of drying, the acceleration of evaporation, and the swelling of cells during drying. After ultrasonic pretreatment, the tissue and cell structure changed noticeably.

In this paper, the drying characteristics and quality characteristics of Codonopsis slices in ultrasonic pretreatment RF vacuum drying were studied, but the more specific heat and mass transfer process inside the slices still remains unclear. In future research, the heat and mass transfer mechanism of Codonopsis slices should be studied in depth through simulation in order to provide a theoretical basis for the optimization of the later drying process.

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