

Effect of different pretreatment methods on drying characteristics and quality of wolfberry (*Lycium barbarum*) by radio frequency-hot air combined segmented drying

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Abstract

In this study, fresh wolfberry in the current season was used as the experimental material and a radio frequency (RF)-hot air combined segmented drying process was adopted for berry preservation. Ultrasonic treatment, hot water blanching, sucrose infiltration, ultrasonic & blanching, ultrasonic & infiltration, and NaOH and NaCl solution impregnation were used for pre-treatment of combined drying. Taking natural drying and conventional Na₂CO₃ dewaxing treatment as the control group, the effects of different pretreatment methods on drying characteristics, quality, and microstructure of wolfberry during combined drying were investigated. The drying time after ultrasonic and blanching pretreatment was the shortest(13.5h), which effectively retained total flavonoids(1.79mg/g) and enhanced their antioxidant activity($I = 60.78\%$). NaCl impregnation treatment significantly increased the total phenol content(8.77 mg/g). The retention rate of soluble sugar (0.73 g/g), ascorbic acid (3.96mg/100g), betaine(2.72%), and other nutrients increased significantly after ultrasonic and infiltration treatment, while the color, rehydration rate and microstructure were better than other treatment methods. The Weibull distribution function can accurately describe the RF-hot air combined drying process of *Lycium barbarum* after different pretreatment, and simulated results were consistent with the results of the combined drying characteristic curve of *Lycium barbarum*. The aim of this study was explored suitable pretreatment methods to improve the drying rate and ensure the quality of dried products of wolfberry.

1. Introduction

As a perennial deciduous shrub of Solanaceae. Wolfberry (*Lycium barbarum*) has orange-red ellipsoid berries. It is an edible and medicinal plant with a long history in China and other Asian countries. Rich in polysaccharides, flavonoids, betaine, and other bioactive substances, it has multiple healthy and pharmacological functions(Montesano et al., 2018). Given that the moisture content of ripe wolfberry fruit is more than 80%, it is very easy to decay owing to the action of microorganisms and enzymes at room temperature, which makes it difficult to transport and store. Meanwhile, drying is one of the most effective and widespread food preservation methods, which can prolong the shelf life and improve the retention rate and bioavailability of active substances. Therefore, apart from a small amount of wolfberry production being used for fresh food and as raw materials for foodstuff processing, most of them are preserved through controlled desiccation(Kafkas et al., 2021).

At present, the drying methods of wolfberry mainly include natural drying and mechanical drying. Natural drying is simple in operation and low in cost, but its drying time is long, and the drying conditions and quality are difficult to control, so the wolfberry is easy to get damp, caking and mildew. Mechanized drying methods mainly include hot air, microwave vacuum, far infrared, and vacuum freezing.

The color, rehydration and quality of wolfberry are typically quite good which dried by hot air, but longer drying time resulting in serious shrinkage of dried wolfberry fruit, loss of nutrients and quality reduction(Dandan Zhao,2018). Microwave vacuum drying technology can significantly shorten the drying cycle of wolfberry and has higher energy utilization rate, but it is easy to cause surface expansion and

rupture, seed out, sugar overflow, and other phenomena, which makes it more suitable for the later drying of semi-dry products(Yue Duan, 2017). After vacuum far-infrared drying, the polysaccharide content and color differences of wolfberry are increased while the rehydration rate does not change significantly, but the surface is prone to crust hardening and forms small bubbles, which affects fruit quality(Lijuan Zhao et al., 2017). Vacuum freeze-drying technology can effectively retain the bioactive components of dried wolfberry, but the energy consumption is large, the output is small and the equipment is expensive. (Mengze Wang, 2017). Therefore, it is necessary to seek a more efficient, suitable, and cost-effective drying technology for wolfberry.

In recent years, radio frequency (RF)-hot air combined drying has been introduced as a new environmental drying technology. It generates heat inside the material by oscillating charged ions and rotating polar molecules and has a good penetration ability, which can achieve rapid heating of the whole material (Mao Y & Wang S, 2021). Hot air-assisted RF heating can effectively avoid thermal deviation and glow discharge caused by excessive heating or uneven heating, reduce the influence of corner effect and arcing effect in RF drying, and greatly improve the drying efficiency. At present, this technique has been successfully applied in the drying of red-jujube(Yao X et al., 2022), apricots(Topcam H et al., 2022), kiwifruit(Zhou X et al., 2018), apple(Peng Jing et al., 2019), mango(Zhang H et al., 2019), carrot(Ozbek, Hatice Neval, 2021), and other fruit slices.

The wax layer on the surface of wolfberry will hinder the evaporation of internal water during drying, so a pretreatment is needed before drying. Alkali immersion is the most common treatment method that can dissolve the long-chain fatty acid hydrocarbon compounds on the wolfberry surface, thus accelerating the drying rate(Zhou Yu-Hao et al., 2020). However, relevant studies have shown that ultrasonic pretreatment can effectively strengthen the internal heat and mass transfer process of fruit and vegetable slices, and improve the drying efficiency and quality of dried fruit (Zhiyuan Cao et al., 2021). For example, appropriate blanching treatment can maintain the quality and color of agaricus bisporus slices(Jiang Ning et al., 2015). Permeation pretreatment can enhance color protection and brittleness of dried carrot products(Souza et al., 2022). Impregnation is beneficial to maintain product shape and color, improve hardness and reduce brittleness((Alipoorfard, F et al., 2020). Therefore, ultrasonic pretreatment, hot water blanching, sucrose infiltration, ultrasonic & blanching, ultrasonic & infiltration, and NaOH and NaCl solution impregnation treatments were used to pretreat wolfberry before RF-hot air combined drying in this study. Then, the combined drying characteristics of wolfberry under different pretreatments were explored and the quality and microstructure of dried wolfberry were compared and analyzed. The purpose of the study was found suitable pretreatment methods and provided a theoretical and practical basis for the postharvest processing of wolfberry, and provided certain technical guidance for the wolfberry rapidly drying with high quality. .

2. Materials and Methods

2.1. Experimental Materials

The variety of wolfberry used in this experiment was the fresh fruit of Ningqi No.1 planted in the Zhongning L.Barbarum Plantation in Ningxia, China. Fresh wolfberries was spread on the material plate of the rapid moisture meter (HKSF-2, Moisture Resolution 0.01%, Precision 0.1%; Wuxi Huake Instrument Co., Ltd., Wuxi, China); the measured average initial moisture content was $79 \pm 2\%$, and fresh wolfberry was purchased and stored in a temperature-controlled cabinet at $(2 \pm 1^\circ\text{C})$ prior to testing.

2.2. Experimental Method

A 3 kW radio frequency heating system at 27.12 MHz (GJS-3-27-JY, Hebei Huashi Jiyuan High Frequency Equipment Co., Ltd., Langfang, China) and an electrically heated drum dryer (YQ101-0A-4A, voltage 220V/50 Hz, power 1.2kW, wind speed 3 m/s; Beijing Yuqin Tengda Pharmaceutical Equipment Co., Ltd., Beijing, China) was used for drying of wolfberry(Xu Y et al., 2022). This study was conducted on the basis of previous RF-hot air combined segmented drying study of wolfberry. The suitable parameters of the combined drying test were plate spacing of 90 mm, vacuum degree of 0.025 MPa, and hot air temperature of 55°C (Xu Y et al., 2022). Wolfberries with an undamaged surface, high moisture content, comparable shape and size were chosen as the raw material, and they were subjected to the following different pretreatments after being removed from the temporary storage 1 hour before the experiment and waiting for the temperature to reach room temperature ($22 \pm 1^\circ\text{C}$).

The pretreatments include: ultrasonic treatment: 40 kHz, 60 W, 30 min(Qian, Zhang et al., 2022); sucrose infiltration: 30% sucrose solution infiltrating 30 min(Lyu Jian et al., 2017); heat blanching: 100°C distilled water blanching for 2 min(Xu Huihuang et al., 2022); ultrasonic & infiltration: ultrasonic parameters were the same as above and the ultrasonic medium was 30% sucrose solution(Li Lu et al., 2021); ultrasonic & blanching: ultrasonic parameters were the same as above and the ultrasonic medium was 100°C distilled water(Sledz et al., 2016); impregnated for 5 min by 1% NaOH solution(Zi-Liang Liu et al., 2022); impregnated for 3 min by 5% NaCl solution(Kaur et al., 2020).

The combined segmented drying process of wolfberry was shown as Fig. 1. 120 ± 0.5 g of qualified fresh wolfberry were selected for each group, among which some were directly soaked when pretreated with NaOH and NaCl solution while the others were placed in 2% Na_2CO_3 solution for 3 min before different pretreatment. Then, the wolfberries were evenly spread on a polypropylene plate (500×300 mm) and placed into the RF vacuum tank for the first drying stage. The previous test results showed that the wolfberry surface would crust, harden, or even scorch when the moisture ratio is decreased to 0.4–0.5 g/g(Xu Y et al., 2022). This is because the dielectric properties of RF whole heating lead to faster evaporation of free water in the epidermis than in the interior, and the viscosity of water molecules increases and becomes difficult to move and diffuse. Therefore, 0.4–0.5 g/g was used as the moisture ratio node of the conversion drying method in the combined drying. The wolfberries were transferred to the electric hot-blast drying box for the second stage of drying when the moisture ratio reached the node, aiming to continue to evaporate the internal moisture of wolfberries.. The total operation time was less than 1 min, and the temperature loss of the sample was less than 5°C during the transfer process. The sample was weighed every 60 min until a constant weight was reached. The natural drying and

conventional Na₂CO₃ solution dewaxing pretreatment were regarded as the control group, and each pretreat test group was repeated for three times.

2.3. Selection of the model

The Weibull distribution function was used to fit the RF-hot air combined drying curves of *Lycium barbarum* after different pretreatments. The variation of moisture ratio in the drying process was analyzed, and the moisture ratio was expressed by Weibull distribution function as follows(Dai J W et al., 2015):

$$MR = \exp \left[- \left(\frac{t}{\alpha} \right)^\beta \right] \quad (1)$$

where α is the scale parameter and represents the drying rate constant, which is approximately equal to the time required for the material to remove 63.2% moisture during the drying process; β is the shape parameter and its value is related to the drying rate at the beginning of the drying process; t represents the drying time ;

The multiple linear regression method was adopted to fit the mathematical model equation to the experimental data, and the fitting accuracy of the model was evaluated by the coefficient of determination(R^2), root mean square error(RMSE) and chi-square value (χ^2).

The fitting accuracy of the mathematical model is higher when R^2 is closer to 1, and RMSE and χ^2 are closer to 0, which indicated that the Weibull distribution function can accurately describe the RF-hot air combined drying process of *Lycium barbarum* after different pretreatments. The R , RMSE and χ were calculated as follows(Ju H Y et al., 2016):

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp,i} - \overline{MR_{exp,i}})^2}{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2} \quad (3)$$

$$\chi^2 = \sum_{i=1}^N n (MR_{pre,i} - MR_{exp,i})^2 \quad (4)$$

Where $MR_{exp,i}$ is the value of the moisture ratio obtained from drying experiments, $MR_{pre,i}$ is the value of the model-predicted moisture ratio, $\overline{MR_{exp,i}}$ is the average value of the experimental moisture ratio, N is the number of observations and n is the number of constants.

2.4. Quality analysis

According to the methods of our previous experiment(Xu Y et al., 2022), the drying parameters including moisture content, dry basis moisture content and moisture ratio of wolfberry were calculated after dried by RF-hot air, and the color, rehydration rate, sugar, total phenol, flavonoid, antioxidant activity, ascorbic acid, betaine content of dried wolfberry were also determined utilized the exact same testing methods as the previous study(Xu Y et al., 2022), and then representative views under different drying conditions were selected for microscopic photography.

2.5. Statistical Analysis

The single-factor test method was adopted, each group was repeated for three times, and all data were expressed as mean $\pm$ standard error (SE). Treatment comparisons were performed by a one-way analysis of variance (ANOVA) using SPSS 26.0 (IBM, Armonk, North Castle, NY, USA) with $\alpha = 0.05$. Origin 2021(OriginLab, Northampton, MA, USA) was used for mapping.

3. Results and Discussion

3.1. Effects of Different Pretreatments on Combined Drying Characteristics

Moisture ratio curves under different pretreatments as a whole showed a descending trend with the extension of drying time (Fig. 2(a)). This is because the material is in a warming state during the combined drying process and the internal moisture is continuously evaporated. Moreover, after the material was pretreated, under the influence of high-voltage electric field generated by RF and hot air convection drying after pretreatment, the energy of its internal drying medium increased, which led to the free water to continuously migrate from the inside to the surface and to complete the drying process with a rapid gasification.

After wolfberries were pretreated with ultrasonic and blanching, ultrasonic and infiltration, ultrasonic, impregnated with NaOH solution, heat blanching, impregnated with Na_2CO_3 and NaCl solution, and sucrose infiltration, the total drying time required to achieve constant weight was 13.5, 14.5, 15, 15.5, 16, 17, 17.5, 18 hours, respectively. The segmented drying moisture ratio node (0.4–0.5 g/g) was first reached after 6 h of RF drying when ultrasonic and blanching combined pretreatment was adopted, and the required time was 7.69%, 21.05%, 18.37%, 5.52%, 4.02%, 17.81%, 19.46% shorter than aforesaid pretreatment methods, respectively. The reason of U&B pretreatment could first reached moisture ratio node was that the simultaneous strong thermophysical effect of ultrasonic and blanching pretreatment softened the internal tissue of wolfberry and enhanced the permeability, which was beneficial to rapid internal moisture diffusion(Wang C et al., 2021).

Since the material would rapidly warm in the heating environment of combined drying and then enter the constant speed and deceleration heating stage. It can be found the materials were all in a constant speed drying stage when the drying process was completed to 5 hours, and they entered a deceleration drying

stage after 10 hours, that's meaning that the drying rate from all pretreatments remained similar consistent throughout 5–10 hours. The drying rate of the material under different pretreatments increased first and then decreased (Fig. 2(b)).

The overall drying rate after infiltration treatment was slow, and the drying time was the longest (18 h), which was 5.56% higher than conventional Na₂CO₃ dewaxing treatment. It's consistent with the finding of Jian Lyu et al(Lyu Jian et al., 2017) studied on the drying characteristics of peach chips that pretreated by osmotic dehydration in sucrose solution. This is because the sucrose molecules in the medium entered the surface cells of wolfberry during infiltration pretreatment, thus reducing the permeability and hindering the effective diffusion of water molecules. The drying rate was significantly accelerated, and the total drying time was the shortest (13.5 h) after ultrasonic and blanching pretreatment, which was reduced by 20.6% compared with the Na₂CO₃ dewaxing treatment. It's consistent with the result of Qian Zhang et al(Qian Zhang et al., 2022) that the drying rate of wolfberry will accelerated which preteated by ultrasonic and blanching.

The main reason is that blanching treatment led to the plasmolysis of surface cells of wolfberry, which increased the permeability of cell wall. In addition, the mechanical effect and cavitation effect of ultrasound increased the number of micropores on the surface of wolfberry, which was conducive to the rapid vaporization and evaporation of moisture inside the material and accelerated the drying rate(Mehta et al., 2017).

3.2. Model analysis

3.2 .1.Simulation analysis of drying process

Table 1
The Simulation results of Weibull distribution function that Lycium barbarum was combined drying under different pretreatment conditions

Pretreatment Method	α/h	β	R ²	RMSE	χ ²
Ultrasound	9.482	1.85551	0.99729	0.00328	1.5209×10 ⁻⁴
Blanching	10.112	1.55169	0.99654	0.00356	2.1872×10 ⁻⁴
Infiltration	11.376	1.60135	0.98692	0.00491	3.2607×10 ⁻⁴
Ultrasound&Blanching	8.532	1.56452	0.99835	0.00267	1.2452×10 ⁻⁴
Ultrasound&Infiltration	9.164	1.62545	0.99763	0.00272	1.2739×10 ⁻⁴
1%-NaOH	9.796	1.60893	0.99668	0.00346	2.1733×10 ⁻⁴
2%-Na ₂ CO ₃	10.744	1.68155	0.99613	0.00416	2.1942×10 ⁻⁴
5%-NaCl	11.065	1.63412	0.98697	0.00427	2.5171×10 ⁻⁴

The simulation results of Weibull distribution function are shown in Table 1. The average value of R^2 is 0.99457, the average value of RMSE is 0.00363, and the average value of χ^2 is 2.0466×10^{-4} , which indicated that the Weibull distribution function could better simulate the RF-hot air combined drying process of *Lycium barbarum* after different pretreatments.

The size parameter a was the smallest (8.532) when pretreated by Ultrasound & Blanching and, while it was the largest when pretreated by Infiltration (11.376), as shown in Table 1. The simulated results explained that the drying time of *Lycium barbarum* was the shortest and the drying rate was the fastest when pretreated by Ultrasound & Blanching and, while the drying time was the longest and the drying rate was the slowest when pretreated by Infiltration, which was consistent with the results of the combined drying characteristic curve of *Lycium barbarum*.

The shape parameter β represents the drying rate of the material at the initial stage of drying, which increased first and then decreased when $\beta > 1$, and the drying process is controlled by both surface and internal moisture. The value of β was 1.55169 ~ 1.85551 as is shown in Table 1, so theoretically there is a short ascending drying stage in the combined drying process, and then a descending drying process controlled by internal moisture.

3.2.2. Verification of the model

The drying time of *Lycium barbarum* was the shortest and the drying rate was the fastest when pretreated by Ultrasound & Blanching and, as shown in Table 1. Therefore, the process parameters of the verification experiment were as follows: plate spacing was 90 mm, vacuum degree was 0.025 MPa and the hot air temperature was 55°C, the *Lycium barbarum* was pretreated by Ultrasound & Blanching and before dried.

The comparison between the experimental value of MR and the simulated value of Weibull distribution function was shown in Fig. 3. The determination coefficient R^2 of the validation model was 0.99835 obtained by fitting analysis, indicating that the experimental values are in good agreement with the predicted value of the model, and the weibull model could better reflect the variation of moisture ratio in the process of *Lycium barbarum* RF-hot air combined drying after different pretreatments.

3.3 Effects of Different Pretreatments on the Quality of Wolfberry

3.3.1 Effect on Color and Rehydration

Table 2
Color and rehydration rate of dried *L. barbarum* under different pretreatments

Pretreatment Method	L^*	a^*	b^*	ΔE	Rehydration /%
Fresh wolfberry	38.95 ± 0.81 ^a	39.39 ± 0.76 ^{ab}	26.02 ± 0.93 ^a	—	—
Natural drying	38.16 ± 0.87 ^{ab}	43.93 ± 1.26 ^a	19.38 ± 0.74 ^b	8.56 ± 1.41 ^c	63.68 ± 0.21 ^a
Ultrasound	33.33 ± 0.96 ^c	27.13 ± 0.21 ^d	13.44 ± 0.51 ^e	10.79 ± 0.13 ^{abc}	43.31 ± 0.13 ^d
Blanching	35.22 ± 0.36 ^{abc}	34.46 ± 0.64 ^{bc}	15.43 ± 0.61 ^{de}	11.23 ± 0.59 ^{abc}	40.25 ± 0.56 ^f
Infiltration	34.65 ± 0.59 ^{bc}	30.95 ± 0.63 ^{cd}	14.72 ± 0.65 ^{de}	12.16 ± 0.21 ^{ab}	45.08 ± 0.25 ^c
Ultrasound& Blanching	38.17 ± 0.92 ^{ab}	34.05 ± 0.46 ^{bc}	18.49 ± 0.92 ^{bc}	11.69 ± 0.14 ^{abc}	41.73 ± 0.37 ^{ef}
Ultrasound& Infiltration	34.52 ± 0.71 ^c	30.31 ± 0.75 ^{cd}	15.43 ± 0.74 ^{de}	10.12 ± 0.19 ^{bc}	48.30 ± 0.58 ^b
1%-NaOH	35.16 ± 0.33 ^{abc}	31.03 ± 0.93 ^{cd}	16.51 ± 0.82 ^{cd}	12.11 ± 0.28 ^{ab}	42.52 ± 0.43 ^{de}
2%-Na ₂ CO ₃	33.84 ± 0.72 ^c	31.05 ± 0.18 ^{cd}	15.16 ± 0.72 ^{de}	11.48 ± 0.32 ^{abc}	43.85 ± 0.27 ^{cd}
5%-NaCl	34.81 ± 0.85 ^{bc}	29.47 ± 0.89 ^{cd}	15.22 ± 0.69 ^{de}	13.26 ± 0.78 ^a	42.74 ± 0.19 ^{de}
Note: Different letters in the same column indicate significant differences (P < 0.05).					

Color difference and rehydration rate of dried wolfberry under different pretreatments differed significantly (P < 0.05; Table 2). The L^* values of all dried wolfberry were less than those of fresh samples, and the L^* values of pretreated wolfberry were generally compared with the natural drying, indicating that RF-hot air combined drying could reduce the brightness of wolfberry epidermis and darken the color. This is because the Maillard reaction was intensified when the material was heated during combined drying, resulting in different degrees of browning and color degradation on the sample surface (Malaikritsanachalee et al, 2020). However, the surface brightness value L^* of dried wolfberry treated by ultrasonic and blanching was higher than that by other pretreatment methods, which indicated that the pretreatment method had a better color protection effect on the samples.

The b^* values of dried wolfberry under different pretreatments were different. In addition to natural drying, the b^* value of ultrasonic and blanching pretreatment was significantly higher than that of other methods, and the surface color of the sample was yellow and showed a good appearance. Judging from

the total chromatic aberration ΔE , the color change of ultrasonic and infiltration was the smallest compared with natural drying, followed by ultrasonic pretreatment, and the change of NaCl solution immersion was the largest, which increased by 15.4%, 20.7%, and 35.4%, respectively, compared with the natural drying. This may result from the fact that sucrose infiltration reduced the activity of water molecules in wolfberry, inhibited the browning reaction, and thus protected color effectively (Mehta et al., 2017). In addition, NaCl solution has high permeability, which accelerated dehydration and led to expansion of materials, thus affecting the color quality of wolfberry (Onal et al., 2019).

From the perspective of rehydration performance, the rehydration rate of dried wolfberry was significantly reduced compared to natural drying ($P < 0.05$) after RF-hot air combined drying. The reason is that the combined drying made the material quickly warm while destroying its cell structure, which increased the elasticity of cell structure, prevented water from penetrating into the kernel of wolfberry and thus reduced the recovery performance of cells. The rehydration rate of dried wolfberry decreased by 24.2% after ultrasonic and infiltration pretreatment compared with natural drying, but significantly increased compared with other pretreatment methods ($P < 0.05$). This is because sucrose infiltration increased the content of soluble solids in the material, enriched cells and strengthened tissue structure, which combined with the mechanical effect and cavitation effect of ultrasonic, could make the internal structure of dried wolfberry become fluffy and porous, and improved its rehydration performance (Bozkir Hamza et al., 2019). The rehydration rate of the material is the lowest after blanching pretreatment, which is 36.8% lower than natural drying. This may be the result of the short-term high temperature of blanching treatment which caused the solidification of protoplasts in wolfberry cells, destroyed their integrity, and further affected the rehydration performance of materials (Doymaz Ibrahim, 2010).

3.3.2 Effects on Total Sugar

RF-hot air combined drying can significantly improve the retention rate of polysaccharides in dried wolfberry compared with natural drying (Fig. 4(a)). This is because the combined drying can enhance the drying rate effectively, shorten the drying cycle of the material, better retain its effective components, and reduce the loss of polysaccharides. The polysaccharide content of dried wolfberry under combined treatment by ultrasonic and infiltration was the highest (0.73 g/g), which was 54.8% and 32.9% higher than that of natural drying and Na_2CO_3 dewaxing, respectively. The main reason is that the medium molecules of sucrose solution infiltrated into the wolfberry and thus increased the polysaccharide content during the combined pretreatment. Moreover, the cavitation effect of ultrasound could increase the number of micropores on the surface structure, which was conducive to more sucrose molecules entering into the material to improve its polysaccharide content (Doymaz Ibrahim, 2010). It was also found that the polysaccharide content decreased by 14.3% after NaCl impregnation compared with Na_2CO_3 dewaxing treatment. The reason may be that because of the high permeability of NaCl solution, the evaporation of water inside wolfberry during drying increased the concentration of salt solution, and the infiltration and dehydration inside the material resulted in the separation of cytoplasmic wall, which increased the loss of sugars. (Bozkir Hamza et al., 2019).

3.3.3 Effect on Total Flavonoids

The total flavonoid content of dry wolfberry obtained by combined drying was significantly higher than natural drying (Fig. 4(b)). Given the broad activity of flavonoids, rapid warming of combined drying resulted in a large release of flavonoids from the wolfberry matrix, which in turn increased the total flavonoid content of the material.. Total flavonoid content of the sample was the highest (1.79 mg/g) after ultrasonic and blanching treatment, which was 58.7% and 16.2% higher than that of natural drying and conventional Na_2CO_3 dewaxing treatment, respectively. This is because the ultrasonic and blanching treatment are strong thermodynamic and physical effects, and the rapid drying after combined pretreatment inactivated oxidases of phenolic substances, which is conducive to the accumulation of flavonoids(Ahmed, Maruf & Eun, Jong-Bang, 2018). Then, the mechanical effect of ultrasonic treatment would break the cell wall inside the material, allowing flavonoids to be more easily extracted(Wiktor, A et al., 2019). In addition, the total flavonoid content of the sample pretreated with Na_2CO_3 dewaxing was 3.34% higher than that of NaCl impregnation. This may be because the increase of the mass concentration of NaCl impregnation medium in the material during the drying process resulted in the separation of cytoplasm wall and the decomposition of flavonoids during the heating process(Ben Abdallah, S et al., 2016).

3.3.4 Effect on Total Phenols

The total phenol content in dried wolfberry increased obviously compared with natural drying after RF-hot air combined drying (Fig. 4(c)). The reason is that phenols are highly active and the heating rate of combined drying is relatively fast, which promoted the polymerization of phenols in the thermal field and thus increased the total phenol content. Moreover, combined drying greatly shortened the drying cycle and reduced the loss of phenols in the sample. It can be seen from the figure that the total phenol content of dried wolfberry treated by NaCl impregnation was the highest (8.77 mg/g), which was 51.8% and 11.8% higher than that of natural drying and Na_2CO_3 wax removal dewaxing treatment, respectively. This is due to the fact that all the other pretreatment methods can lead to different degrees of wax layer loss on the surface of wolfberry except for NaCl impregnation treatment, Which resulted in the loss of active substances and the dissolution and destruction of phenolic substances while increasing the drying rate(Augusto Batista de Medeiros et al., 2022).. The total phenol content (7.74 mg/g) of the sample by ultrasonic treatment was 3.62% higher than that of Na_2CO_3 dewaxing treatment. This was mainly due to the short drying time after ultrasonic pretreatment, which reduced the oxygen contact time of phenols and improved the retention rate. The total phenol content of samples treated by blanching and infiltration decreased by 15.8% and 11.9%, respectively, compared with Na_2CO_3 dewaxing treatment. This is because the oxidation of phenolic compounds was intensified after the cell structure was damaged by blanching pretreatment, and a large number of phenolic compounds are degraded because the drying rate of infiltration treatment is relatively low(Araújo, A.C et al., 2016).

3.3.5 Effect on Antioxidant Activity

Antioxidant activity of plants is derived from the synergistic inhibition of oxidative chain reaction by antioxidants such as phenolic compounds and is reflected by the phenol content in the sample and the scavenging capacity of free radical 1, 1-diphenyl-2-trinitrophenylhydrazine. In this study, the antioxidant

activity is expressed by inhibition rate, and a greater inhibition rate means a stronger oxidation resistance(Nencini C et al., 2011). The antioxidant activity of dried wolfberry obtained by RF-hot air combined drying was significantly higher than that of natural drying, and the degradation of flavonoids, phenols, and other antioxidants in the material was inhibited effectively because the combined drying has a fast heating rate and short drying time, thus improving antioxidant activity (Fig. 4(d)). Moreover, it was found that the inhibition rate of dried wolfberry treated by ultrasonic and blanching was the highest (60.78%) compared with other pretreatment methods, and the rate was 43.7% and 22.9% higher than that of natural drying and conventional Na_2CO_3 dewaxing, respectively. A fast drying rate after ultrasonic and blanching combined pretreatment with rapid blanching can inactivate the oxidase in wolfberry and inhibit the degradation of phenolic compounds, and then release antioxidants through non-enzymatic reactions, thus increasing the inhibition rate(Thuwapanichayanan, R et al., 2014). In addition, the inhibition rates of NaCl and NaOH impregnation were 10.1% and 16.8%, lower than those of conventional dewaxing treatments, respectively, indicating that these two pretreatment methods may reduce the antioxidant activity of dried wolfberry.

3.3.6 Effect on VC

V_C content of the combined drying wolfberry was significantly higher than that of natural drying (Fig. 4(e)), which may be because the chemical instability of vitamin C makes it easy to be oxidized and decomposed in the presence of heating, luminescence, and aerobic environment. In addition, the content of ascorbic acid would also be reduced if the drying temperature is too high or the time is too long(Sheng-Jiao Lei, et al., 2022). The RF vacuum drying stage was performed under the conditions of proper temperature, light avoidance, and vacuum. Moreover, combined drying shortened the drying time and effectively avoided the degradation of V_C . The V_C content of dried wolfberry obtained by ultrasonic and infiltration was the highest (3.96 mg/100 g) compared with other pretreatment methods, and the content was increased by 40.4% and 18.9% compared with natural drying and conventional Na_2CO_3 dewaxing treatments, respectively. The reason is that the combined pretreatment enhanced the drying rate of materials, and that after the sugary medium infiltrated into the wolfberry cells by the effect of ultrasound, the cells were enriched and the density of cell tissue and structure were strengthened, thus greatly improving the retention rate of ascorbic acid greatly(Lyu, Ying et al., 2022). The ascorbic acid content of dried wolfberry decreased by 17.2% and 7.41% compared with Na_2CO_3 dewaxing treatment, which was pretreated by ultrasonic and blanching, and blanching. The main reason is that V_C is extremely sensitive to temperature, and blanching at a high temperature led to softening of wolfberry cell tissue, which destroyed the structure of V_C and degrades it.

3.3.7 Effect on Betaine

RF-hot air combined drying can improve the betaine content of dried wolfberry effectively compared with natural drying (Fig. 4(f)). This is mainly because as an osmotic regulator similar to amino acid amphoteric ions, betaine has strong hygroscopicity and its content decreases with the increase of drying temperature and time(Sadowska-Bartosz Izabela & Grzegorz Bartosz, 2021). In this context, the proper

temperature and combined drying can accelerate the drying rate and shorten the drying time, thus retaining the betaine components better in the material. The betaine content of dried wolfberry obtained by ultrasonic and infiltration pretreatment was the highest (2.72%), which was 46.7% and 13.2% higher than that of natural drying and conventional Na_2CO_3 dewaxing, respectively. Since betaine is an internal quaternary ammonium compound, its content is closely related to the environmental conditions and betaine aldehyde dehydrogenase activity. It is possible that ultrasound and infiltration treatment significantly stimulated and accumulated betaine aldehyde dehydrogenase under the adversity conditions of RF electric field, thus increasing the betaine content of materials (Luengo et al., 2016). The betaine content of dried wolfberry decreased by 14.4% and 7.63% compared with Na_2CO_3 dewaxing treatment, which was pretreated by sucrose infiltration and NaCl impregnation, respectively. The main reason is that the drying rate of this pretreatment method is slower and more time-consuming compared with combined drying, resulting in the decrease of betaine retention rate.

3.3.8. Microstructure Analysis

Figure 5(a) and Fig. 5(b) show that the surface of fresh wolfberry is smooth and orderly arranged in bundles, and the wax layer is attached obviously, while the epidermis of wolfberry is arranged in a cord-like pattern after natural drying, with clear cellular tissue structure and some waxy layer film fragments.. The microstructure of wolfberry under different pretreatment varied, as cells on the material surface were arranged in a regular pattern but presented with dense micropores and bubbles after ultrasonic pretreatment (Fig. 5(c)). This is because the cavitation effect expands the cell gap when ultrasonic sound impacts the material repeatedly (Bengang Wu, et al., 2021). The surface of wolfberry was smooth and relatively stretched when pretreated by blanching (Fig. 5(d)). This is due to the thermal effect of short-term blanching, which made the material tissue cells soften and helped to mitigate the shrinkage caused by drying (An NN et al., 2022). The surface structure of wolfberry was arranged closely, and there were colloidal substances attached when pretreated by sucrose infiltration (Fig. 5(e)), which is mainly due to sucrose molecules adsorbed on the surface tissue cells (R. Lemus-Mondaca et al., 2009). When pretreated by ultrasonic and blanching (Fig. 5(f)), the surface of the dried wolfberry was arranged loosely in bundles, and the local surface became rough and concave.

It may be that blanching can destroy the structure of the cell biofilm, resulting in the adhesion of wolfberry epidermal cells, while the mechanical effect of ultrasonic treatment makes the softened internal organizational structure produce internal crack and collapse during drying (Ren, F et al., 2018). By contrast, ultrasonic and infiltration pretreatment caused wolfberry surface tissue cells to be arranged regularly, yet the number of micropores and bubbles increased (Fig. 5(g)). This may be because sucrose molecules enrich tissue cells, strengthen tissue structure, and consolidate micropore channels (Xu, B et al., 2022). The surface microstructure of dried wolfberry treated with Na_2CO_3 solution (Fig. 5(i)) was more regular than that treated with NaOH (Fig. 5(h)) or NaCl (Fig. 5(j)) and the wax layer particles were decreased. This is due to the residual salts on the wolfberry surface after pretreatment by NaCl impregnation and wax layer removal by Na_2CO_3 solution.

4. Conclusions

In this study, fresh wolfberry was dried by RF-hot air combined segmented drying, and effects of different pretreatment methods on its drying characteristics and quality were explored. The results showed that the drying time was the shortest (13.5 h) when ultrasonic and blanching pretreatment was adopted before the combined drying of wolfberry, which was 20.6% shorter than that of conventional Na_2CO_3 dewaxing treatment. The total flavonoid content of dried wolfberry was the highest (1.79 mg/g), and the antioxidant activity was the strongest ($I = 60.78\%$). Those two quality indexes increased by 58.7% and 43.7%, respectively, compared with natural drying, and increased by 16.2% and 22.9%, respectively, compared with Na_2CO_3 . It was showed that U&B pretreatment could accelerated the drying rate and retained flavonoids of wolfberry effectively. When ultrasonic and infiltration pretreatment was used, the dried wolfberry had the smallest change of total color difference ΔE , the highest rehydration rate (48.30%), the highest polysaccharide content (0.73 g/g), the highest betaine content (2.72%), and the highest Vc content (3.96 mg/100 g). The three nutritional ingredients increased by 54.8%, 46.7%, and 40.4%, respectively, compared with natural drying, and increased by 32.9%, 13.2% and 18.9%, respectively, compared with Na_2CO_3 dewaxing treatment. This indicated that U&I pretreatment could protected color and retained nutrients such as sugars and Vc effectively during the drying process of wolfberry. The total phenol content (8.77 mg/g) of dried wolfberry pretreated by NaCl impregnation was the highest, which was 51.8% and 11.8% higher than that of natural drying and Na_2CO_3 dewaxing drying, respectively. It showed that NaCl impregnation treatment was beneficial to retained phenolic substances in the drying process of *Lycium barbarum*.

The Weibull distribution function was used to fit the RF-hot air combined drying curves of *Lycium barbarum* after different pretreatments. The average value of R^2 , RMSE and χ^2 was 0.99457, 0.00363 and 2.0466×10^{-4} respectively, and the variation described by the size parameter α and the shape parameter β is consistent with the drying characteristics in the drying characteristic curve.

In terms of microstructure, the dried wolfberry surface structure was arranged relatively neatly after natural drying, but there were bubbles generated after ultrasonic pretreatment. The surface was more stretched after heat blanching pretreatment and the colloidal substances were produced on dried wolfberry surface after sucrose infiltration pretreatment. Ultrasonic and blanching pretreatment resulted in epidermal tissue collapse of dried wolfberry. The wax layer particles on the dried wolfberry surface pretreated with Na_2CO_3 solution were reduced more significantly than pretreated with NaOH solution, and there were salt residues on the wolfberry surface. After pretreatment by NaCl impregnation, the epidermal tissue of dried wolfberry was arranged more regularly and the number of micropores and bubbles increased. This ensured energy conservation and efficiency while improving its economic value.

Declarations

Author contribution: Conceptualization, Xu.Y. and Huang.X.; methodology, Xu.Y., Huang.X., Zang.Z. and Zhang.Q.; software, Xu.Y.; validation, Xu.Y., Huang.X., Zang.Z., Jiang.C. and Zhang.Q.; formal analysis,

Xu.Y.; in-vestigation, Wang.T., Shang.J. and Wan.F.; resources, Wang.T., Shang.J. and Wan.F.; data curation, Xu.Y.; writing - original draft preparation, Xu.Y.; writing - review and editing, Xu.Y., Huang.X., Zang.Z., Jiang.C. and Zhang.Q.; visualization, Xu.Y.; supervision, Huang.X.; project administration, Huang.X. and Wan.F.; funding acquisition, Huang.X. and Wan.F. All authors have read and agreed to the published version of the manuscript.

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Figures

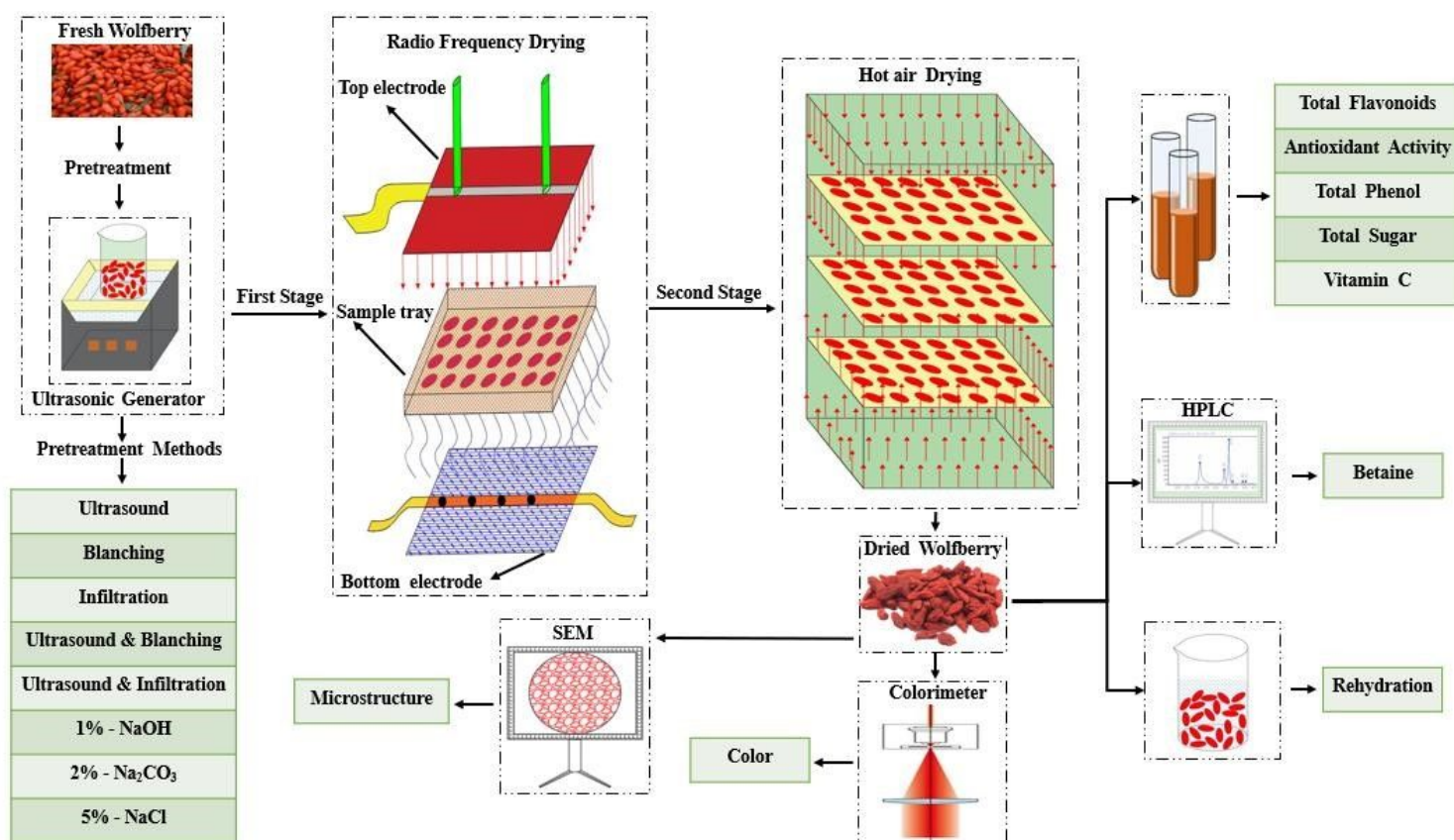


Figure 1

Lycium barbarum combined segmented drying process flow

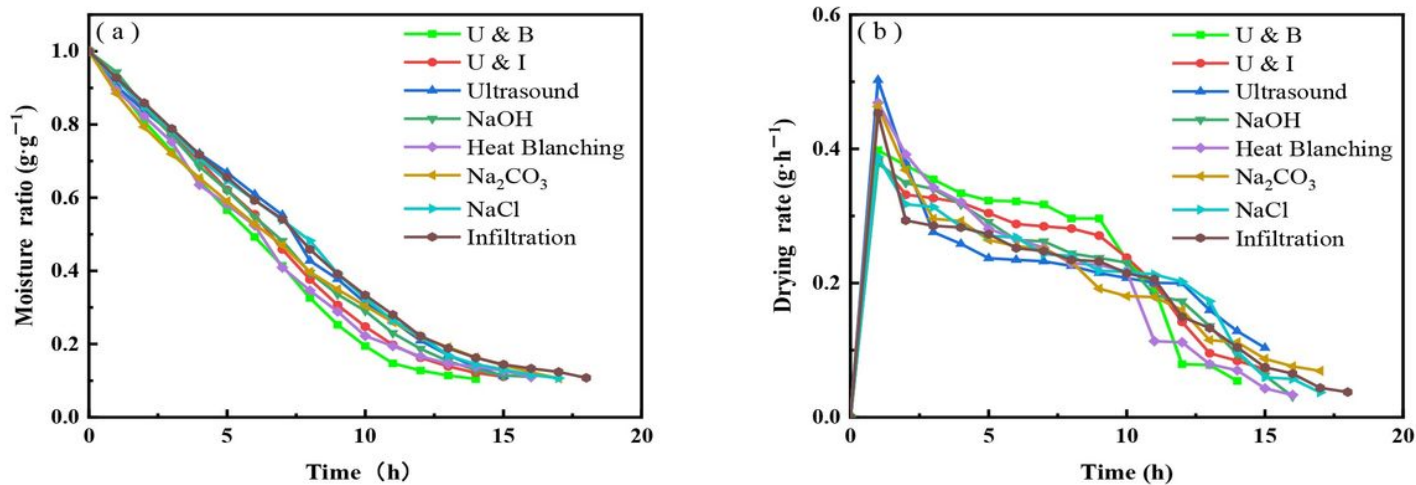


Figure 2

Combined drying curve (a) and drying rate curve (b) of *L. barbarum* under different pretreatments. Abbreviations: U&B, ultrasound and heat blanching; U&I, ultrasound and infiltration in Figure 2(a), (b).

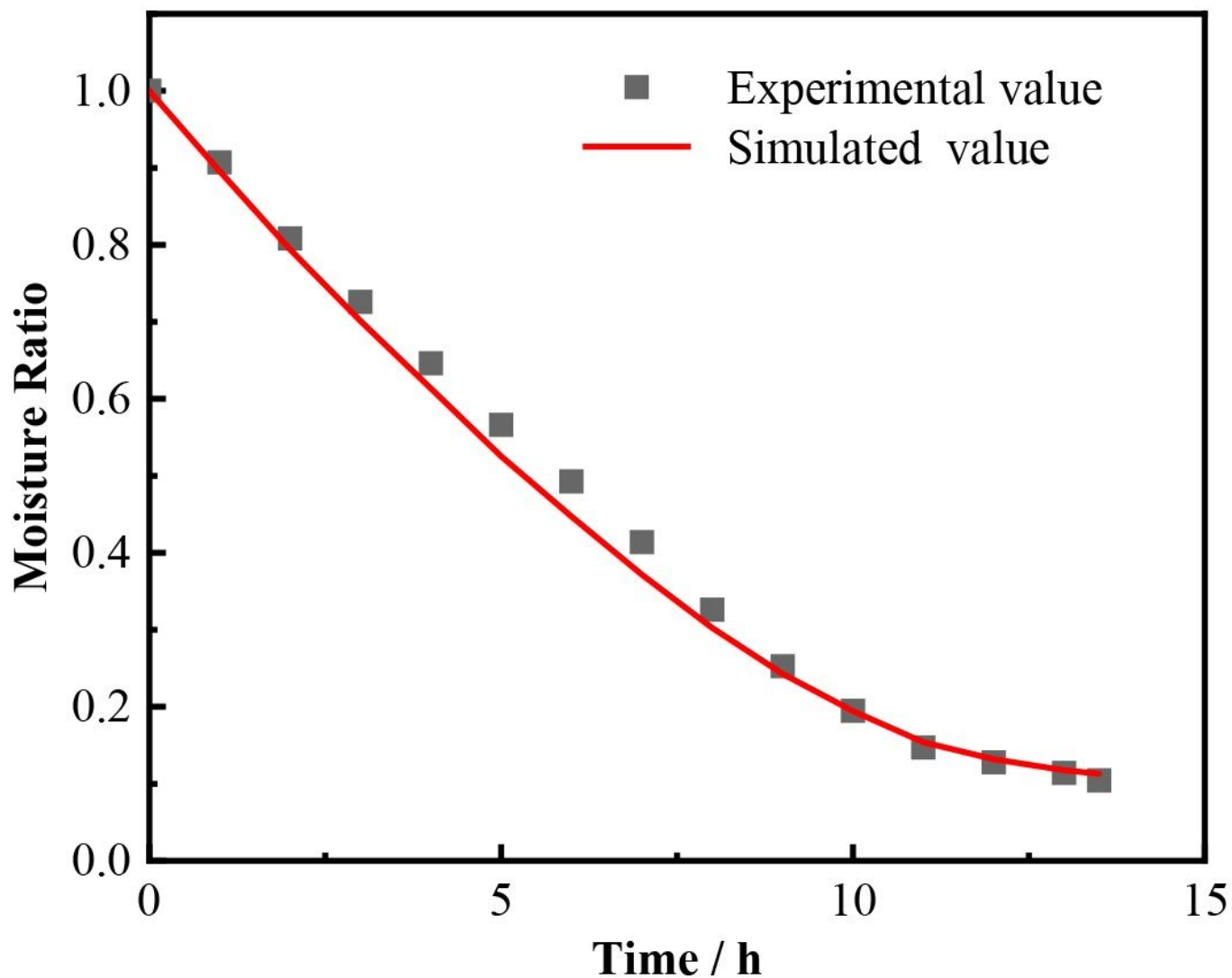


Figure 3

Verification of the Weibull mode

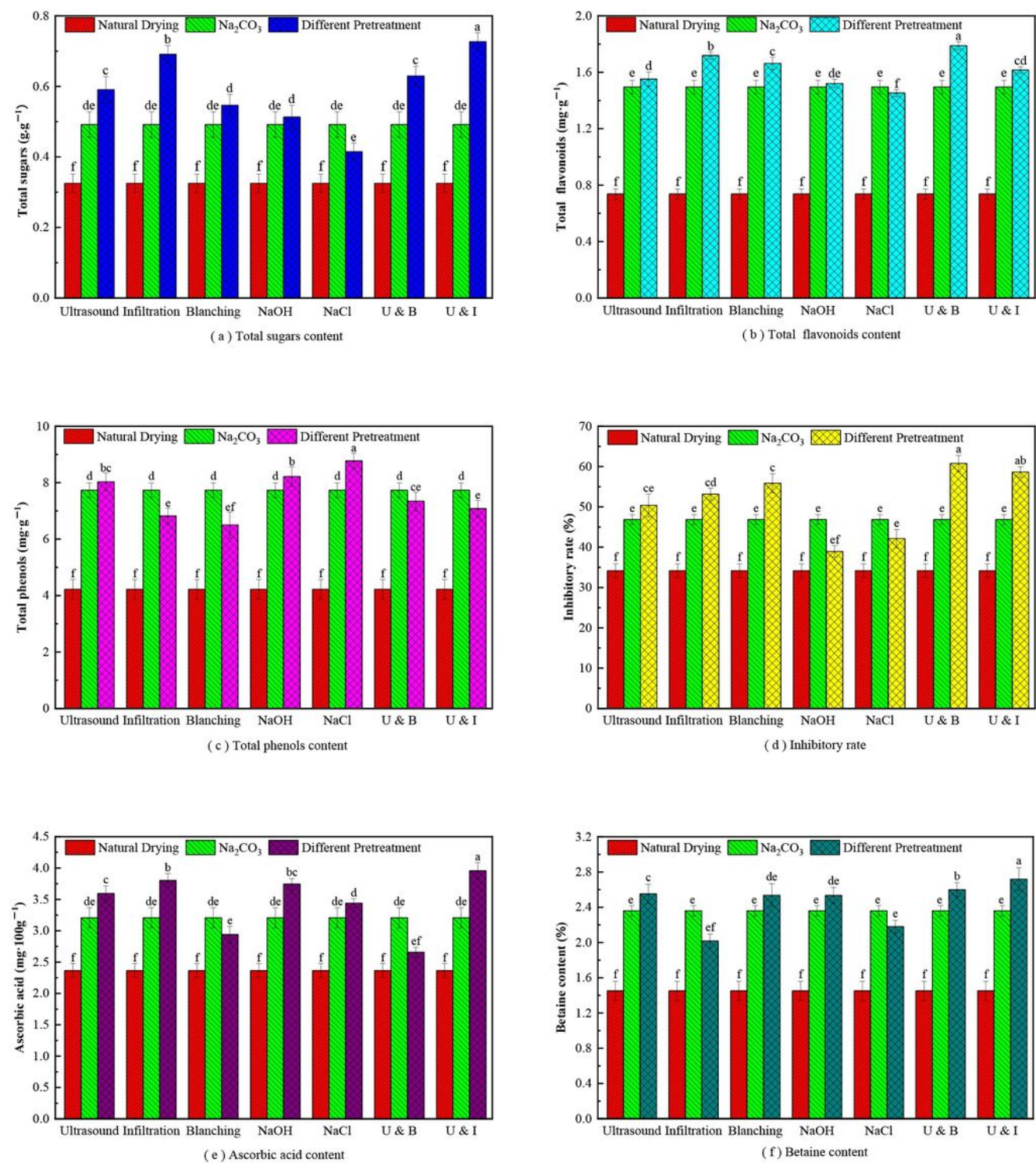


Figure 4

Effects of different pretreatment conditions on the quality of *L. barbarum*. Abbreviations: U&B, ultrasound and heat blanching; U&I, ultrasound and infiltration in Figure 4(a)–(f). Significant differences are represented by different letters ($P < 0.05$).

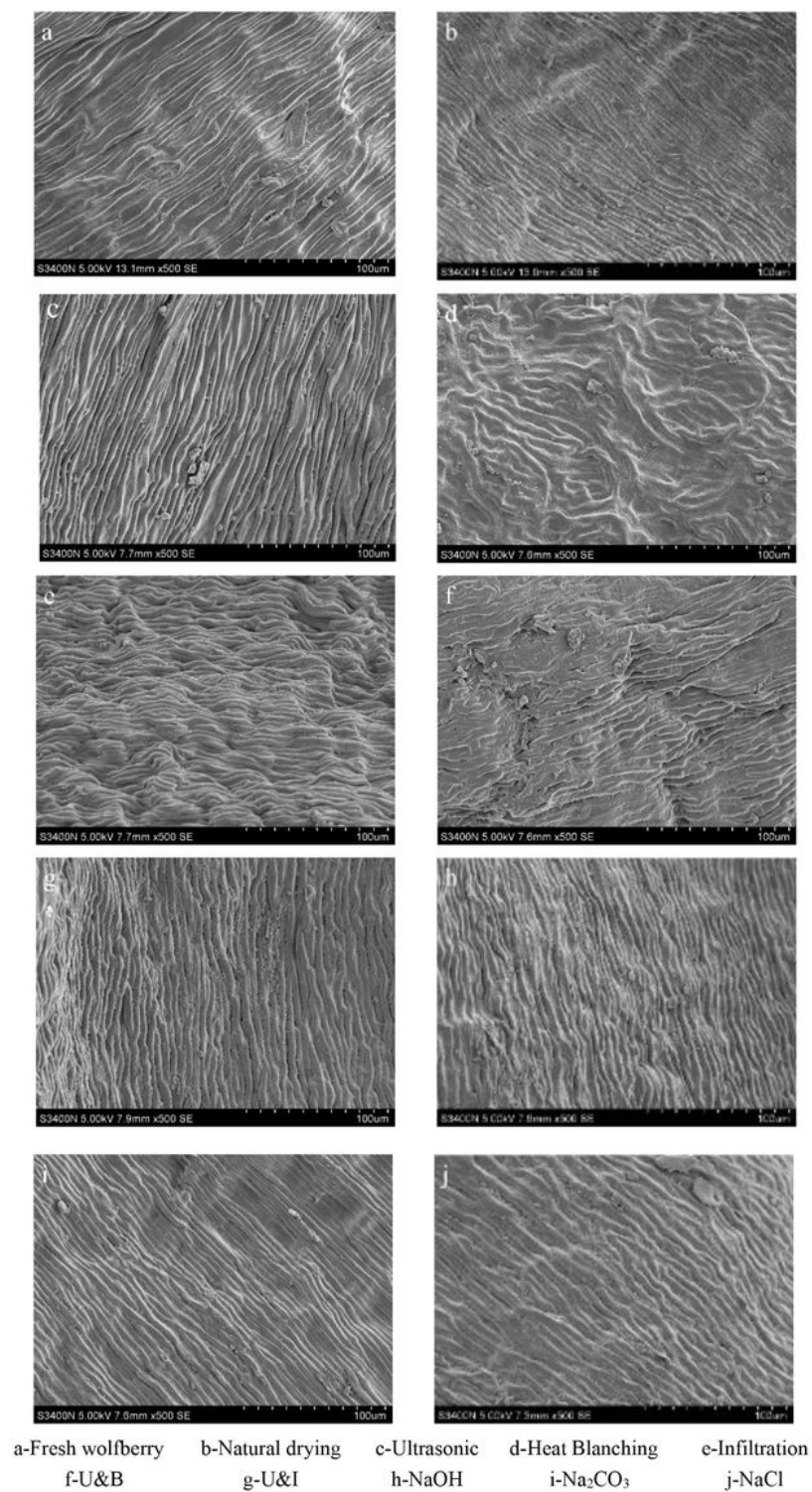


Figure 5

Microstructure of *L. barbarum* under different pretreatment methods. Abbreviations: U&B, ultrasound and heat blanching; U&I, ultrasound and infiltration in Figure 5(a)–(j).

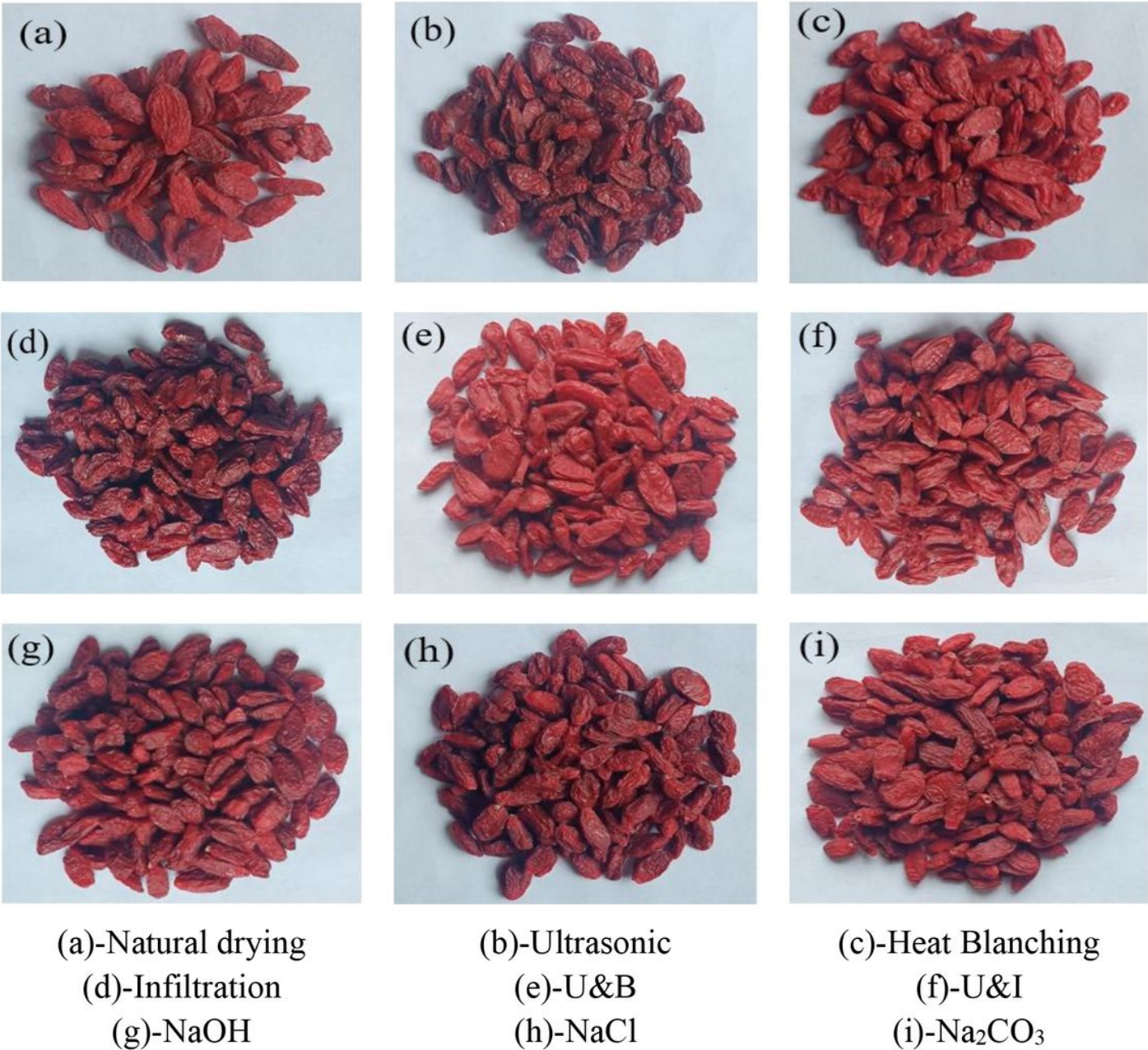


Figure 6

Dried *L. barbarum* under different pretreatment methods. Abbreviations: U&B, ultrasound and heat blanching; U&I, ultrasound and infiltration in Figure 6(a)–(i).