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Optimization of *Scutellaria baicalensis* Drying Using Combined Ultrasound and Vacuum Far-Infrared Technology: Drying Kinetics and Bioactive Preservation

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Abstract: To address the thermal degradation and efficiency limitations of traditional drying methods on the active compounds of *Scutellaria baicalensis*, a novel drying technique combining ultrasonic pretreatment with vacuum far-infrared drying (US-VFIRD) was developed. The ultrasonic cavitation effect (power: 40-80 W, frequency: 20-60 kHz, time: 10-30 min) was employed to disrupt the hydrogen bond network of the cell wall, promoting the release of bound water and reducing mass transfer resistance. This was subsequently coupled with vacuum far-infrared drying (50°C, -20 kPa), which created a mild thermal environment to inhibit the degradation of heat-sensitive components. The results demonstrated that this synergistic approach significantly optimized the drying kinetics, with the peak drying rate of the 60 W/40 kHz/20 min group reaching 0.02853 g/(g·min), a 30% increase compared to the untreated group. The XGBoost multi-objective model ($R^2 > 0.99$, MSE = 0.00013) was used to quantify the effects of ultrasonic parameters on water migration, revealing that the interaction between power and frequency was the dominant

influencing factor. Quality analysis indicated that the 60 W/40 kHz/30 min group exhibited the highest total flavonoid retention rate (218.7 mg/g), with total phenolic content increasing by 34.2% and antioxidant activity improving by 46.00%. These improvements were attributed to the preservation of cell microstructure (confirmed by SEM) and minimized thermal damage. This integrated technology not only enhances energy efficiency (COP_d up to 0.0144) but also ensures quality retention, providing valuable theoretical support for the high-quality and efficient processing of *Scutellaria baicalensis*.

Key words: Ultrasonic pretreatment; Vacuum far-infrared drying; *Scutellaria baicalensis* slices; XGBoost model; Drying characteristics; Quality analysis

1. Introduction

Scutellaria baicalensis (Lamiaceae family, *Scutellaria* genus) is a valued traditional medicinal plant. Its dried roots are widely utilized in clinical therapeutics and nutraceutical formulations. With a long history of medicinal use (Zhao et al., 2019), its core therapeutic value lies in the presence of several bioactive flavonoid compounds, such as baicalin and wogonoside (Li et al., 2018; Pei et al., 2022). These compounds are well-documented for their significant pharmacological activities, including anti-inflammatory, antioxidant, antibacterial, antiviral, and potential antitumor effects, forming the material basis for the plant's traditional uses, such as clearing heat and detoxifying, purging fire and drying dampness, as well as stopping bleeding and stabilizing the fetus (Liu et al., 2021; Kim et al., 2019). Modern pharmacological studies have further illuminated the plant's potential in

cardiovascular protection, neuroprotection, and immune modulation, underscoring its considerable value for contemporary drug development (Tan et al., 2022; Chan et al., 2011). Despite these remarkable properties, the production of high-quality *Scutellaria baicalensis* products faces substantial challenges. The fresh roots and rhizomes are characterized by high moisture content, making them susceptible to microbial growth and enzymatic browning during post-harvest handling, transportation, and processing. These factors lead to the rapid degradation of bioactive compounds (Vhangani et al., 2021; Mogol et al., 2010), diminishing their therapeutic efficacy and, in some cases, rendering them ineffective. Consequently, an optimized and high-quality drying process is vital for preserving the medicinal qualities of *Scutellaria baicalensis* and ensuring the safety and efficacy of the resulting products.

Currently, traditional drying methods including natural sun-drying and hot air drying still remain predominant in the processing of *Scutellaria baicalensis*. However, these methods present significant drawbacks. Natural sun-drying is characterized by prolonged drying times, substantial dependence on environmental conditions, and poor retention of bioactive compounds. On the other hand, hot air drying can induce thermal degradation, oxidation, and the alteration of heat-sensitive compounds such as flavonoids and baicalin (Vhangani et al., 2021; Mogol et al., 2010). Additionally, this method often results in uneven drying and surface hardening, which impedes the migration of internal moisture. These challenges not only reduce drying efficiency but also compromise the retention of active compounds and biological activity, rendering the final product unsuitable for the high standards required in modern Chinese

67 medicinal material production.

68 To overcome the drawbacks of traditional drying methods, novel physical drying
69 technologies have received extensive attention. Vacuum far-infrared drying (VFIRD)
70 technology, as a combined drying method, integrates the advantages of both a vacuum
71 environment and far-infrared radiation (Zhang et al., 2022;Chen et al., 2024). The
72 vacuum environment substantially lowers the boiling point of water, enabling
73 evaporation at temperatures well below the normal boiling point. Meanwhile,
74 far-infrared radiation exhibits exceptional penetration and thermal effects, which are
75 efficiently absorbed by water and organic molecules in the material, inducing
76 molecular resonance and facilitating uniform heating from the interior (Wang et al.,
77 2023;Jiang et al., 2022). This highly efficient drying method is particularly
78 advantageous for heat-sensitive medicinal materials, such as *Codonopsis pilosula*
79 (Chen et al., 2023) and *Rheum officinale* (Ying et al., 2024), as it enables rapid
80 moisture removal while minimizing the degradation of bioactive compounds caused
81 by high temperatures and prolonged exposure. Further studies have also demonstrated
82 the potential of this technology in the drying of various other medicinal plants
83 (Saengrayap et al., 2014).

84 Ultrasonic pretreatment technology, characterized by high efficiency, low energy
85 consumption, and non-thermal operation, has demonstrated considerable potential in
86 the drying of food and agricultural products (Li et al., 2024; Yan et al., 2023; Yılmaz
87 et al., 2019). When ultrasonic waves propagate through a liquid medium, they induce
88 intense cavitation phenomena. During the negative pressure half-cycle of the acoustic

89 wave, cavitation bubbles collapse, releasing substantial energy that generates
90 localized high temperatures and pressures, powerful micro-jets, and vigorous
91 mechanical vibrations (Salehi et al., 2023; Kong et al., 2023). These physical effects
92 effectively disrupt cell walls and membranes, loosen the internal structure of the
93 material, and markedly reduce resistance to water migration both within the material
94 and throughout subsequent drying processes. Numerous studies have shown that
95 ultrasonic pretreatment can significantly shorten drying time, enhance drying
96 uniformity, promote the development of porous microstructures, and contribute to the
97 preservation or improvement of product quality. For example, Li et al. (2022) reported
98 that ultrasonic pretreatment substantially enhanced drying efficiency and physical
99 properties of adzuki beans; Zhang et al. (2024) demonstrated that ultrasonic-assisted
100 freeze vacuum drying effectively reduced product hygroscopicity; Ni et al. (2024)
101 investigated the effects of ultrasound on protein structural characteristics. Collectively,
102 these findings underscore the efficacy of ultrasonic pretreatment in improving drying
103 performance.

104 This experiment, based on the respective advantages of vacuum far-infrared
105 drying and ultrasonic pretreatment technology, proposes the combined application of
106 the two. By leveraging the cavitation effect of ultrasound to loosen the tissue structure
107 of *Scutellaria baicalensis*, disrupt cell barriers, and reduce water migration resistance,
108 while simultaneously harnessing the characteristics of vacuum far-infrared drying for
109 efficient and uniform dehydration under mild conditions, this approach aims to
110 optimize the drying process. Theoretically, this synergistic strategy is expected to

significantly enhance drying efficiency by shortening processing time, reducing energy consumption, and maximizing the retention of the physicochemical properties of *Scutellaria baicalensis*. This approach offers a promising solution for the production of high-quality medicinal materials.

2. Materials and Methods

2.1. Test Materials and Instrumentation

Scutellaria baicalensis roots were purchased from Longxi County, Dingxi, Gansu Province. The raw materials were washed with deionized water, trimmed, and air-dried in a shaded, ventilated area. Roots exhibiting intact morphology, free from damage, and with uniform diameter (3.0 ± 0.5 cm) were selected as samples and stored in an environmental chamber at 5°C and 60% relative humidity (RH).

The initial moisture content of samples was determined as $61.5\% \pm 0.3\%$ (wet basis) using a QL-200A moisture analyzer. Roots were then sliced into uniform 4-mm-thick sections with a KD-0281 precision slicer, ensuring smooth cutting surfaces. All slices were sealed in light-proof containers to prevent oxidation and moisture absorption for subsequent pretreatment.

Instrumentation included a CR-500 spectrophotometer (Konica Minolta, Japan), JM-B4004 electronic balance (Yuao, China), TS-300C incubator shaker (Jinwen, China), TGL 30N high-speed centrifuge (Maijiasen, China), and T3600U UV spectrophotometer (Jingcheng, China). Ultrasonic pretreatment was performed using a KQ-300VDE triple-frequency CNC cleaner, while vacuum far-infrared drying employed a direct-contact dryer co-developed by the College of Mechanical and

Electronic Engineering at Gansu Agricultural University and Tianshui Shenghua
Microwave Vacuum Co. (China). The structural diagram of the equipment is shown in
Figure 1.

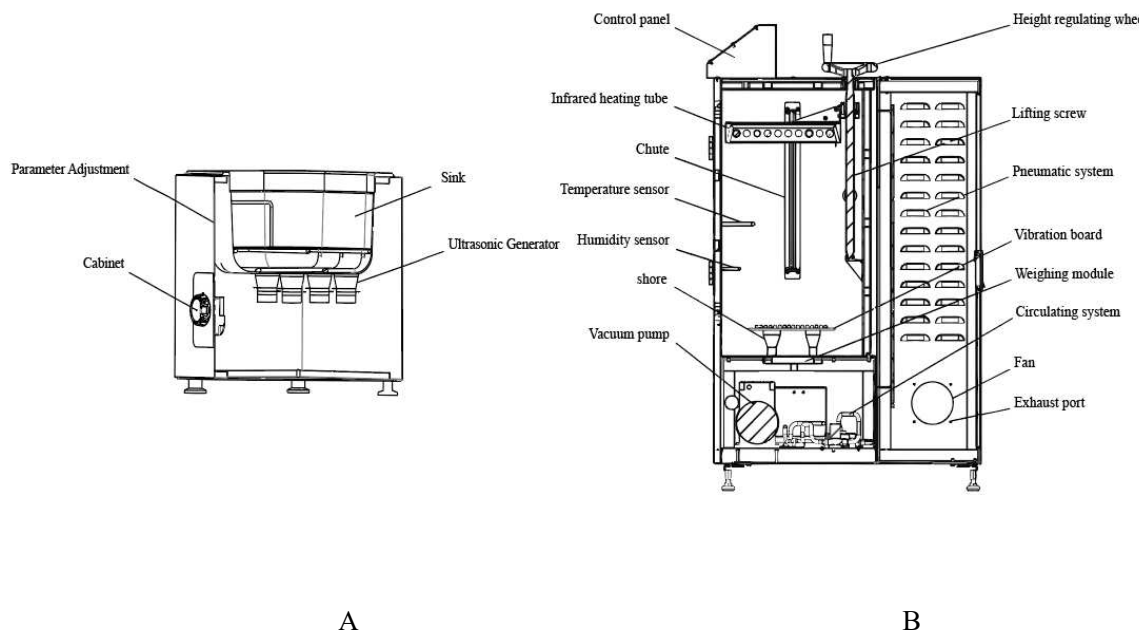


Figure 1 Three-frequency numerical control ultrasonic cleaner (A) Direct contact far infrared
dryer (B)

2.2. Test Method

2.2.1. Ultrasonic Pretreatment Combined with Vacuum Far-Infrared Drying Procedure

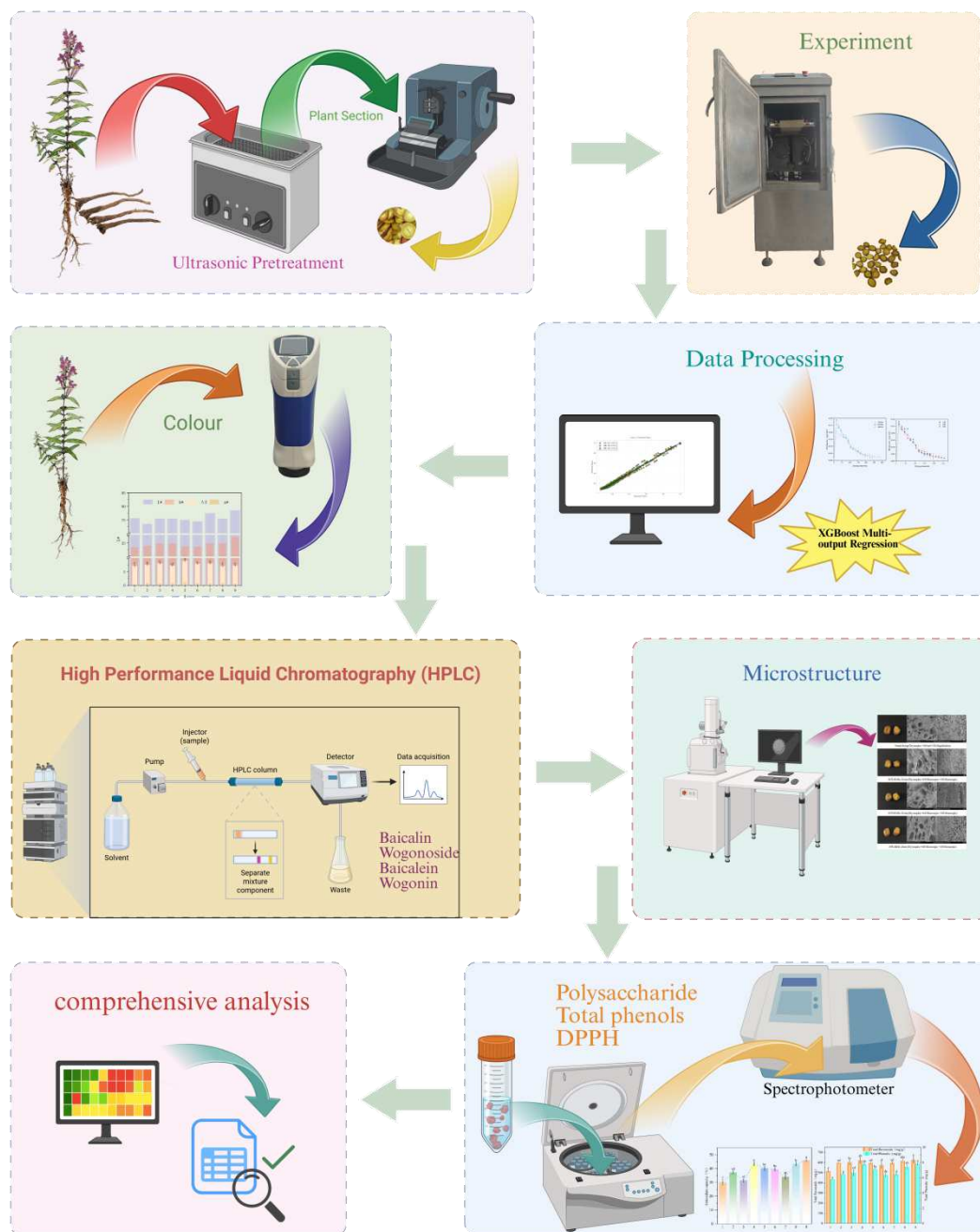


Figure 2 Dry process diagram

Raw material pre-treatment: The roots and stems were rinsed with deionized water to remove surface mud, and the forked and damaged parts were discarded. The materials were then placed in an ultrasonic cleaning device, with 5:1 (v/w) distilled water added.

Setting ultrasonic pre-treatment parameters: Various ultrasonic treatment

conditions were tested, including time (10, 20, 30 min), power (40, 60, 80 W), and frequency (20, 40, 60 kHz), to explore the effects of different combinations on the drying characteristics of *Scutellaria baicalensis*.

Slicing and surface treatment: Immediately after pre-treatment, the surface moisture was absorbed with sterile absorbent paper. The roots and stems were then sliced into 4 mm thick sections using a high-precision Chinese medicine slicing machine (accuracy ± 0.1 mm), ensuring the slices were smooth and free from cracks.

Sample preparation: A 200 ± 0.05 g sample was weighed and evenly spread on a polypropylene porous drying tray (with a pore size of 2 mm), with a stacking density of 10 g/cm^2 to avoid hindering heat transfer due to excessive layering.

Sample preparation: Accurately weigh 200 ± 0.05 g of sample material and spread it evenly on a drying tray.

Experimental design: The sample tray, containing the prepared samples, was placed in the vacuum far-infrared drying machine. During the drying process, samples were periodically weighed every 15 minutes to calculate the moisture content based on mass loss. The quality changes were recorded, and the samples were promptly returned to the drying machine until the moisture content dropped to the safe threshold ($\leq 15\%$). The experiments were divided into 7 groups based on varying drying conditions. Each group was repeated three times, and the average values were analyzed. The experimental conditions are summarized in Table 1.

Table 1 Single factor experiment design

Order number	Pre-Treatment Power (W)	Pre-Treatment Frequency (kHz)	Pre-treatment Time (min)
--------------	-------------------------	-------------------------------	--------------------------

1		Nature drying	
2		Vacuum far- infrared	
3	40	40	20
4	60	40	20
5	80	40	20
6	60	20	20
7	60	60	20
8	60	40	10
9	60	40	30

2.3. Drying Kinetic Parameters

2.3.1. Moisture Content

The moisture content of the material is calculated using the formula (Shi et al., 2020):

$$M_w = \frac{M_m - M_R}{M_0 - M_r} \quad (1)$$

Among them, M_w denotes the sample's moisture content during drying; M_m represents the dry basis moisture content at time t^* (unit: g/g), M_r the equilibrium moisture content (g/g), and M_0 the initial dry basis moisture content (g/g).

2.3.2. Dry Basis Moisture Content

The dry basis moisture content is calculated according to the formula (Macedo et al., 2021):

$$M_t = \frac{W_t - W_d}{W_d} \quad (2)$$

Here, W_t represents the sample mass at time t , with the unit being grams; W_d represents the mass after drying, also with the unit of grams.

2.3.3. Drying Rate

The drying rate of the dried samples can be calculated using the formula (Xu et

al., 2020):

$$D_R = \frac{M_t - M_{t-\Delta t}}{\Delta t} \quad (3)$$

Among them, D_R denotes the sample's drying rate (unit: g/(g·min)), while M_{t_1} and M_{t_2} represent the dry basis moisture content at times t_1 and t_2 , respectively (unit: g/g).

2.4. Multi-objective Modeling of Moisture Ratio Based on XGBoost Ensemble Learning

To overcome the limitations of traditional mathematical models in addressing the multi-parameter coupling effects of ultrasonic pre-treatment on drying kinetics, this study focuses on a multi-objective regression problem that aims to predict different moisture ratios under various ultrasonic pre-treatment conditions. The XGBoost ensemble learning method is employed to build the model. Initially, the raw data is preprocessed through binning and the creation of second-order polynomial features. This preprocessing step enhances the feature space by incorporating both main effects and interaction effects of pre-treatment parameters (temperature, time, and frequency), which improves the model's ability to capture nonlinear relationships (Maharjan et al., 2024). Next, the XGBoost hyperparameters, such as tree depth and regularization parameters, are optimized using 5-fold cross-validation within the Optuna framework. The objective function for optimization is defined as the average R^2 minus 0.2 times the average mean squared error (MSE), in order to strike a balance between the model's goodness of fit and its prediction error. To predict multiple related target variables (MR1, MR2, MR3) from three experimental trials simultaneously, a pipeline

model comprising RobustScaler and MultiOutputRegressor is constructed. The performance of the model is evaluated using the R^2 metric, and various visualization techniques, including 3D scatter plots, residual kernel density estimation (KDE) plots, and MSE plots, are generated using Python's visualization module.

2.4.1. Binning Processing

Discretize continuous features into k intervals (equal-frequency binning) (Zhou et al., 2023):

$$Bin(x_i) = \sum_{j=1}^k j \cdot I(x_i \in (b_{j-1}, b_j]) \quad (4)$$

Among them, I represents the indicator function, and b_j represents the binning interface.

2.4.2. Second-order Polynomial Feature Generation

The extended feature space includes main effects and interaction effects (Zhou et al., 2023):

$$Poly_2(X) = [x_i, x_i^2, x_i x_j] \forall i, j \in \{\text{Temperature, time, power}\}, i \neq j \quad (5)$$

Among them, x_i^2 generates the squared term and the interaction term $x_i x_j$.

2.4.3. XGBoost Objective Function Tree Model Prediction Function

The prediction result of the t -th tree is (Zhou et al., 2023):

$$\hat{y}_i^{(t)} = \hat{y}_i^{(t-1)} + f_t(x_i) \quad (6)$$

Among them, f_t represents the t -th tree, and $\hat{y}_i^{(t-1)}$ is the cumulative predicted value of the first $t-1$ trees.

Regularization objective function:

$$\Gamma^{(t)} = \sum_{i=1}^n l(y_i, \hat{y}_i^{(t-1)} + f_t(x_i)) + \Omega(f_t) \quad (7)$$

Regularization term:

$$\Omega(f_t) = \gamma T + \frac{1}{2} \lambda \omega^2 \quad (8)$$

Among them, γ represents the minimum reduction in loss for the splitting of leaf nodes, λ is the regularization weight, T is the number of leaf nodes, and ω is the weight vector of the leaf nodes.

2.4.4. Optuna Hyperparameter Optimization Objective

The objective function integrates the balance between fitting goodness and error (Abdel Hady et al., 2024):

$$O_{bjective} = R^2 - 0.2 \times MSE \quad (9)$$

The average determination coefficient of 5-fold cross-validation:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (10)$$

The average mean square error of 5-fold cross-validation:

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (11)$$

2.4.5. Multiple Output Regressor

Joint prediction of target variables = ($\{\text{MR1}\}$, $\{\text{MR2}\}$, $\{\text{MR3}\}$) (Mathew et al., 2021):

$$\hat{Y} = \begin{cases} f_1(X) \\ f_2(X) \\ f_3(X) \end{cases} \quad (12)$$

Train an XGBoost model independently for each target, while sharing the feature

243 engineering process.

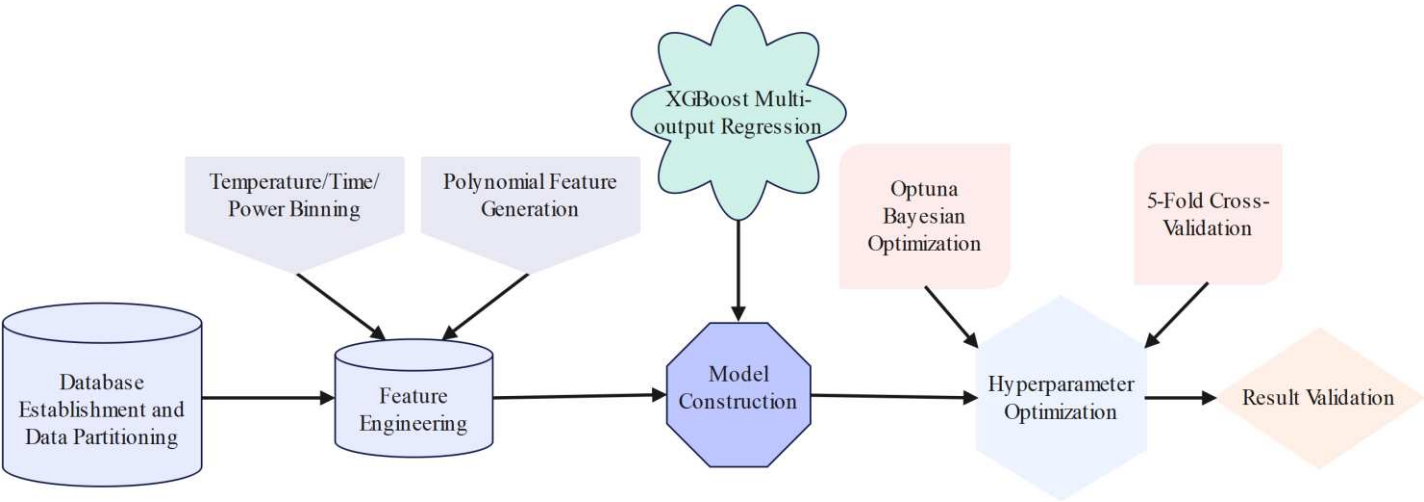


Figure 3 Machine learning principles

244 **2.4.6. Parameter Settings**

245 Table 2 Machine learning parameter table

Hyperparameter	Hunting zone	Distribution pattern	Optimization method
Tree depth	(5,15)	Integers are evenly distributed	Bayesian optimization
Learning rate	(0.001,0.1)	The logarithm is uniformly distributed	
Number of trees	(500,2000)	The logarithm is uniformly distributed	
Sample sampling ratio	(0.7,1.0)	Equidistribution	
Feature sampling ratio	(0.7,1.0)	Equidistribution	
L ₁ regularization coefficient	(1e-6,10)	The logarithm is uniformly distributed	
L ₂ regularization coefficient	(1e-6,10)	The logarithm is uniformly distributed	
Minimal loss of fragmentation	(0,5)	Equidistribution	
Minimum child node weight	(1,10)	Integers are evenly distributed	

246 **2.5. Energy Efficiency Evaluation**

247 In this experiment, the coefficient of performance (COP) for drying was
248 introduced as an evaluation metric to assess the energy efficiency of the drying system.
249 The physical definition of COP is the ratio of the theoretical energy required to
250 remove one unit of moisture to the total energy input of the actual system. This
251 calculation is based on the first law of thermodynamics. The core formula for
252 calculating the COP is as follows:

$$COP_d = \frac{m_w \times \Delta h_{vap}}{E_{total}} \quad (13)$$

$$m_w = m_r \times \frac{X_r - X_d}{1 + X_r} \quad (14)$$

$$E_{total} = E_1 + E_2 \quad (15)$$

Among them, evaporation amount (kg), Δh_{vap} represents the latent heat of vaporization of water, m_r is the initial mass of the wet material (kg), X_r and X_d are the initial and final moisture contents of the dry basis, E_{total} is the total output energy of the system, E_1 is the energy consumption of pre-treatment ultrasonic pre-treatment, and E_2 is the energy consumption of vacuum far-infrared.

2.6. Color Difference

Based on the research methodology of Zheng et al., (2023) the total color difference (ΔE) serves as a direct evaluation metric for surface color quality of materials.:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (16)$$

2.7. The Effects of Ultrasonic Pretreatment Combined with Vacuum Far-Infrared on the Quality of *Scutellaria baicalensis*

2.7.1. Determination of Total Phenolic Content

Total phenolic content (TPC) was determined by the Folin-Ciocalteu method, (Xu et al., 2022).

2.7.2. Determination of Total Flavonoid Content

Total flavonoid content (TFC) was quantified via the $\text{NaNO}_2\text{-AlCl}_3\text{-NaOH}$ method (Feng et al., 2020).

2.7.3. Determination of Antioxidant Activity

Antioxidant activity was determined by the DPPH method (Yu et al., 2020).

2.8. Determination of Natural Active Component Content

The dry matter content of natural active components under different ultrasonic pretreatment conditions was determined by HPLC, referring to the method of Zhang et al., (2023).

2.9. Microscopic Structure

The samples were slightly trimmed and observed using a scanning electron microscope (S-4800N, Hitachi, Japan). They were cut into 2 mm × 2 mm pieces, immediately fixed in 2.5% glutaraldehyde solution, and observed at 5.0 kV acceleration voltage after gold sputter coating.

2.10. Principal Component Analysis (PCA)

To thoroughly investigate the comprehensive impact of different drying processes on the multi-dimensional physicochemical quality indicators of *Scutellaria baicalensis* and their inherent correlation patterns, this study employed Principal Component Analysis (PCA) and Pearson correlation analysis. Using Origin 2025 software for the analysis, PCA was applied to identify the key principal components driving the overall differences among samples and their corresponding load factors, as well as to visualize the distribution patterns of different treatment groups within the quality space. Pearson correlation analysis was used to quantify the relationship between each specific indicator. The combined application of these two methods aimed to objectively analyze the complex multivariate relationships between the

ultrasonic-assisted drying process parameters and the overall quality characteristics of the final *Scutellaria baicalensis* products.

2.11. TOPSIS-CRITIC Comprehensive Evaluation Method

To determine the optimal drying process, this study utilized the coupled evaluation method of TOPSIS-CRITIC. TOPSIS was employed to quantify the proximity of each process to the optimal solution, while the CRITIC method was used to objectively assign weights to factors such as drying time, peak drying rate, energy efficiency ratio, total flavonoids, total phenols, antioxidant activity, baicalin, wogonoside, effectively addressing potential subjective weight biases.

2.11.1. Data Standardization

Positive indicator formula:

$$x'_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \quad (17)$$

Negative indicator formula:

$$x'_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \quad (18)$$

Among them, x_{ij} represents the original value: the value of the j -th indicator of the i -th plan, $\max x_j$ is the maximum value of this indicator, and $\min x_j$ is the minimum value of this indicator.

2.11.2. Weight Determination Method of CRITIC

Standard Deviation:

$$\sigma_j = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_{ij} - \bar{x}_j)^2} \quad (19)$$

Among them, n represents the total number of schemes, and represents the

average value of the indicators.

Weight calculation:

$$\omega_j = \frac{\sigma \times \sum_{k=1}^m (1 - |r_{jk}|)}{\sum_{j=1}^n [\sigma_j \times \sum_{k=1}^m (1 - |r_{jk}|)]} \quad (20)$$

Among them, m represents the total number of indicators, and r_{jk} is the correlation coefficient between indicator j and indicator k .

2.11.3. Implementation of TOPSIS Algorithm

Standardized values of the weighted matrix:

$$v_{ij} = \omega_j \times x'_{ij} \quad (21)$$

Positive and negative ideal solutions:

$$\begin{aligned} S^+ &= (\max v_1, \max v_2, \dots, \max v_n) \\ S^- &= (\min v_1, \min v_2, \dots, \min v_n) \end{aligned} \quad (22)$$

Euclidean distance calculation:

$$S_i^\pm = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^\pm)^2} \quad (23)$$

Degree of proximity assessment:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (24)$$

The C_i value lies within the range of (0, 1), with larger values indicating better overall performance.

2.12. Statistical Analysis

All results represent the mean values of three trials, with significance verified using SPSS software at $*p* < 0.05$.

3. Results and Discussion

3.1. Effects of Different Ultrasonic Pretreatment Conditions on the Drying Characteristics of *Scutellaria baicalensis*

3.1.1. Effects of Ultrasonic Pretreatment Time on the Drying Characteristics of *Scutellaria baicalensis*

Under the conditions of a pre-treatment power of 60 W, a frequency of 40 kHz, an irradiation height of 250 mm, a temperature of 50 °C, a vacuum degree of -20 kPa, the effects of different ultrasonic pre-treatment times on the drying of *Scutellaria baicalensis* were investigated. The experimental results, shown in Figure 4, indicate that none of the groups exhibited a constant rate stage. The drying rate curve demonstrated an initial increase followed by a decrease as the moisture content reduced. The 20-minute pre-treatment group exhibited the best dehydration performance: the peak drying rate in the initial stage (15 minutes) reached 0.02877 g/(g·min), which was 29.4% higher than the 10-minute group (0.02224 g/(g·min)). Simultaneously, the moisture ratio of the 20-minute group decreased the fastest, dropping to 0.69731 at 30 minutes, significantly lower than the 10-minute group (0.77505) and the 30-minute group (0.74265). However, extending the pre-treatment time to 30 minutes did not further enhance the effect. Although the moisture ratio at the end of drying (0.08905) was the lowest, the total drying time (240 minutes) was 23.1% longer than that of the 20-minute group (195 minutes). This phenomenon is attributed to the dual effects of ultrasonic cavitation: moderate treatment (20 minutes) breaks the hydrogen bond network in the cell wall, promoting the conversion of bound water to free water and reducing internal diffusion resistance (Kudryavtsev et

al., 2023). In contrast, excessive treatment (30 minutes) causes cell structure collapse,
obstructing water migration channels in the later stages and counteracting the initial
advantage. Therefore, 20 minutes is the optimal pre-treatment time, balancing rapid
dehydration with the preservation of structural integrity.

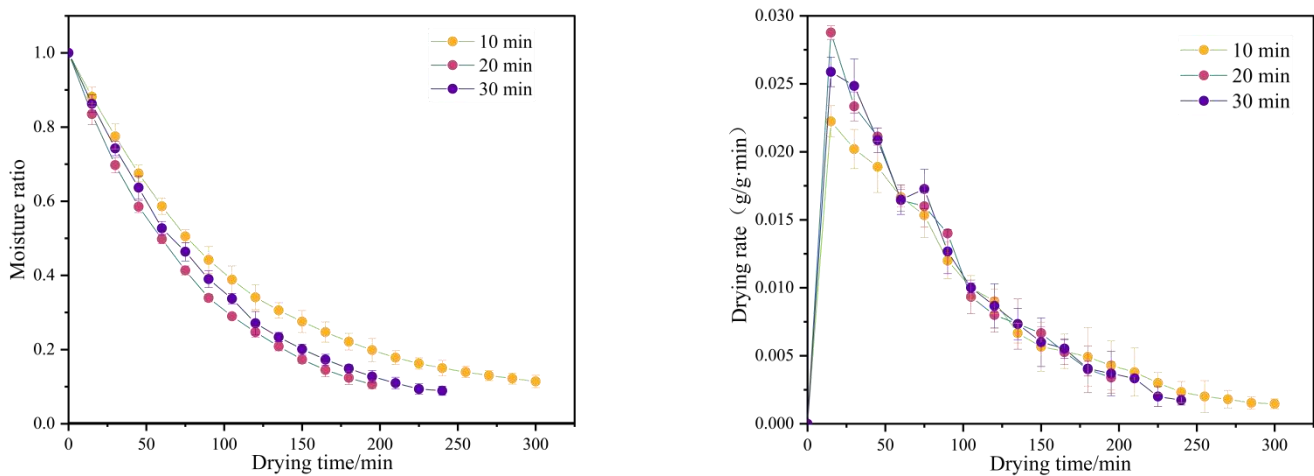


Figure 4 Influence of pretreatment time on drying curve and drying rate curve.

3.1.2. The influence of ultrasonic pre-treatment frequency on the drying characteristics of *Scutellaria baicalensis*

Under the conditions of a pre-treatment power of 60 W, a duration of 20 min, an irradiation height of 250 mm, a temperature of 50 °C, a vacuum degree of -20 kPa, and different ultrasonic pre-treatment frequencies, the influence of ultrasonic pre-treatment frequency on the vacuum far-infrared drying characteristics of *Scutellaria baicalensis* was investigated. The experimental results, shown in Figure 5, reveal that ultrasonic pre-treatment frequency significantly influenced the drying characteristics of *Scutellaria baicalensis*. With a 60 W power and 20-minute treatment, the effect of different frequencies on drying characteristics followed a synergistic

pattern between moisture ratio and drying rate. The high-frequency group exhibited a notable initial dehydration advantage, with moisture content reduced by 5.6% compared to the 40 kHz group and 10.3% compared to the 20 kHz group. During this stage, high-frequency ultrasonic treatment enhanced the cavitation effect, promoting the release of bound water within the cells and reducing initial diffusion resistance (Defferriere et al., 2022). The mid-stage evolution showed frequency-specific behavior: the 40 kHz group displayed an unusual synergistic pattern in moisture ratio and drying rate at 135 minutes—when the moisture ratio dropped to 0.2085, the rate increased to 0.0074 g/(g·min), 16.4% higher than the 60 kHz group. However, at 180 minutes, the moisture ratio of 0.1241 corresponded to a drying rate drop to 0.004 g/(g·min), representing a 45.4% decrease. This was due to local structural collapse induced by medium-frequency ultrasonic treatment, which temporarily obstructed water transport channels after water release. The drying behavior in the later stage differentiated: at 195 min with a moisture ratio of 0.1848, the 60 kHz group showed a secondary peak rate (0.0051 g/(g·min)), reflecting the continuous dehydration ability maintained by the microchannels, which conforms to the typical boundary resistance increase model (Yang et al., 2021).

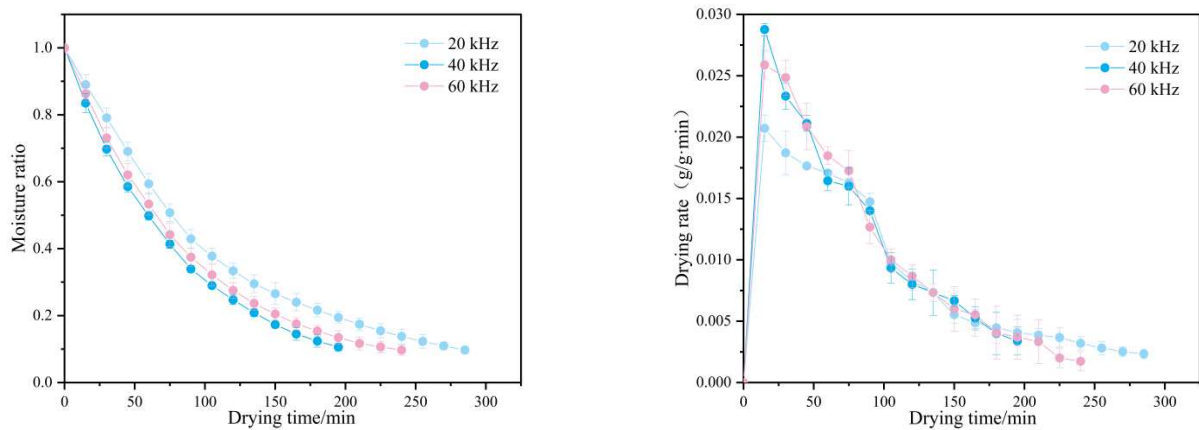
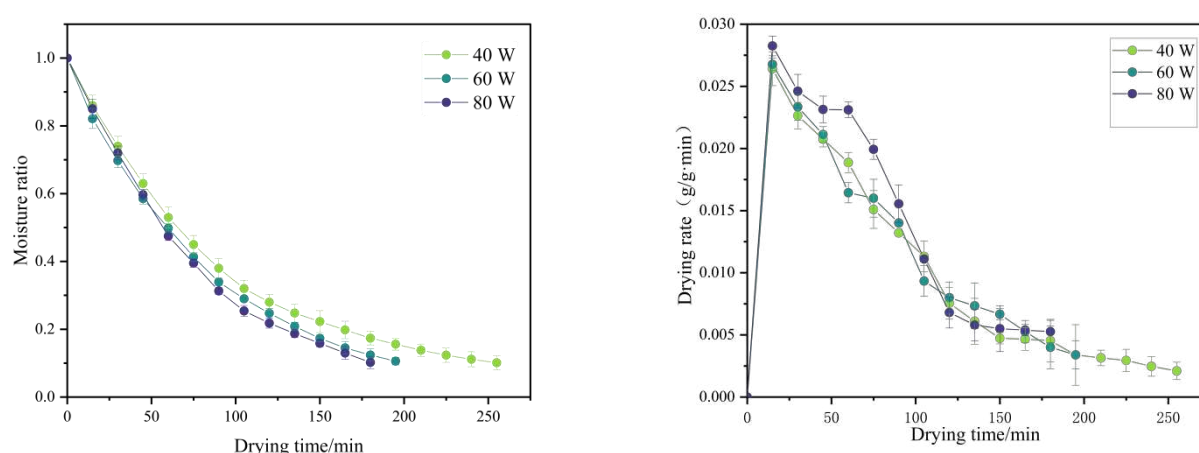


Figure 5 Influence of pretreatment power on drying curve and drying rate curve.

3.1.3. The Effect of Ultrasonic Pretreatment Power on the Drying Characteristics of *Scutellaria baicalensis*

Under the conditions of a pre-treatment frequency of 40 kHz, a duration of 20 minutes, an irradiation height of 250 mm, a temperature of 50 °C, and a vacuum degree of -20 kPa, the test results, shown in Figure 6, revealed that increasing ultrasonic power significantly enhanced the dehydration process of *Scutellaria baicalensis*. The peak drying rate in the 80 W group was the highest (0.0285 g/(g·min)), significantly higher than the 40 W and 60 W groups, indicating that increased power effectively promoted initial water removal by enhancing ultrasonic cavitation intensity. By 75 minutes, the moisture ratio in the 80 W group dropped to 0.3915, lower than the 40 W and 60 W groups, further confirming the accelerating effect of power on initial dehydration. During the middle and later stages of drying, the drying rate exhibited different patterns: the 40 W group maintained a relatively high rate, while the 60 W and 80 W groups experienced significant decreases in their drying rates, which became closer to each other. This suggests that the change in

material structure under medium and high power may create greater resistance to internal water migration(Kong et al., 2023). In the later stages of dehydration, the impact of power differences on drying rate attenuation became more pronounced. The drying rate of the 80 W group exhibited an accelerating attenuation trend, while the 60 W group maintained a low rate with relatively gentle or fluctuating attenuation. The 40 W group (with a moisture ratio below 0.22261 from 150 to 195 minutes) also



experienced a decrease in rate, but the overall attenuation was slower (from 0.03253 g/(g·min) at 150 minutes to 0.01722 g/(g·min) at 195 minutes). In summary, increasing power effectively accelerated initial dehydration of *Scutellaria baicalensis*. However, at high power (80 W), greater internal resistance in the later low-moisture stage led to faster attenuation of the drying rate. The 60 W power maintained better rate stability than the 80 W power while ensuring efficient initial dehydration during the later stages(Wang et al., 2024).

Figure 6 Influence of pretreatment frequency on drying curve and drying rate curve

3.2. Prediction of Water Ratio by XGBoost Model and Analysis of Parameter Effects

In this study, a multi-output XGBoost model, incorporating polynomial feature engineering, was developed to predict water ratios (MR_1 , MR_2 , MR_3) during the drying process of *Scutellaria baicalensis* under ultrasonic pretreatment. The feature expansion included second-order interactions between pretreatment parameters (power, time, frequency), and hyperparameter optimization via Optuna enhanced prediction accuracy through a composite objective function. The model showed exceptional performance: the scatter plot of actual versus predicted values (Figure 7) demonstrated that data points for all three water ratio groups were closely aligned with the diagonal line, with MR_1 at 0.9935, MR_2 at 0.9942, and MR_3 at 0.9947, the results are shown in Table 3. The intercept was near zero, indicating strong consistency between predicted and actual values, with an average model MSE of 0.00013. The KDE plot of residual distribution (Figure 8) revealed that residuals were normally distributed around zero with a narrow bandwidth, suggesting stable prediction accuracy across different drying stages and no significant deviations or overfitting.

The XGBoost model effectively revealed the nonlinear correlation between ultrasonic pretreatment parameters and drying kinetics through feature engineering and machine learning methods. This provides data-driven model support for the multi-objective optimization of the *Scutellaria baicalensis* drying process. The visualization results further verified the conclusion that parameter synergy effects dominate the drying efficiency, outperforming traditional mathematical models.

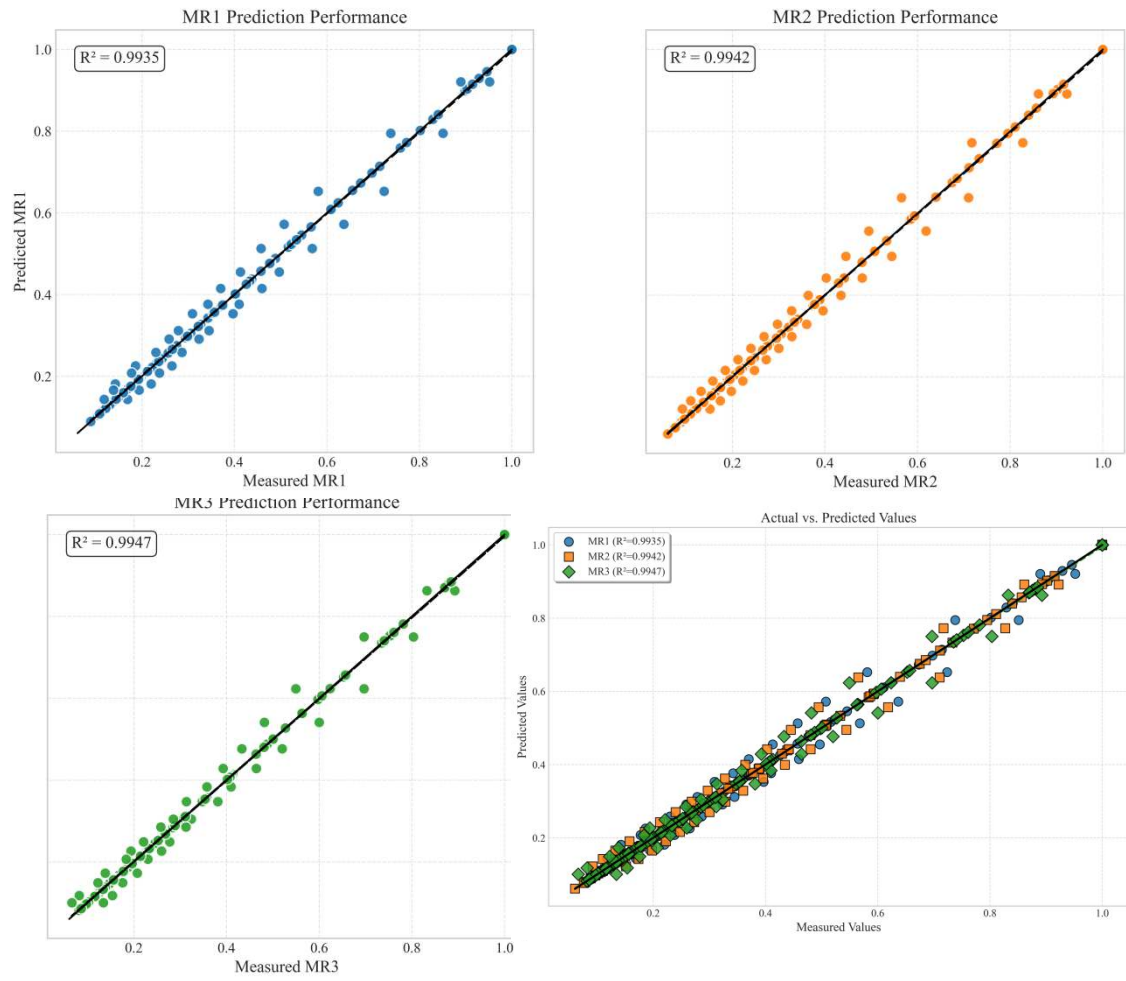


Figure 7 Comparison Chart of Actual and Predicted Water Content

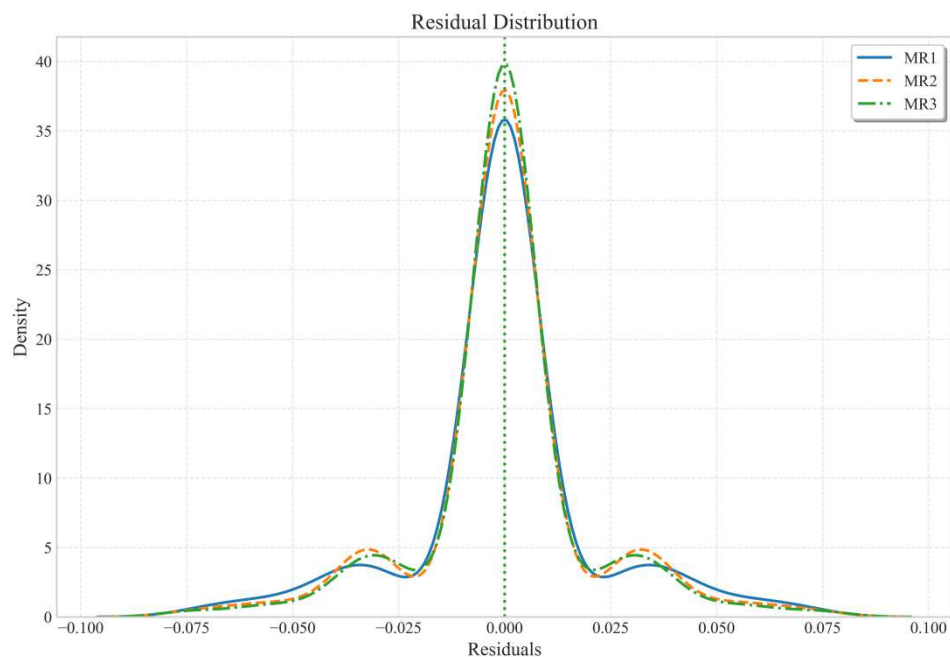


Figure 8 Model residual curve

Table 3 Model result diagram

Ta rget	R^2	MSE	RMSE
M R1	0.9934	0.000478	0.02188
M R2	0.9942	0.000426	0.02064
M R3	0.9947	0.000387	0.01968

3.3. Analysis of Energy Efficiency Ratio of Drying System

Table 4 Energy efficiency ratio of drying system results

Order number	Process mode	Drying time (min)	Total energy consumption (kWh)	COP_d
1	Natural drying	7200	0	N/A
2	Vacuum far-infrared	330	5.500	0.0079
3	40W/40kHz/20min	255	4.263	0.0102
4	60W/40kHz/20min	195	3.450	0.0125
5	80W/40kHz/20min	180	3.027	0.0144
6	60W/20kHz/20min	270	4.700	0.0092
7	60W/60kHz/20min	225	3.950	0.0110
8	60W/40kHz/10min	315	5.350	0.0081
9	60W/40kHz/30min	210	3.800	0.0114

Note: The natural drying group COP_d has no practical significance, and infinity

is given here

The results (Table 4) show that the energy efficiency values range from 0.0079 to 0.0144. The optimal energy efficiency is observed in the 80W/40kHz/20min pre-treatment group, while the group without pre-treatment has the lowest energy efficiency (0.0079), with significantly prolonged drying time. Increasing the power from 40W to 80W results in a 41.2% increase in energy efficiency. As the pre-treatment time is extended from 10 minutes to 30 minutes, the COP_d value initially increases, then decreases, suggesting that excessively long pre-treatment times may reduce energy efficiency, making them less effective. The 40kHz frequency group (0.0125) shows a 35.9% higher energy efficiency than the 20kHz group (0.0092) and a 13.6% higher efficiency than the 60kHz group (0.0110). There is a negative correlation between energy efficiency and drying time. The 80W group demonstrates a 45.5% reduction in drying time, corresponding to an 82.3% increase in energy efficiency. This confirms that optimizing the pre-treatment process enhances energy efficiency by simultaneously reducing final moisture content and shortening drying time.

3.4. Effect of Ultrasonic Pretreatment on Color Difference of *Scutellaria baicalensis* Slices:

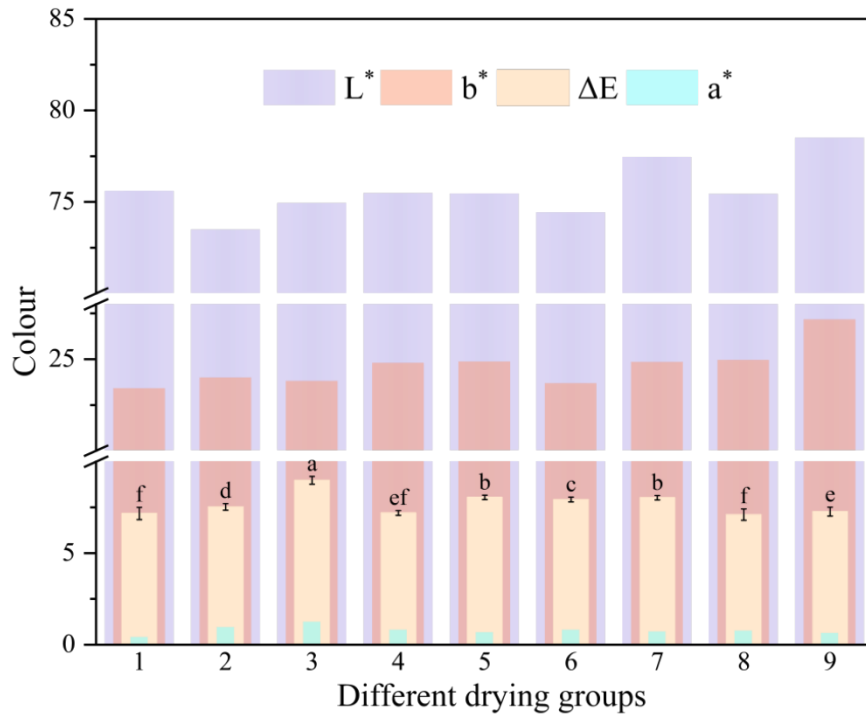


Figure 9 Color of *Scutellaria baicalensis* after drying

467 Color difference is a key indicator for assessing the quality of dried *Scutellaria*
 468 *baicalensis*, as changes in parameters directly affect product quality. Figure 9 shows
 469 systematic color differences between ultrasound-treated samples and the natural
 470 air-drying control group. For the red-green index (a value), all ultrasound groups,
 471 except for the 40W/40kHz/20min group, exhibited slightly higher values than the
 472 natural air-drying group, indicating that ultrasound treatment generally enhanced the
 473 red tone. In terms of brightness (L value), all ultrasound groups were significantly
 474 brighter than the untreated group. The overall color difference (ΔE) was lowest in the
 475 60W/40kHz/10min group, 25.2% lower than the natural air-drying group, while the
 476 40W/40kHz/20min group showed the largest ΔE , 25.2% higher, highlighting the
 477 critical impact of power selection on color stability. The parameter regulation
 478 mechanism study indicates that when the fixed power is 60 W and the time is 20 min,

increasing the frequency from 20 kHz to 40 kHz did not significantly increase the L value, but brightness increases at 60 kHz. For the 40kHz/20min condition, the 40W treatment significantly decreased the L value and increased ΔE , while the 80W group maintained a normal L value but had an increased ΔE . In the 60W/40kHz system, ΔE increased monotonically with the extension of treatment time, confirming that 10 minutes is the optimal treatment duration. These phenomena result from the dual effects caused by the cavitation effect of ultrasound waves (ElGamal et al., 2023): on the one hand, it changes the cell wall permeability to promote the migration of polyphenols, and on the other hand, it may cause the degradation of heat-sensitive components. The key phenomena such as the high a value caused by 40 W power, the high L value produced by 60 kHz/30 min, and the high ΔE caused by 80 W, together indicate that the ultrasonic parameters need to be optimized by balancing power, frequency, and time to achieve color optimization.

3.5. The influence of ultrasound pre-treatment on the content of flavonoids and total phenols in *Scutellaria baicalensis* slices

The data analysis of the experiment is shown in Figure 10. Different ultrasound pre-treatment conditions have a significant impact on the total flavonoids and total phenols content of *Scutellaria baicalensis* after drying. Flavonoids, as the core active components, are directly related to the pharmacological activity of the product. The total flavonoid content in the natural air-drying group is 173.82 mg/g, while the untreated drying group has 201.03 mg/g, suggesting that traditional drying, due to thermal effects or oxidation, leads to flavonoid degradation (Qiao et al., 2014). Under

ultrasound pre-treatment, the highest total flavonoid content (218.7 mg/g) is achieved under the 60W/40kHz/30min condition. Meanwhile, total phenol content shows a non-linear variation. The natural air-dried group and the unprocessed group were 8.517 mg/g and 9.541 mg/g, respectively, and under the 60W/40kHz/20min condition, total phenol content reaches 11.429 mg/g, which is 34.2% higher than the natural air-drying group and 19.8% higher than the unprocessed group. The optimization of power, frequency, and time parameters indicates that moderate ultrasonic conditions effectively promote component release and inhibit degradation (Jirasuteeruk et al., 2019). However, excessive power or inappropriate frequency and time can reduce the effect and even cause component loss. In the time gradient study, it was observed that under the 60W/40kHz condition, total phenol content significantly increased from the 10min group to the 20min group, but only showed a slight 0.87% increase from the 20min to the 30min group, which may risk enzymatic browning (Vo et al., 2019).

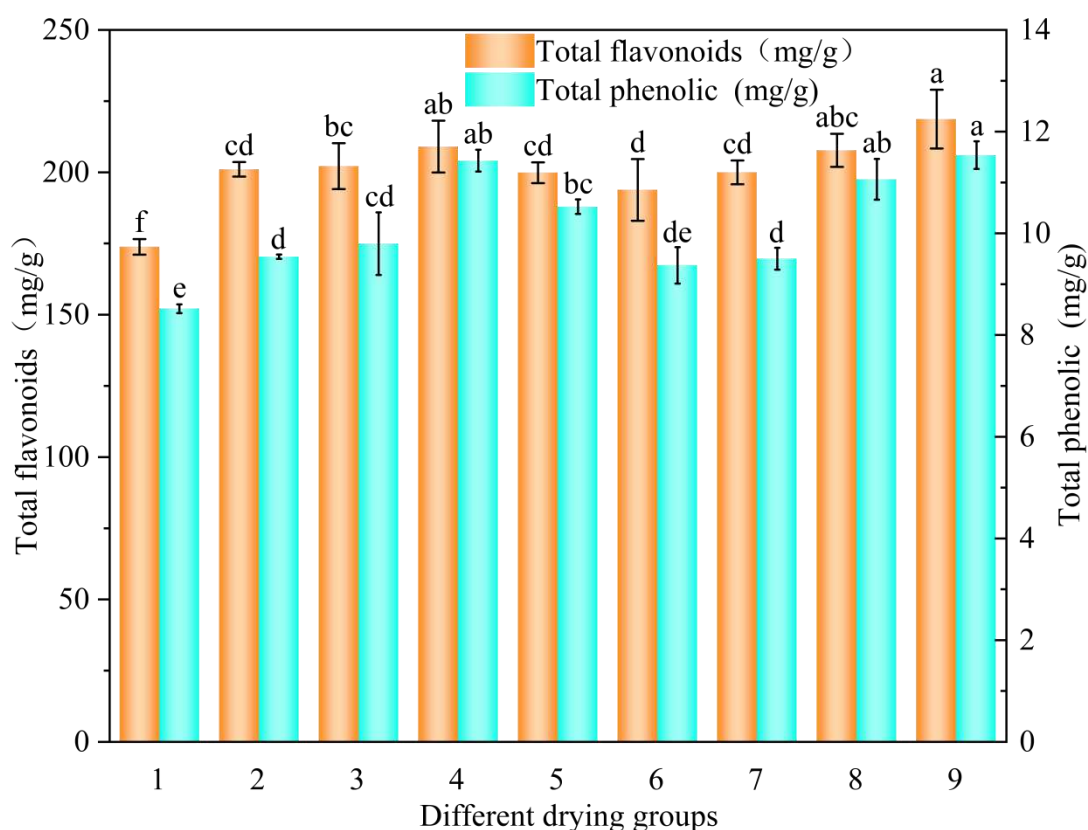


Figure 10 Total flavonoids and total phenols after drying of *Scutellaria baicalensis*

3.6. The Effect of Ultrasonic Pretreatment on the Antioxidant Activity of *Scutellaria baicalensis* Slices

The results of the experimental data analysis, as shown in Figure 11, indicate that the ultrasonic pretreatment parameters have a significant nonlinear regulatory effect on the antioxidant activity of *Scutellaria baicalensis*. The 60W/40kHz/30min group exhibited an antioxidant activity of 46.00%, significantly higher than that of both natural, as well as the untreated group. The antioxidant activity was strongly positively correlated with the total phenol ($r = 0.87$) and total flavonoid ($r = 0.76$) content, confirming that phenolic substances are the main contributors to free radical scavenging. Power had a threshold effect on antioxidant activity: the 60W/20min group outperformed both the 40W and 80W groups, suggesting that excessive power

induces thermal damage, accelerating the oxidation and degradation of phenolic compounds. Frequency optimization revealed that the 40kHz group performed significantly better than the 20kHz group. Compared to the 60kHz group, the 40kHz frequency's cavitation effect effectively disrupts cell walls to release antioxidant components while avoiding the molecular damage caused by high-frequency (60kHz) mechanical vibrations. The duration of treatment had a crucial impact: the 30-minute treatment showed only a slight improvement over the 20-minute and 10-minute treatments, likely due to sufficient ultrasonic treatment that promoted the release of hydrophobic flavonoids such as baicalin. These flavonoids enhance free radical scavenging via the hydrogen-donor mechanism (Yudina et al., 2012).

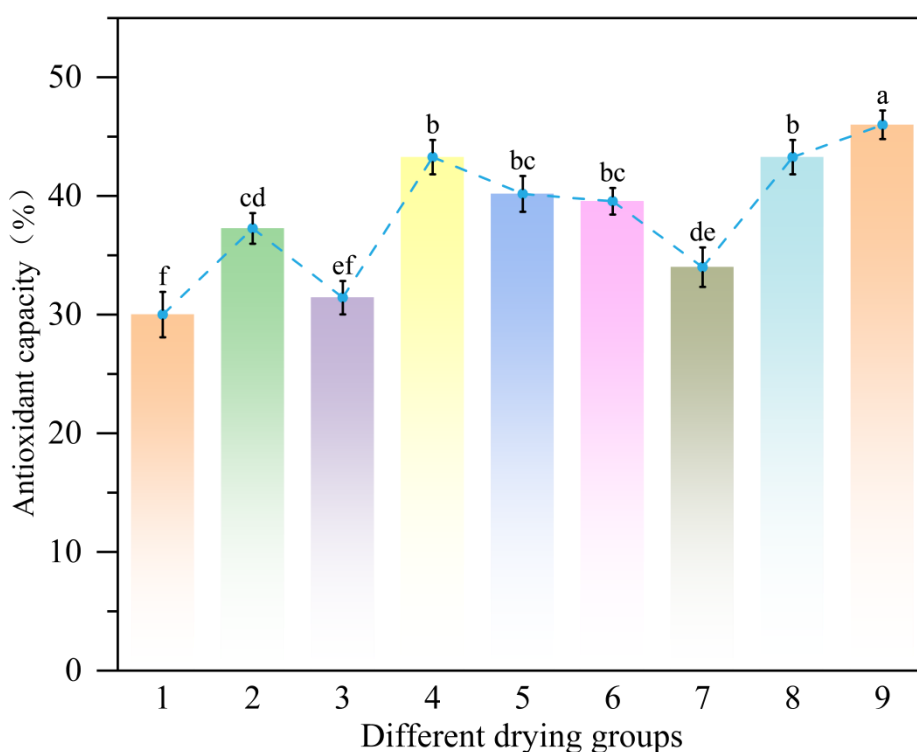


Figure 11 Antioxidant capacity of *Scutellaria baicalensis* after drying

3.7. Analysis of Active Component Content

The results, shown in Figure 12, demonstrate that different ultrasonic pre-treatment conditions significantly affected the retention rates of baicalin and wogonoside. The highest baicalin content was achieved under the conditions of 60W power, 40kHz frequency, and 20-minute treatment, which was significantly higher than that of both the natural drying group and other ultrasonic treatment groups. This indicates that this specific combination of ultrasonic parameters was most effective for its dissolution. In contrast, the retention rate of wogonoside was highest under natural drying conditions, with all ultrasonic pre-treatment conditions leading to a significant decrease in its content. The extent of wogonoside loss was influenced by ultrasonic parameters: while its content fluctuated among different treatment groups, a decreasing trend was observed with increasing ultrasonic power (from 40W to 80W, fixed at 40kHz/20min). The lowest retention value was found at 60W/20min. Notably, high-frequency treatment at 60kHz showed a relatively favorable trend for wogonoside retention compared to low-frequency treatments at 20kHz or 40kHz. Optimizing the ultrasonic parameters (60W/40kHz/20min) effectively increased baicalin yield, but inevitably led to the loss of wogonoside. The extent of this loss was negatively correlated with power, while increasing the frequency somewhat mitigated the loss (Yudina et al., 2012).

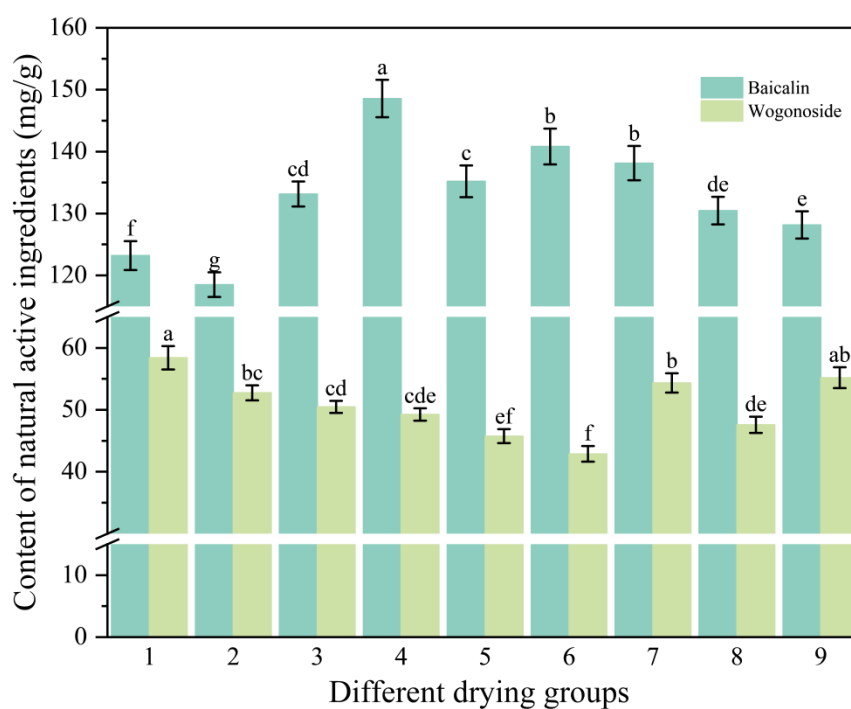
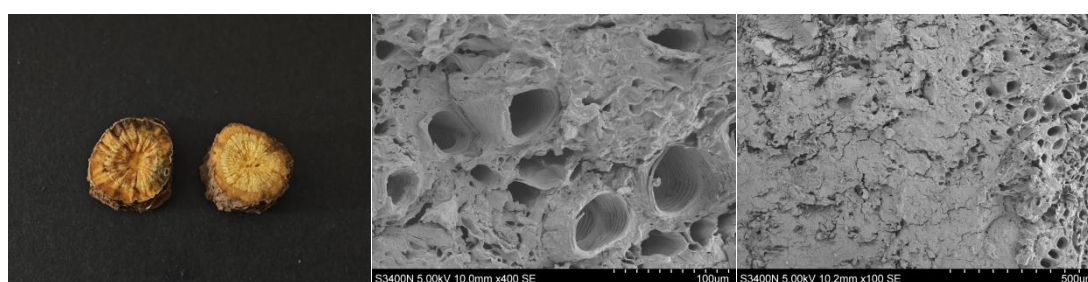
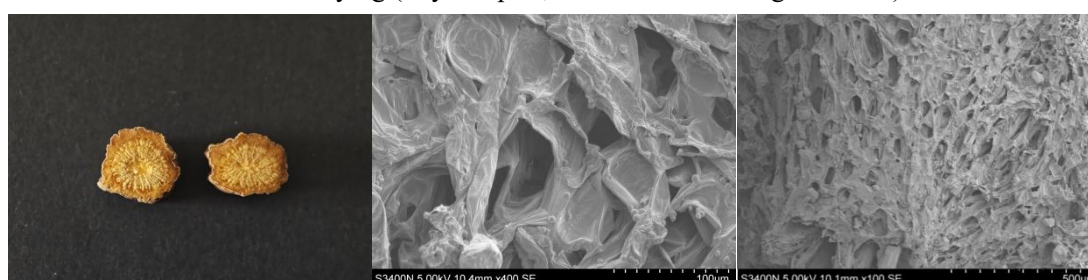


Figure 12 Content of natural active ingredients after drying of *Scutellaria baicalensis*

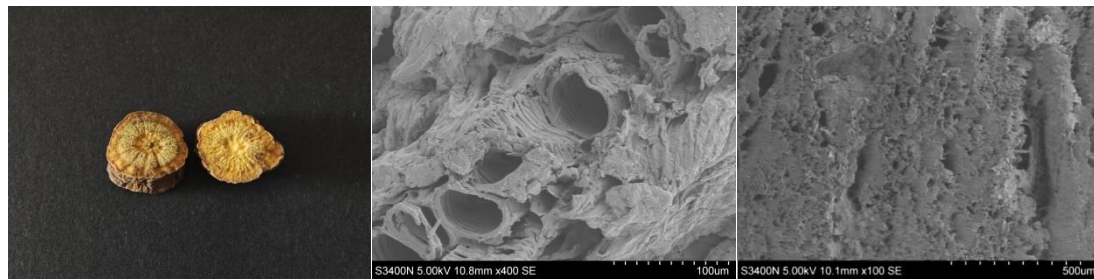
3.8. Microscopic Structure



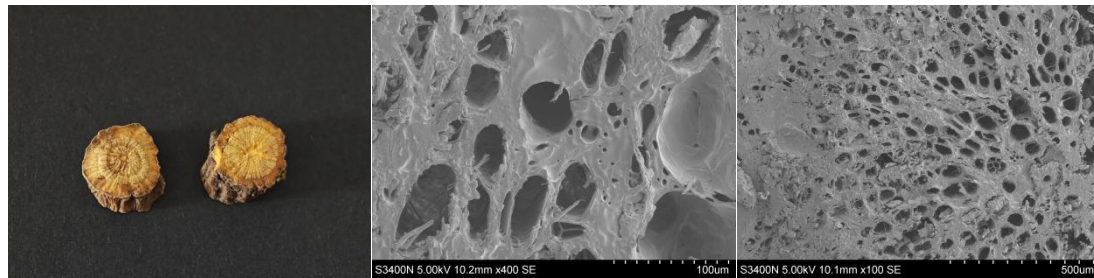
Natural drying (Dry samples, $\times 400$ and $\times 100$ Magnification)



80 W, 40 kHz, 20 min (Dry samples, $\times 400$ Microscopic, $\times 100$ Microscopic)



g h i
60 W,60 kHz, 20 min (Dry samples, ×400 Microscopic, ×100 Microscopic)



j k l
60 W,40 kHz, 20 min (Dry samples, ×400 Microscopic, ×100 Microscopic)

Figure 13 Microstructure of dried *Scutellaria baicalensis*

The microstructure is shown in Figure 13. The samples in the natural drying group The samples in the natural drying group exhibited relatively intact cell structures under a 400x microscope, with clear stomatal morphology and open pore channels. Under a 100x field of view, the cell arrangement was compact, with no obvious contraction. The samples treated with 60W/40kHz/20min displayed superior microscopic characteristics compared to natural drying, with distinct stomatal outlines, intact cell wall structures, and a continuous microchannel system.

In contrast, the cell structures in the 60W/60kHz/20min treatment group showed significant changes, including noticeable stomatal shrinkage, partial pore collapse, and increased cell gaps, indicating mechanical damage from excessive processing. Notably, the 80W/40kHz/20min treatment group exhibited more severe structural deformation under a 400x microscope, with a significantly increased stomatal closure

rate and a disrupted pore network. This may result from the intensified cavitation effect caused by high-power ultrasound(Saengrayap et al., 2014), suggesting that both processing power and frequency play a crucial role in maintaining cell structure integrity.

3.9. PCA Analysis and Pearson Correlation Analysis

Principal component analysis (PCA) and Pearson correlation analysis revealed the comprehensive impact of ultrasonic pretreatment on the physicochemical properties of *Scutellaria baicalensis* and the intrinsic correlations among the variables. As shown in Figure 14, PC1 and PC2 explained 44.8% and 29.8% of the total variance, respectively, reflecting the primary variation patterns of the dataset. The PCA spatial distribution indicated that the strongly loaded variables on the positive half-axis of PC1—baicalin, antioxidant capacity, red-green value, total flavonoids, and total phenols—formed a synergistic enhancement trend. Conversely, the negative half-axis was associated with homobaealin and total color difference, suggesting a negative correlation with the retention of active components. The positive half-axis of PC2 was linked to brightness and yellow-blue value, highlighting the independent response characteristics of color parameters. The component synergy and antagonism analysis in Figure 15 showed that total phenols (TPC) were positively correlated with antioxidant capacity ($r = 0.76$), and both were significantly positively correlated with total flavonoids ($r = 0.87$; $r = 0.88$), forming a core antioxidant synergy group. Baicalin and wogonoside show a moderate negative correlation ($r = 0.53$) and was positively associated with total flavonoids and antioxidant capacity, while

homobacalin showed a moderate negative correlation with total phenols, total flavonoids, and antioxidant capacity ($r = 0.24$, $r = 0.39$, $r = 0.21$). Regarding drying parameters, brightness (L) was positively correlated with yellow-blue value (B), and red-green value (A) was negatively correlated with brightness (L), confirming that color parameters can serve as non-destructive quality monitoring indicators.

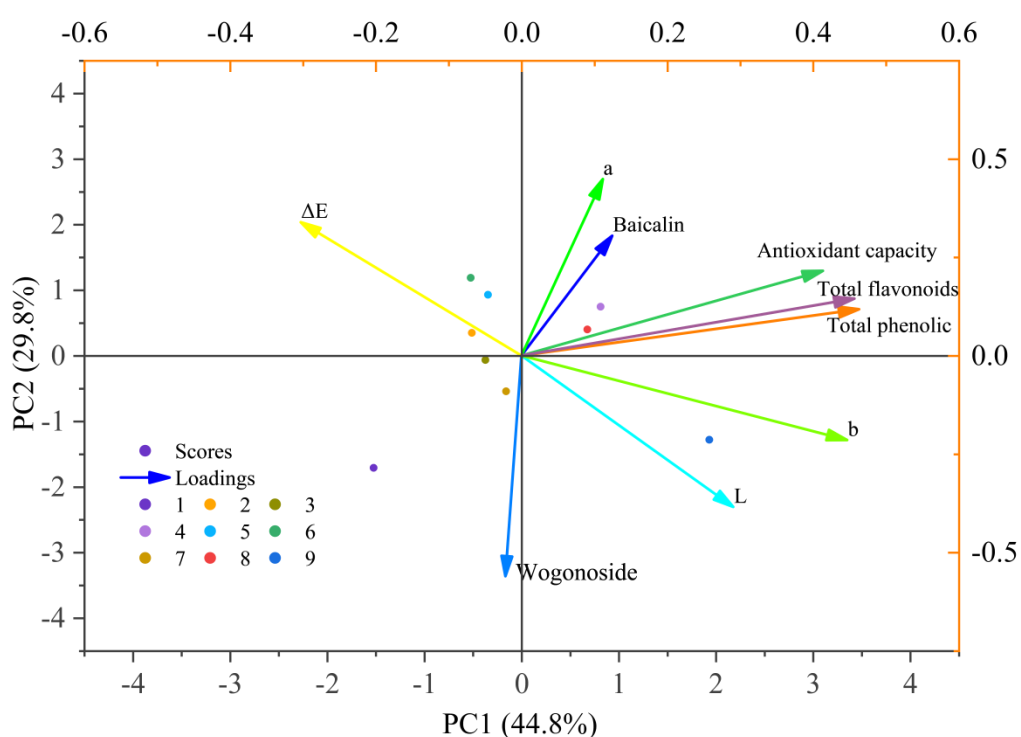
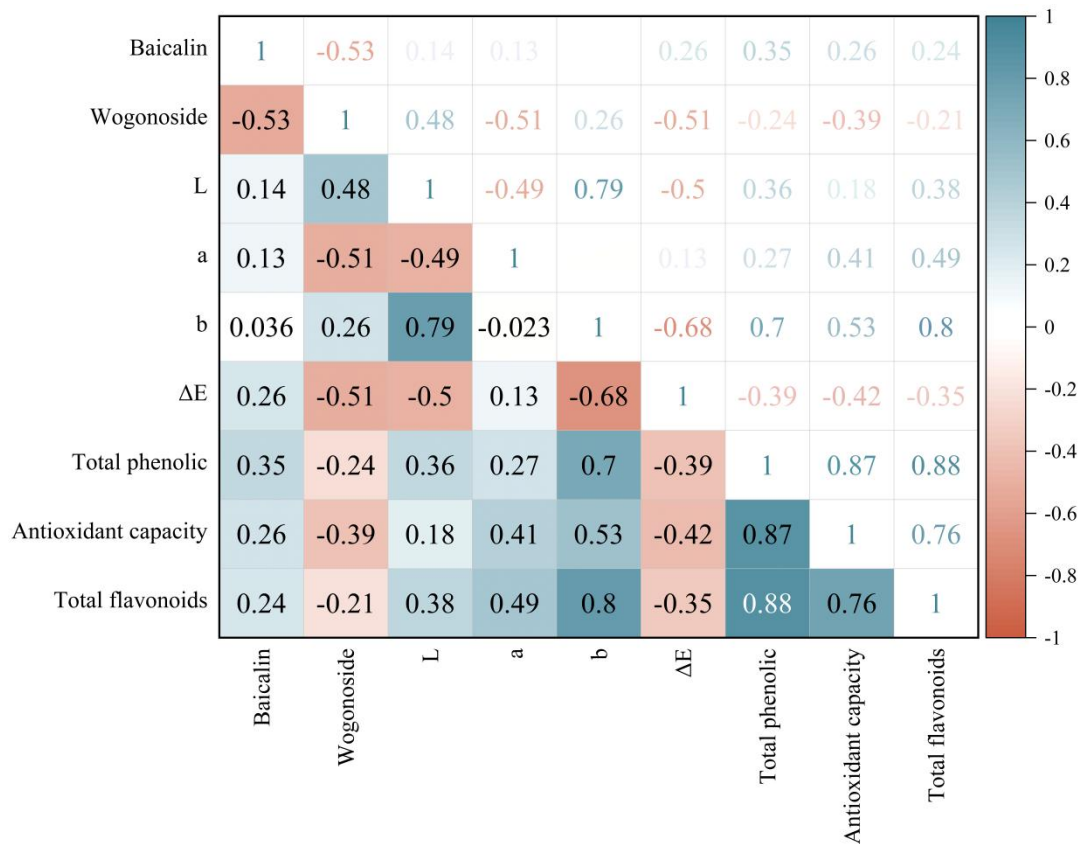


Figure 14 Principal component analysis of physicochemical quality obtained by different drying treatments

622



623

624 Figure 15 Pearson correlation analysis of physicochemical quality obtained by different drying
625 treatments

626 3.10. TOPSIS-CRITIC Comprehensive Evaluation Method

627 By combining the distribution graph of positive and negative solutions of
628 Euclidean distance (Figure 16) and the proximity degree ranking graph (Figure 17),
629 the TOPSIS-CRITIC model quantified the comprehensive performance differences of
630 the ultrasonic collaborative drying process. The 60W/40kHz/30min group achieved
631 the highest proximity degree (0.655) with the smallest positive ideal solution distance
632 (0.035) and the largest negative ideal solution distance (0.056). Its advantage lies in

the collaborative optimization of active component retention and energy efficiency:
the total flavonoid content and antioxidant capacity are excellent, and the integrity of
the microstructure ensures the stability of the components. Additionally, the energy
efficiency ratio is superior to most other processes. Although the drying time of the
60W/40kHz/20min group is slightly better than that of the 30min group, Baicalein is
significantly lost, confirming that insufficient ultrasonic time (20 minutes) limits the
dissolution of hydrophobic components. Parameter analysis shows that increasing the
ultrasonic time significantly increases the proximity degree, but excessive power will
reduce the retention of Wogonoside.

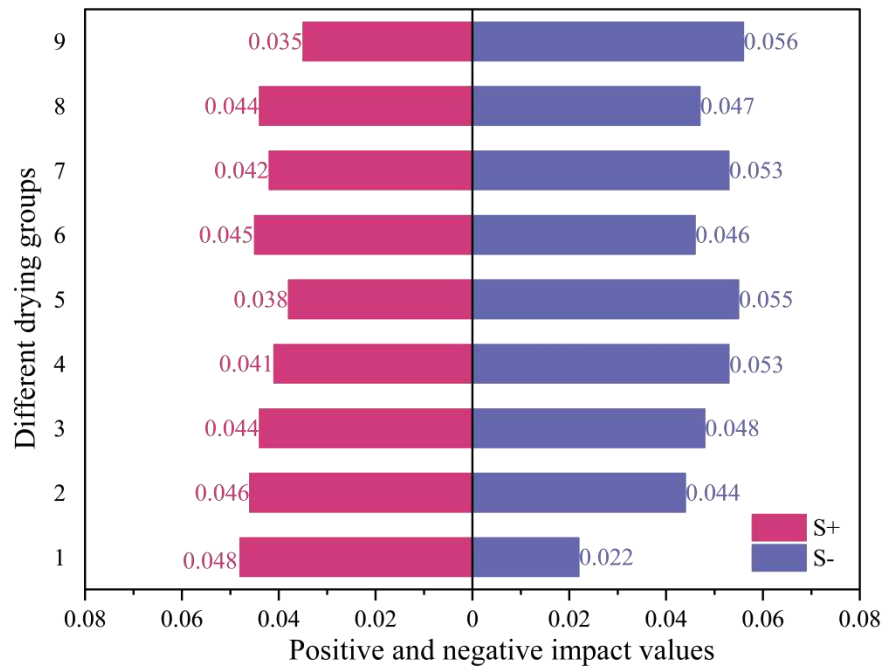


Figure 16 Distribution of positive and negative solutions of Euclidean distance

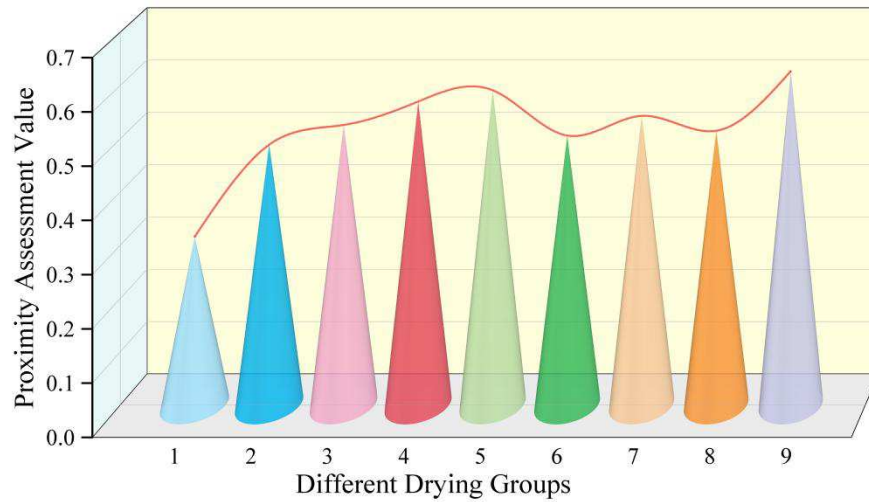


Figure 17 Proximity sorting diagram

4. Conclusion

This study systematically elucidated the physical synergy mechanism by which ultrasonic pre-treatment in combination with vacuum far-infrared drying (US-VFIRD) technology enhances the processing efficiency of *Scutellaria baicalensis*. The ultrasonic cavitation effect (40-80 W, 20-60 kHz, 10-30 min) significantly promotes the transformation of bound water to free water by disrupting the hydrogen bond network of cell walls (verified by SEM), thereby reducing internal mass transfer resistance. Meanwhile, the mild thermal field of vacuum far-infrared drying (50 °C, -20 kPa) effectively inhibits the thermal degradation of flavonoid glycosides. This synergy optimizes the drying kinetics: The peak drying rate of the 60 W/40 kHz/20 min group reached 0.02853 g/(g·min), which is 30% higher than the untreated group, with drying time reduced by 45.5%. The energy efficiency ratio (COP_d) was maximally increased to 0.0144 in the 80 W/40 kHz/20 min group. The XGBoost multi-objective model ($R^2 > 0.99$, MSE = 0.00013) accurately quantifies the

parameter effects, revealing that the power-frequency interaction dominates water migration, while the retention of active components correlates with the color parameter. Quality analysis indicates that the total flavonoid retention rate (218.7 mg/g) and total phenol content (11.538 mg/g) in the 60 W/40 kHz/30 min group increased by 28.5% and 34.2%, respectively, compared to traditional methods, and the antioxidant activity was enhanced to 46.00% through the synergistic effect. Microscopic structure analysis confirmed that moderate ultrasonic power (60 W/40 kHz) maintained the continuity of cell channels, while high power (80 W) caused structural collapse, leading to component loss. Based on the TOPSIS-CRITIC evaluation, the 60 W/40 kHz/30 min process was identified as the optimal condition (proximity degree 0.655), balancing drying efficiency, energy efficiency, and component retention. This technology offers a reliable solution for high-quality, efficient processing of *Scutellaria baicalensis*. Future studies should explore its expansion to other materials rich in heat-sensitive components, and industrial equipment parameters can be further optimized through life cycle assessment (LCA).

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Table 1 Single factor experiment design

Order number	Pre-Treatment Power (W)	Pre-Treatment Frequency (kHz)	Pre-treatment Time (min)
1	Nature drying		
2	Vacuum far- infrared		
3	40	40	20
4	60	40	20
5	80	40	20
6	60	20	20
7	60	60	20
8	60	40	10
9	60	40	30

Table 2 Machine learning parameter table

Hyperparameter	Hunting zone	Distribution pattern	Optimization method
Tree depth	(5,15)	Integers are evenly distributed	Bayesian optimization
Learning rate	(0.001,0.1)	The logarithm is uniformly distributed	
Number of trees	(500,2000)	The logarithm is uniformly distributed	
Sample sampling ratio	(0.7,1.0)	Equidistribution	
Feature sampling ratio	(0.7,1.0)	Equidistribution	
L ₁ regularization coefficient	(1e-6,10)	The logarithm is uniformly distributed	
L ₂ regularization coefficient	(1e-6,10)	The logarithm is uniformly distributed	
Minimal loss of fragmentation	(0,5)	Equidistribution	
Minimum child node weight	(1,10)	Integers are evenly distributed	

Table 3 Model result diagram

Ta	R ²	MSE	RMSE
rget			
M	0.9934	0.000478	0.02188
R1			
M	0.9942	0.000426	0.02064
R2			
M	0.9947	0.000387	0.01968
R3			

Table 4 Energy efficiency ratio of drying system results

Order number	Process mode	Drying time (min)	Total energy consumption (kWh)	COP _d
1	Natural drying	7200	0	N/A
2	Vacuum far-infrared	330	5.500	0.0079
3	40W/40kHz/20min	255	4.263	0.0102
4	60W/40kHz/20min	195	3.450	0.0125
5	80W/40kHz/20min	180	3.027	0.0144
6	60W/20kHz/20min	270	4.700	0.0092
7	60W/60kHz/20min	225	3.950	0.0110

8	60W/40kHz/10min	315	5.350	0.0081
9	60W/40kHz/30min	210	3.800	0.0114

693 Note: The natural drying group COP_d has no practical significance, and infinity
694 is given here