Parameter optimization for microwave coupled with hot air drying process of hawthorn slices using response-surface methodology

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Abstract: The microwave coupled with hot air (MCHA) drying method was used in this test to dry hawthorn slices The effect of initial microwave power density level (6 W/g to 12 W/g), hot air temperature (55℃ to 70℃), and hot air velocity (1 m/s to 3 m/s) on the quality attributes of rehydration ratio (R_f), organic acid (OA) and ascorbic acid (AA) of the dehydrated hawthorn slices was analyzed using a response surface methodology. An orthogonal rotatable central composite with three factors and at five levels was used to develop predictive regression models for the responses. The prediction mathematical model of R_f, OA and AA of the hawthorn slice was determined by analysis of variance. Factor and response variables as well as the prediction mathematical model, the optimal drying process of R_f, OA and AA of the hawthorn slice were determined by using the Design-Expert software. The comprehensive optimal conditions were as follows: initial microwave power density 12 W/g, hot air temperature 55℃ and hot air velocity 1.56 m/s.

Keywords: parameter optimization, response surface methodology, hot air drying, microwave, hawthorn slice
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1 Introduction

Hawthorn fruit is rich in vitamin C, flavonoid compounds, saponins, organic acids (OA), polysaccharides and other nutrients, and contains various minerals with high nutritional value. Hawthorn has the healthcare functions in many areas, such as spleen digestion, anti-inflammation, cough cure and so on. In addition, the dehydrated slices of the fresh hawthorn are a popular food, and also the main materials of hawthorn products, including hawthorn jelly, hawthorn beverage and hawthorn wine, etc. Therefore, varieties of hawthorn are widely used as pharmaceuticals and food ingredients in China and Europe[1-3]. The moisture content of fresh hawthorn is approximately 80%. Because the hawthorn has crisp organic composition, it is vulnerable to mechanical damage resulting juice outflow and resulting in hawthorn rot, which brings enormous losses every year[4]. Drying process has been used worldwide for centuries to preserve different foodstuff, fruits, and other agricultural products of high moisture content[4-6]. Microbiological spoilage and deteriorative chemical reactions in fruits and vegetables are significantly minimized by reducing the moisture to a certain level[7].

Two conventional drying techniques are available, namely, solar drying and hot air drying. However, these

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techniques have many defects, which may be due to processing deficiencies, such as excessively high temperature, long drying time and inefficient application of energy. Such limitations have led to the development of new technologies in drying foodstuff, fruits, and other agricultural products[5,7-16]. Compared with conventional hot air drying, the microwave drying technique could maintain the nutritional and sensory properties of the product, shorten drying time, generate volumetric heating, higher drying rate and lower energy consumption; thus, this drying technique has received significant attention and has been widely used in recent years[16-19]. To date, the microwave drying technique is used in drying various herbs[20], fruits[14,21], vegetables[22-24], foods[25] and other agricultural products[16,26]. However, microwave processing has the disadvantage of inhomogeneous distribution in microwave cavity, causing problems of non-uniform heating for certain products depending on their dielectric and thermal and physical properties. Another drawback of microwave processing is that excessively rapid mass transport by microwave power damages quality and causes undesirable changes in product texture, especially in the late stage of drying, such that the dried products easily undergo sticky state[14,27,28]. An effective measure to overcome some of the limitations of single microwave and hot air drying is to combine microwave with the vacuum or hot air drying technique[28]. Vacuum–microwave drying is a modern, efficient method of food, vegetable, fruit and other agricultural product preservation. Vacuum–microwave drying has many advantages and can obtain products with acceptable quality[12,27], but the vacuum–microwave drying equipment has limited commercial production because of high price, complex structure, high air tightness of the drying equipment, and operating difficulties in the drying process of products.

Microwave coupled with hot air (MCHA) drying combines the advantages of microwave and hot air drying[29]. The microwave energy could be absorbed directly and internally by drying materials and converted into heat that is generated throughout the material by volumetric heating. Thermal energy is conducted from the surface of the drying products toward the interior; water in the drying material is also removed from the surface toward the interior of the drying material while products are dried by hot air. Therefore, water removal from the drying material is commonly affected by microwave and hot air in the MCHA drying[29-32]. Some researchers[28,33-36] have successfully studied potato slices, red pepper, pumpkin slices, garlic cloves and spinach using MCHA drying. However, studies on drying hawthorn slices using MCHA drying have not been reported in the literature.

Although the MCHA drying could ensure acceptable quality of drying materials, a critical factor is that the processing conditions of optimization ensures that the drying materials have acceptable quality. Response-surface methodology (RSM) is an effective and frequently used tool for optimization studies. Several authors have employed RSM to optimize various unit operation processes, resulting in acceptable responses[37-41]. A comprehensive evaluation method using the analytic hierarchy process to determine the weights was designed by comprehensively considering the effects of these variables and their interactions on the rehydration ratio (R_f) and nutritional quality of hawthorn slices.

The purpose of this study is to optimize the main operating conditions, contains initial microwave power density, hot air temperature and hot air velocity, on certain product and process characteristics, namely, rehydration ratio (R_f) and nutritional quality, as well as to determine the optimum MCHA drying conditions for high-quality production of dried hawthorn slices using RSM.

2 Materials and methods

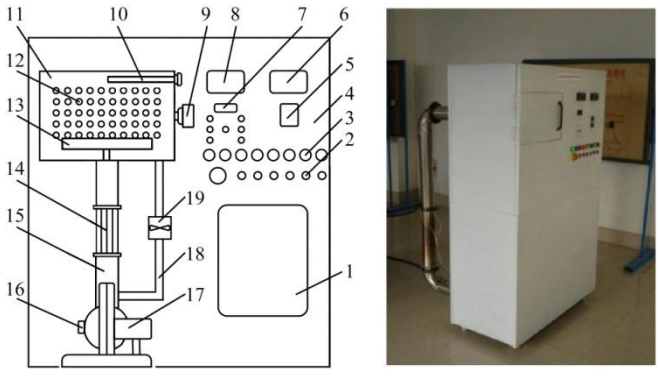
2.1 Experiment material

The hawthorns used in this experiment were cultured in Shandong Province and selected as the dried materials in December 2013. The hawthorns were classified according to their colors, sizes, degrees of mechanical damage and decays after purchase. The test samples with fresh color, same size, no mechanical damage, and no sign of decay were packed into plastic bags in 0.5 kg after being washed and drained, and then stored in a

refrigerator at 4 ℃. The fresh hawthorns were placed in a hot oven after being sliced into 5 mm-thick pieces and were continuously dried for 12 h with hot air at 70 ℃. The moisture content of the hawthorn slices was measured after these processes. These experiments were replicated three times to obtain a reasonable average. After drying, the moisture content of the samples was approximately 77% (w. b.).

2.2 Microwave coupled with hot air dryer (MWCHAD)

The drying tests of the hawthorn slices were mainly completed using an MWCHAD (YHMW900-100) manufactured at the College of Engineering, Heilongjiang Bayi Agricultural University, Daqing, China. The schematic and the physical device are shown in Figure 1. The size of the MWCHAD is 1 570 mm ×1 000 mm × 505 mm, which mainly consisted by a microwave drying system and a hot air drying system. The microwave drying system consisted of a magnetron, a control system, and a microwave resonator cavity. The hot air drying system mainly consisted of an air flow distributor, a heater, a control system, and a centrifugal fan with 550 W power. An interconnection was placed between the microwave cavity of the microwave drying system and the distributor of the hot air drying system to feed hot air uniformly into the microwave cavity. The moisture loss of the test samples was measured by a digital electronic balance (T1000, China) with a measurement range of 0-1 000 g and an accuracy of 0.1 g.



1. Electric controller 2. Control buttons 3. Indicator 4. Control panel 5. Regulator 6. Temperature control device 7. Microwave control digital display 8. Wind velocity indicator 9. Magnetron 10. Temperature sensor 11. Microwave cavity 12. Hot air distributor inlet 13. Rotating glass plate 14. Heater 15. Stainless steel inlet duct 16. Wind velocity sensor 17. Centrifugal blower 18. Stainless steel air outlet duct 19. Axial fan

Figure 1 Object and schematic diagram of microwave coupled with hot air dryer

2.3 Quality measurements

2.3.1 Rehydration ratio

The rehydration ratio was used as a quality index to indicate the physical and chemical changes of the drying products during drying and the capacity of being rehydrated prior to their final use[32]. The dried samples of hawthorn slices were rehydrated by immersing in a water tank filled with distilled water at a controlled temperature of (80±1) ℃. The mass used in each experiment was (10±0.02) g. The change in sample weight was measured at 5 min intervals for 5 times. The dried samples of hawthorn slices were placed on fiberglass wire mesh and drained over a mesh for 3 min to remove superficial water in the sample before the measurement. Each rehydration test was replicated three times; experiment error was controlled within the range of ±0.1 each time. The R_f of the dehydrated hawthorn slice was calculated using the following formula:

$$R_f = \frac{W_f - W_0}{W_0} \quad (1)$$

where, R_f is the rehydration ratio of the dried samples of hawthorn slices; W_f is the weight of the dried samples of hawthorn slices that have been rehydrated, g; and W_0 is the weight of the dried samples of hawthorn slices before rehydration, g.

2.3.2 Determination of OA

The OA content in hawthorn was determined according to the Chinese standards (GB/T123456-2008); the total acid content was calculated based on citric acid. The specific methods are as follows: (a) The dried hawthorn sample of 20 g was placed in the high-velocity universal pulverizer (FW80, 80 mm, Tianjin Test Instrument Co. Ltd.), and the crushed sample was stored in a sealed bottle; (2) 3 g (accurate to 0.001 g) of a powder sample was weighed and placed in a 25 mL beaker, added with 3 mL of distilled water and then stirred uniformly; the sample was slurry; (3) 5 g of the slurry sample was precision weighed, poured into a 50 mL beaker, and then transferred to a 100 mL volumetric flask with approximately 80 ℃ boiled distilled water. The flask was placed in boiling water for 30 min and shaken three times during the boiling process to

dissolve all hawthorn OAs; (4) the flask was taken out of the boiling water and cooled to room temperature of 20℃ with boiled distilled water volume to 100 mL (20-fold dilution), the solid matter was filtered off with rapid filter paper, and the filtrate was collected from the solution to prepare for a test; (5) 10 mL of the test solution was taken and placed into a 50 mL conical flask, added with 25 mL water, and 0.1 mL of 1% phenolphthalein indicator was titrated to reddish without fading for 30 s with 0.1 mol/L NaOH solution, recording V_1 of the consumption of 0.1 mol/L NaOH volume; (6) 10 mL of filtrate distilled water was taken and placed in a 50 mL conical flask with 25 mL water added, and 0.1 mL of 1% phenolphthalein indicator was titrated to reddish without fading for 30 s with 0.1 mol/L NaOH solution, recording V_2 of the consumption of 0.1 mol/L NaOH volume. The entire test was conducted twice, and the average value with two-decimal accuracy was taken as the OA content. The OA content of the dehydrated hawthorn slice was calculated using the following formula:

$$\phi = \frac{c \times (V_1 - V_2) \times K \times F}{m} \times 1000 \quad (2)$$

where, ϕ is the OA content of the dried hawthorn slice; c is the accurate value of the concentration of the standard NaOH titration solution, mol/L; V_1 is the volume value of the standard sodium hydroxide solution consumed in the titration test, mL; V_2 is the volume of the standard sodium hydroxide solution consumed in the blank test, mL; K is the acid conversion factor which is 0.064 (in this study, the total acid content of dried hawthorn was calculated by citric acid); F is the dilution of the test solution; m is the mass of the sample values, g, calculated by the mass of the dried hawthorn slices.

2.3.3 Determination of AA

The 2, 6-dichloro-indophenol titration method was used to determine the AA content in hawthorn (Chinese standard GB 6195-1986). The method is as follows: (1) 3 g of powder was added with 3 mL of extraction agent and stirred uniformly; (2) 5 g of the slurry sample with the extraction agent was transferred into a 100 mL volumetric flask, diluted to scale, shaken uniformly, and then filtered; (3) 10 mL of filtrate was drawn into the conical flask; the calibrated 2, 6-dichloro-indophenol was used for titration until the solution was pink and does not fade in 15 s; a blank test was also conducted. The AA content of the dehydrated hawthorn slices was determined based on the following equation:

$$\psi = \frac{(V - V_0) \cdot T \cdot A}{W} \times 100 \quad (3)$$

where, ψ is the AA content of the dried hawthorn slice, mg/100 g; V is the volume of the dye solution consumed by sample liquid titration, mL; V_0 is the volume of the dye solution consumed by blanket test titration, mL; T is the dye titer of 2. 6-dichloro-indophenol, mg/mL; A is the dilution; W is the weight of the samples, g.

2.4 Experimental Design

The experimental independent variables chosen in the MCHA drying experiment of hawthorn slices were initial microwave power density (D), hot air temperature (T), and hot air velocity (V). Codes x_1, x_2, x_3 were used as experimental independent variables of T, D, V, respectively. The experimental independent variable levels, including the maximum and minimum levels, were selected based on the preliminary drying experiments. The levels of experimental independent variable in coded and actual unit are shown in Table 1. Table 2 shows that 23 experiments were conducted according to an orthogonal rotatable central composite design with the three variables and using five levels of each variable; the experimental center point was repeated nine times to calculate the reproducibility of the method.

Experiments were randomized to minimize the effects of unexplained variability in the observed responses because of extraneous factors. The RSM was used to determine the relative contributions of D, T and V to R_f, OA content and AA content. A second-order polynomial response surface model was used to fit each of the response variables, as shown in the following equation:

$$Y_m = \alpha_{m0} + \sum_{=i}^{3} \alpha_{mii} x_i^2 + \sum_{i \neq j=1}^{3} \alpha_{mij} x_i x_j + \sum_{i=1}^{3} \alpha_{mi} x_i \quad (4)$$

where, α_{m0}, α_{mi}, α_{mii}, and α_{mij} are the constant, linear, quadratic, and cross-product regression coefficients, respectively; x_i, x_j are the coded experimental independent variables of D, V, and T; Y_m are the response variables of R_f, OA content, AA content, and response value of the comprehensive evaluation.

Table 1 Level of variables

Variable	Name (unit)	Level				
		1.6818	1	0	−1	−1.6818
D	Initial microwave power density/(W g^{-1})	12	10.8	9	7.2	6
T	Hot air temperature/ ℃	70	67	62.5	58	55
V	Hot air velocity/(m s^{-1})	3	2.59	2	1.4	1

Table 2 Experimental design and data for response surface analysis

Expt. No.	Variable levels			Responses (Y_m)		
	x_1	x_2	x_3	R_f/g g^{-1}	OA/g kg^{-1}	AA/mg 100 g^{-1}
1	−1	−1	−1	1.15	116.23	103.68
2	1	−1	−1	1.24	125.77	105.75
3	−1	1	−1	1.139	116.63	98.25
4	1	1	−1	1.2	120.82	102.03
5	−1	−1	1	1.15	116.34	101.08
6	1	−1	1	1.23	119.51	102.14
7	−1	1	1	1.12	107.65	95.27
8	1	1	1	1.18	109.39	97.34
9	−1.6818	0	0	1.17	116.45	99.50
10	1.6818	0	0	1.27	121.17	103.38
11	0	−1.6818	0	1.22	128.03	107.11
12	0	1.6818	0	1.14	112.57	99.85
13	0	0	−1.6818	1.13	114.19	100.71
14	0	0	1.6818	1.115	102.38	93.31
15	0	0	0	1.178	115.61	100.47
16	0	0	0	1.176	116.87	101.25
17	0	0	0	1.174	117.95	101.93
18	0	0	0	1.169	110.99	100.42
19	0	0	0	1.16	116.88	100.93
20	0	0	0	1.175	117.79	100.42
21	0	0	0	1.159	118.09	101.93
22	0	0	0	1.155	117.02	100.42
23	0	0	0	1.164	117.85	101.92

2.5 Comprehensive evaluation

The test argument value of respective optimal response could be determined by response surface methodology and model Equation (4), namely, the optimal drying process. The optimal drying process is different because of the differences of model equations on rehydration ratio, organic acid content, and ascorbic acid content, the integrative effects of the drying independent variables on dried hawthorn could not be reflected. Therefore, a comprehensive assessment of the drying process is needed. The drying process is further optimized to achieve the highest efficiency under the synthesis optimal response. The resulting set of comprehensive evaluation is shown in Equation (5). An assessment index set includes the R_f parameters, OA content, and AA content, as shown in Equation (6)[14].

$$Z = \beta_1 H_1 + \beta_2 H_2 + \beta_3 H_3 \quad (5)$$

$$H = \{H_1(\text{rehydration ratio}),\ H_2(\text{content of oganic acid}),\ H_3(\text{content of ascorbic acid})\} \quad (6)$$

$$H_{ni} = \frac{Y_{ni} - Y_{n\min}}{Y_{n\max} - Y_{n\min}} \quad (7)$$

where, $Y_{n\ \min}$ and $Y_{n\ \max}$ are the minimum and maximum values of the responses of Y_n (n=1-3), respectively; Y_{ni} represents the component values of the responses of Y_n (i=1-3); H_{1i}, H_{2i}, and H_{3i} are the membership grade function value of each index; and β_1, β_2, and β_3 are the weight coefficients for each assessment index.

2.6 Determination of weight coefficient

Weight is an objective indicator of their physical attributes, and plays a role in ruling the target value. The weight coefficients of β_1, β_2, and β_3 were calculated by analytic hierarchy process. The weights were constructed based on a three-scale method that is explained in Table 3. We assumed that X_1, X_2, and X_3 were the three factors that influence the quality of the products, which were sequenced as $X_1 > X_2 > X_3$ by the importance of product quality influence. Thus, the scale matrix was presented as Equation (8) and the judgment matrix was constructed as Equation (9). Matrix B must be optimized to meet the compliance requirements. The transfer matrix D and the optimal transfer matrix G were set based on matrix B. Thus, the optimized judgment matrix P was shown as Equation (13). The maximum eigenvalue λ and the corresponding feature vector W were calculated according to the judgment matrix P. The feature vector W was normalized according to Equation (14) and a weight vector β was obtained, the weight vector $\beta = [\beta_1, \beta_2, \beta_3]^T$. Therefore, the weights of the three factors that affected product quality X_1, X_2, and X_3 were β_1, β_2 and β_3, respectively.

Table 3 Meaning of three-scale method

Comparison between *x* and *y*	Explanation	Scale
x is less important than *y*	contribution rate of *x* is less than *y*'s	0
x is as important as *y*	*x* and *y* have the same contribution rate	1
x is more important than *y*	contribution rate of *x* is larger than *y*'s	2

$$C=\begin{array}{c} \\ X_1 \\ X_2 \\ X_3 \end{array}\begin{array}{c} \begin{array}{ccc} X_1 & X_2 & X_3 \end{array} \\ \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \end{array} \quad (8)$$

$$B=\begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \quad (9)$$

$$b_{ij}=\begin{cases} \dfrac{r_i-r_j}{r_{\max}-r_{\min}}(k_m-1) & r_i \geq r_j \\ \left[\dfrac{r_j-r_i}{r_{\max}-r_{\min}}(k_m-1)+1\right]^{-1} & r_i < r_j \end{cases} \quad (10)$$

$$d_{ij}=\lg b_{ij} \qquad (i,j=1,2,3) \quad (11)$$

$$g_{ij}=\frac{1}{n}\sum_{k=1}^{n}(d_{ik}-d_{jk}) \qquad (i,j=1,2,3) \quad (12)$$

$$P=\begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix} \quad (13)$$

$$\beta_i=w_i/\sum_{i=1}^{n}w_i \qquad (i=1,2,3) \quad (14)$$

where, c_{ij} is the scale; r_i is the indicated importance, and $r_i=\sum_{j=1}^{3}c_{ij}$, $k_m=r_{\max}/r_{\min}$, $r_{\max}$, and $r_{\min}$ are the maximum and minimum of the indicated importance; $p_{ij}=10^{g_{ij}}\,(i,j=1,2,3)$.

3 Results and discussion

Experimental data of the various responses during the drying of hawthorn slice using the MCHA are shown in Table 2. According to the experimental data, the quadratic polynomial model [Equation (4)] was fitted and regression analysis was conducted using the Design-Expert software. The regression equation coefficient, correlation coefficient R^2, and coefficient of variation of the various response values are shown in Table 4. Analysis of variance (ANOVA) of the various response values is presented in Table 5.

Table 4 shows that the coefficient of determination of the three prediction models obtained from experimental data fitting are greater than 0.8[7], indicating that the experimental values could be represented for the prediction model. Therefore, these responses could be fully explained by the model. Table 4 also shows that the coefficient variation of the prediction model Y_1, Y_2, and Y_3 are 0.72%, 1.78%, and 0.65%, respectively, which are less than 10%[42], showing the variation of the test values within a reasonable range.

Table 4 Estimate coefficients of the second-order polynomial model (in coded units)

Factors	Estimate coefficients					
	R_f (Y_1)		OA (Y_2)		AA (Y_3)	
	Coefficient variables	Coefficient values	Coefficient variables	Coefficient values	Coefficient variables	Coefficient values
Constant	a_{10}	1.1677	a_{20}	116.54	a_{30}	101.186
x_1	a_{11}	0.0336	a_{21}	1.95	a_{31}	1.136
x_2	a_{12}	−0.0194	a_{22}	-3.62	a_{32}	-2.342
x_3	a_{13}	−0.0054	a_{23}	-3.40	a_{33}	-1.928
x_1x_2	a_{112}	−0.0061	a_{212}	-0.85	a_{312}	0.341
x_1x_3	a_{113}	−0.0014	a_{213}	-1.10	a_{313}	-0.340
x_2x_3	a_{123}	−0.0036	a_{223}	-1.78	a_{323}	-0.183
x_1^2	a_{111}	0.0188	a_{211}	0.96	a_{311}	0.106
x_2^2	a_{122}	0.0046	a_{222}	1.49	a_{322}	0.827
x_3^2	a_{133}	−0.0157	a_{233}	-2.76	a_{333}	-1.460
R^2	0.971		0.9148		0.9714	
CV/%	0.72		1.78		0.65	

Table 5 ANOVA for the second-order polynomial models of Y_1, Y_2, Y_3

Source	Df	R_f, Y_1		OA, Y_2/%		AA, Y_3/10^{-2}mg	
		MS	*F*-value	MS	*F*-value	MS	*F*-value
Model	9	0.00348	48.43*	66.77	15.50	21.177	49.055
x_1	1	0.01544	214.662*	51.79	12.02	17.613	40.799
x_2	1	0.00516	71.790*	178.55	41.45	74.902	173.506
x_3	1	0.00040	5.61*	157.71	36.62	50.757	117.575
x_1x_2	1	0.00030	4.173	5.75	1.34	0.932	2.158
x_1x_3	1	0.00002	0.210	9.69	2.25	0.926	2.145
x_2x_3	1	0.00011	1.462	25.41	5.90	0.268	0.620
x_1^2	1	0.00561	77.994*	14.56	3.38	0.177	0.411
x_2^2	1	0.00034	4.771*	35.07	8.14	10.878	25.198
x_3^2	1	0.00391	54.334*	121.21	28.14	33.858	78.429
Residual	13	0.0000719		4.31		0.432	
Lack of Fit	5	0.0000711	0.981	3.25	0.65	0.226	0.403
Pure Error	8	0.0000724		4.97		0.560	
Cor Total	22						

Note: Df is degree of freedom; MS is mean square; *F*-value is the ratio of variance estimate; Significant at α = 0.05.

Table 5 shows that the values of lacking fit *F* of the prediction model Y_1, Y_2 and Y_3 are 0.98122, 0.65 and 0.225698, respectively. At a level of α = 0.01, $F_{0.01}(5,8)=6.63$, which was significantly higher than the value of lacking fit *F* of the prediction model Y_1, Y_2 and Y_3, indicating that lack of fit items is extremely insignificant. Factors that cannot be ignored contained in the square sum of the lacking fit had a minimal

influence on the test results, and the fitting of model Y_1, Y_2 and Y_3 is significant. Thus, the statistical variable value F of model Y_1, Y_2 and Y_3 could be further used for testing. Table 5 also shows that the value F of model Y_1, Y_2 and Y_3 are 48.4298, 15.50, and 49.055, respectively. However, at the level of α = 0.01, $F_{0.01}(9,13)$ = 4.19, which are significantly larger than the $F_{0.01}(9,13)$ values, indicating that the test data are consistent with the second-order polynomial response surface model and the forecast model Y_1, Y_2 and Y_3 fit the actual situation.

3.1 Rehydration ratio

Moisture content of the dehydrated hawthorn slices increases with rehydration time, whereas the absorption rate of water decreases with the increase in time. The rehydration process was conducted for 25 min under rehydration temperature at 80 ℃. Under various drying conditions, the R_f of the hawthorn slices ranged from 1.15 to 1.27. Figure 2 shows that the rehydration properties of dried hawthorn slice was improved at lower temperatures and higher power density, that is, a high rate of rehydration. Similar results have been reported in other studies[42, 43]. According to the ANOVA (Table 5), at the level of α=0.01, the final prediction model equation for the R_f in terms of actual factor levels could be obtained by removing items x_1x_2, x_1x_3 and x_2x_3 that insignificantly affect the R_f. The equation for R_f is shown as follows:

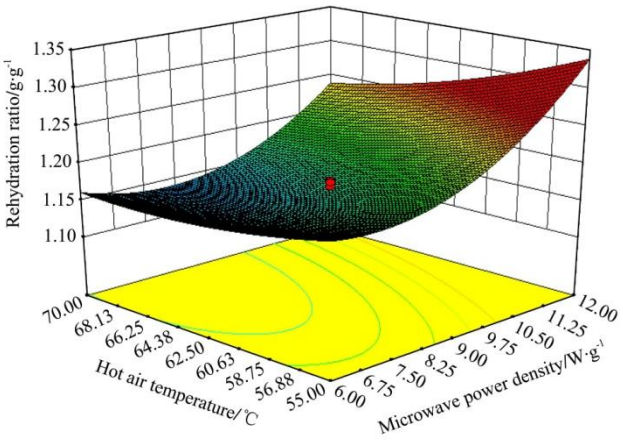
$$Y_1=1.8605-0.035882D-0.023499T+0.26378V+0.00579909D^2+0.000229477T^2-0.044297V^2 \quad (15)$$

The F values (Table 5) could be determined according to ANOVA. The initial microwave power density had the maximum effect on the rehydrated hawthorn slice, followed by air temperature, and hot air velocity had the minimum effect[44]. Thus, the initial microwave power density was a major factor that influences the rehydration of hawthorn slices.

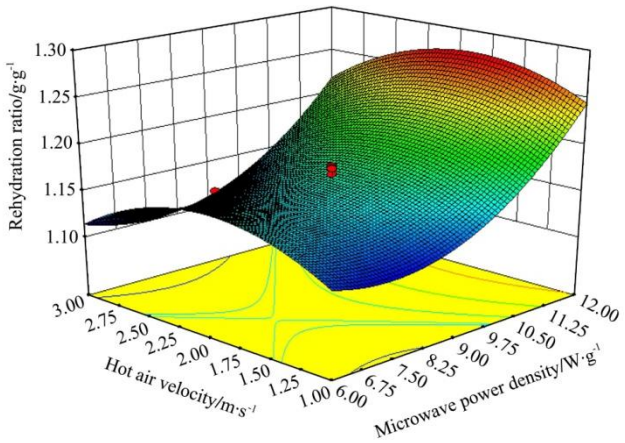
Figure 2a shows that the relationship between the R_f of hawthorn slices and the initial microwave power density was positive as the hot air velocity was kept at 2 m/s, and the R_f of hawthorn slices will be increased with initial microwave power density increasing. Meanwhile, the relationship between the R_f of hawthorn slices and hot air temperature was negative, and the R_f of hawthorn slices decreased with a decrease in hot air temperature. This variation may be attributed to the fact that the influence of hot air temperature on drying hawthorn slices gradually increased as the hot air temperature increased because of the influence of initial microwave power density on drying hawthorn slices and hot air temperature becoming a major factor in drying the hawthorn slices[45]. Under the hot air temperature drying conditions, tissue shrinkage and collapse of hawthorn slices gradually became serious that the open holes and pores of the internal structure of the hawthorn slices decreased and resulted in rehydration decrease[43]. The internal stress of the hawthorn slices increased with the increase in initial microwave power density. The rapid absorption of microwave energy prompted fast evaporation of moisture inside the hawthorn slices and generated a flux of rapidly escaping vapor, which helped prevent the shrinkage and case hardening of the hawthorn slices[42] and generated more open holes and pores, thereby increasing the rehydration of the hawthorn slices. Similar results have been reported by other researchers[46]. Figure 3 shows that the largest number of open holes and pores of hawthorn slices were obtained with microwave drying, the smallest amount was obtained with hot air drying, and an intermediate amount was obtained with the MCHA drying. The volume shrinkage of the hawthorn slices of the hot air drying was greater than that of the hawthorn slices of the microwave coupled with hot air drying. This further confirmed the rehydration variation of hawthorn slices in the drying conditions presented.

Figure 2b shows that, as the hot air temperature was kept constant at 62.5 ℃, the relationship between the R_f of hawthorn slices and the hot air velocity was a quadratic function. The R_f increased first and then decreased with an increase in hot air velocity. This variation was attributed to the fact that the hot air gradually increased evaporation of the surface moisture of the hawthorn slices when hot air velocity was gradually increased and was lower than a certain velocity. This condition decreased the drying time and reduced the effect of hot air temperature on the rehydration of hawthorn slices, thereby gradually increased the R_f of hawthorn slices. When the hot air velocity increased to a certain value,

high air velocity took away the heat of the hawthorn slice surface gradually but increased with an increase in hot air velocity. This delayed the surface evaporation of hawthorn slices. In addition, the drying time and effects of air temperature on rehydration of hawthorn slices increased, worsening the rehydration process. In the range of test variables, the conditions of optimal drying process of R_f, which are shown in Table 6, were obtained based on rehydration prediction model 15. The R_f of dried hawthorn slices was 1.34 g/g when the initial microwave power density was 12 W/g, the hot air temperature was 55 ℃, and the hot air velocity was 1.96 m/s.

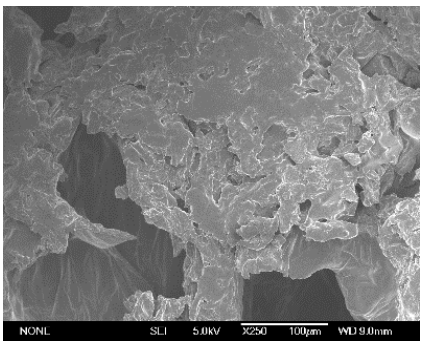


a. Initial microwave power density and hot air temperature at 2 m/s of hot air velocity

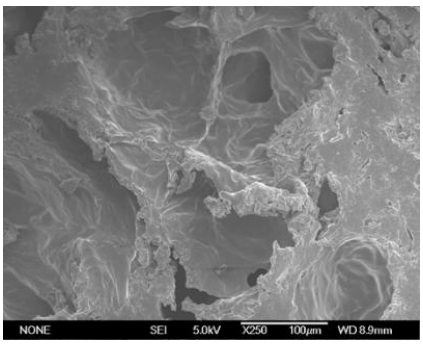


b. Initial microwave power density and hot air velocity at 62.5 ℃ of hot air temperature

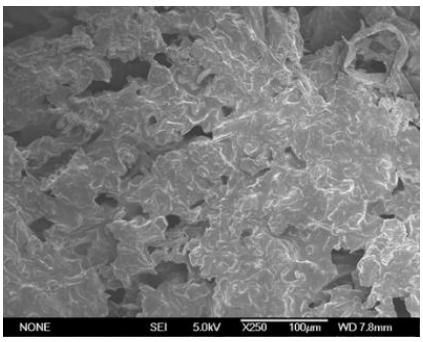
Figure 2 Response surface plot for rehydration ratio (R_f)



a. Microwave dried at initial microwave power density of 12 W/g



b. Microwave coupled with hot air dried at initial microwave power density of 12 W/g, hot air temperature of 55 ℃, and hot air velocity of 1.56 m/s



c. Hot air dried at hot air temperature of 55 ℃ and hot air velocity of 1.56 m/s

Figure 3 Scanning electron micrographs of dried hawthorn slices

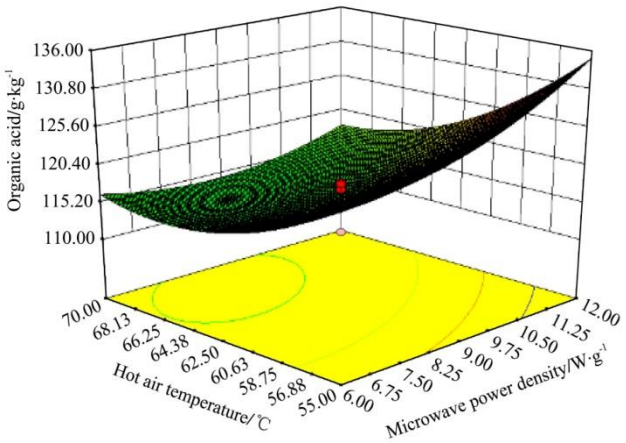
3.2 OA content

The OA content of fresh hawthorn slices calculated in accordance with the dried product was 174.29 g/kg. The OA content of the dehydrated hawthorn slices was 102.38-128.03 g/kg, according to the dried product. According to the ANOVA presented in Table 5, at the level of α = 0.01, the final prediction model equation for OA in terms of actual factor levels was obtained by removing insignificant items of x_1x_2, x_1x_3, and x_1^2, the equation for OA is shown as follows:

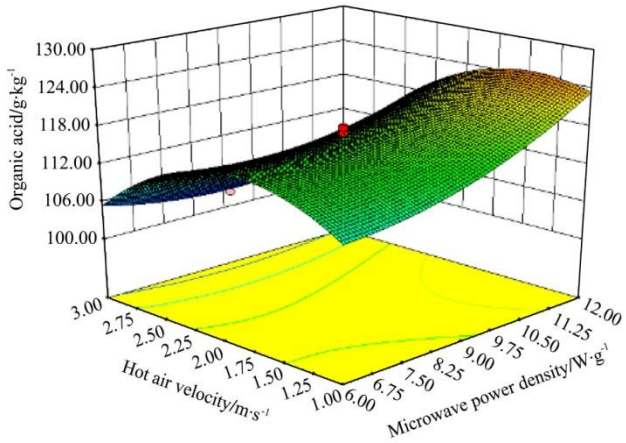
$$Y_2=287.58+4.36D-7.7T+76.27V-0.67TV+0.07T^2-7.8V^2 \quad (16)$$

The F value of variance analysis in Table 5 shows that hot air temperature had the greatest effect on the OA content of dried hawthorn slices, followed by hot air velocity and initial microwave power density. Therefore, hot air temperature was the prime factor that affected the OA content of dried hawthorn slices. Figure 4a shows that, as the hot air velocity was kept at 2 m/s, the relationship between the OA content of dried hawthorn slices and hot air temperature was negative, which decreased with increase in hot air temperature. The relationship between the OA content of dried hawthorn slices and initial microwave power density was positive,

and the OA content of dried hawthorn slices will be increased with an increase in initial microwave power density. At the level of the test variable, the main reason for this variation is the poor thermal stability of organic acids, the destructive effect of temperature on the OA increased as the temperature increased. The surface temperature of the hawthorn slices was increased gradually with the hot air temperature increasing. The temperature became the main drying factor and gradually replaced the microwave power density. This lead to the drying time increasing gradually[45]. The OA content of the dried hawthorn slices was decreased gradually by the combined effect of high temperature and long drying time. It can be seen from Figure 5a that the surface temperature of the drying hawthorn slices under the drying condition of hot air temperature at 55 ℃ was less than that at 70 ℃ during most time of the whole drying period. When hot air temperature was 70 ℃, the drying time of the hawthorn slices that could meet the requirement of the safety storage moisture content would be longer than that of 55 ℃, which indicated that the temperature gradually became a main factor of the hawthorn slices drying with the temperature increasing, and it also further indicated that the OA of the hawthorn slices was decreased with the temperature increasing. As the initial microwave power density gradually increased, the drying time which met the drying requirements of the safe moisture content of hawthorn slices gradually decreased. This reduced the time for temperature destruction of the OA; so the OA content of dried hawthorn slices gradually increased. Figure 5b also demonstrated the change law of the drying time of hawthorn slices. This finding was consistent with the results of other studies[46, 47].

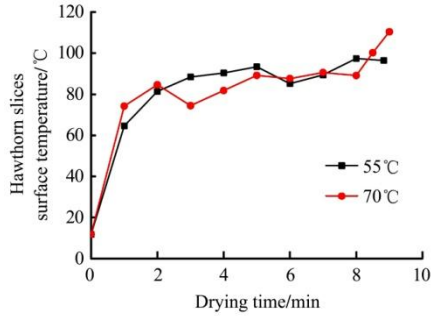


a. Initial microwave power density and hot air temperature at 2 m/s of hot air velocity

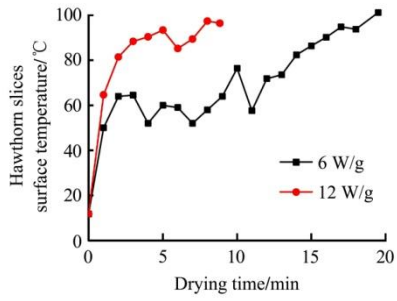


b. Initial microwave power density and hot air velocity at 62.5 ℃ of hot air temperature

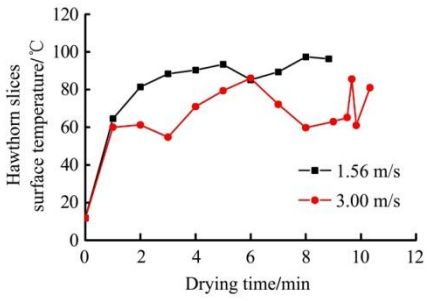
Figure 4 Response surface plot for OA



a. Hot air temperature and drying time at 12 W/g of initial microwave power density and 1.56 m/s of hot air velocity



b. Initial microwave power density and drying time at 1.56 m/s of hot air velocity and 55 ℃ of hot air temperature



c. Hot air velocity and drying time at 12 W/g of initial microwave power density and 55 ℃ of hot air temperature

Figure 5 Hawthorn slice surface temperature

Figure shows that, as the hot air temperature was kept constant at 62.5 ℃, the relationship between the OA content of dried hawthorn slices and hot air velocity was a quadratic function. The OA content of dried hawthorn

slices increased with hot air velocity, and gradually decreased when the hot air velocity reached a certain value. At the level of the test variable, the main reason for this variation was that the surface evaporation of hawthorn slices increased because of the increase in hot air velocity, which shortened the drying time and met the drying requirements of the safe moisture content of hawthorn slices and reduced the time for the temperature destruction to the OA; thus, the OA content of dried hawthorn slices increased gradually. When hot air velocity increased to a certain value, the surface heat of hawthorn slices taken away by high air velocity was gradually increased with an increase in hot air velocity. This delayed the surface evaporation of hawthorn slices and prolonged the drying time, resulting in longer time of destruction caused by temperature, so the OA content of dried hawthorn slices decreased gradually. Figure 5c also demonstrated the change law of the surface heat of hawthorn slices. This result was in agreement with the observations of quality protection principle of camellia seeds in the literature[48]. In the range of test variables, the conditions of optimal drying process of the OA, shown in Table 6, were obtained based on prediction model 16. The OA content of dried hawthorn slice was 135.42 g/kg when the initial microwave power density was 12 W/g, the air temperature was 55℃, and hot air velocity was 1.75 m/s.

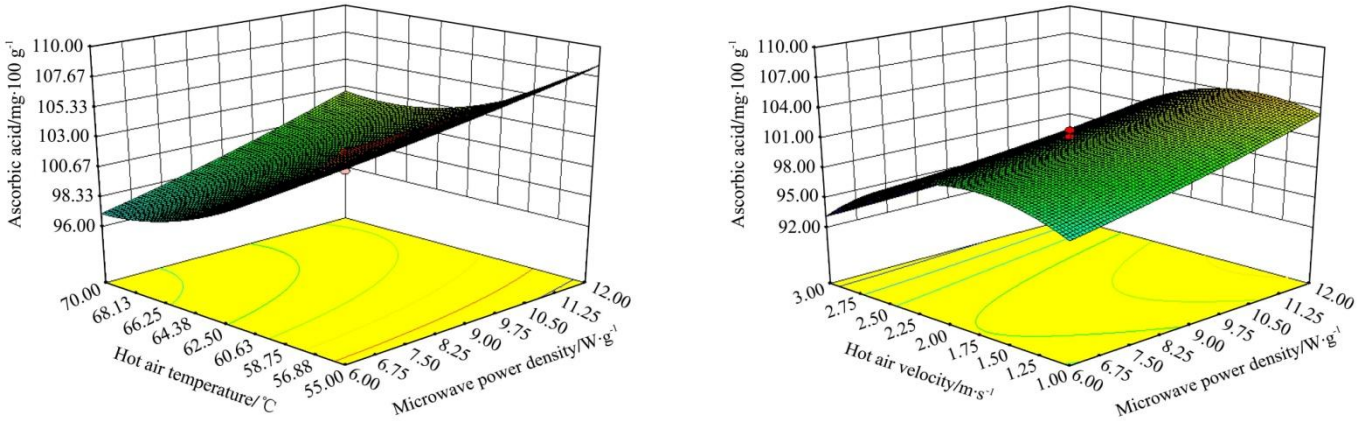
3.3 AA content

The AA is a highly unstable nutrient in fruits and vegetables, especially in terms of temperature. The inappropriate choice of drying method and drying process often results in a significant loss of AA, so the AA content is often considered as an important indicator of the feasibility of the drying method and drying process evaluation. The AA content in fresh hawthorn slices was approximately 72.68 mg/100 g, whereas that of dried hawthorn slices was from 93.31 to 107.109 mg/100 g. According to the ANOVA in Table 5, at the level α = 0.01, the final prediction model equation for AA in terms of actual factor levels was obtained by removing insignificant effect items of x_1x_2, x_2x_3, x_1x_3, and x_1^2, the equation for AA is shown as follows:

$$Y_3=289.81-1.9552D-5.8707T+20.342V+0.04086T^2-4.1233V^2 \quad (17)$$

The F value of ANOVA in Table 5 shows that the hot air temperature had the greatest effect on the AA content of dried hawthorn slices, followed by the hot air velocity and initial microwave power density. Therefore, the hot air temperature was the prime factor that influenced the AA content of dried hawthorn slices. Figure 6a shows that, as the hot air velocity was kept at 2 m/s, the relationship between the AA content of dried hawthorn slices and hot air temperature was negative, and the AA content of dried hawthorn slices decreased with an increase in hot air temperature. The relationship between the AA content of dried hawthorn slices and initial microwave power density was positive, and the AA content of dried hawthorn slices increased with an increase in initial microwave power density. At the level of the test variable, the main reason for this variation was the poor thermal stability of AA and the increased destructive effect of temperature on the AA as the temperature increased, which gradually decreased the AA content of dried hawthorn slices. Figure 5a also demonstrates the change law of the hawthorn slices surface temperature. As the microwave power gradually increased, the drying time that met the drying requirements of the safe moisture content of hawthorn slices gradually decreased. This reduced the time of temperature destruction of the AA, so the AA content of dried hawthorn slices gradually increased. Figure 5b also demonstrated the change law of the drying time of hawthorn slices. This result is consistent with the results of other studies[46,47]. Figure 6b shows that, as the hot air temperature was kept constant at 62.5℃, the relationship between the AA content of dried hawthorn slices and hot air velocity was a quadratic function. The AA content of dried hawthorn slices increased with an increase in hot air velocity, and gradually decreased when the hot air velocity reached a certain value. The main reason for this variation is that the surface evaporation of hawthorn slices was increased because of an increase in hot air velocity. This shortened the drying time which meet the drying requirements of the safe moisture content of hawthorn slices and reduced the time of the

temperature destruction of the ascorbic acid, so the ascorbic acid content of dried hawthorn slices gradually increased. After the hot air velocity increased to a certain value, the surface heat of hawthorn slices that was taken away by high air velocity gradually increased with the increasing of hot air velocity. This delayed the surface evaporation of hawthorn slices and prolonged the drying time, resulting in a longer time of destruction caused by temperature; thus, the ascorbic acid content of dried hawthorn slices gradually decreased. Figure 5c also demonstrates the change law of the surface heat of hawthorn slices. This result was in agreement with the observations of quality protection principle of camellia seeds in the literature[48]. Within the range of test variables, the condition of optimal drying process of the ascorbic acid, which is shown in Table 6, was obtained based on prediction equation (17). The ascorbic acid content of dried hawthorn slices was 109.45 mg/100 g when the initial microwave power density was 12 W/g, the air temperature was 55 ℃, and hot air velocity was 1.55 m/s.



a. Initial microwave power density and hot air temperature at 2 m/s of hot air velocity

b. Initial microwave power density and hot air velocity at 62.5 ℃ of hot air temperature

Figure 6 Response surface plots for ascorbic acid

Table 6 Optimization criteria for different factors and responses and optimization process conditions

Factors or responses	Goal	Lower limit	Upper limit	Optimization process conditions		
Power density/W g^{-1}	In the range	6	12	12	12	12
Hot air temperature/ ℃	In the range	55	70	55	55	55
Hot air velocity/m s^{-1}	In the range	1	3	1.96	1.75	1.55
R_f/g g^{-1}	Maximize	1.12	1.34	1.34		
OA/g kg^{-1}	Maximize	102.383	136		135.42	
AA/mg 100 g^{-1}	Maximize	93.3105	110			109.45
Desirability				0.993	0.983	0.967

3.4 Comprehensive Evaluation

3.4.1 Determination of weight coefficient

Although OA and AA are important nutrients in hawthorn, OA has a protective effect on the ascorbic acid content of dried hawthorn slices in subsequent processing. Thus, the importance of OA is greater than that of AA for the drying quality of dried hawthorn slices. Given that the rehydration of dried hawthorn slices is a physical process that does not involve a change of nutrients; the importance of rehydration of dried hawthorn slices for drying quality is less than that of OA and AA. According to this principle and Equations (8) to (14), the weight vectors of R_f, OA, and ascorbic acid are presented as follows:

$$\beta=[\beta_1, \beta_2, \beta_3]^T=[0.105, 0.637, 0.258]^T \quad (18)$$

3.4.2 Comprehensive optimization process conditions

According to the variables listed in Table 2 as the response value of the R_f Y_1, OA content Y_2, and AA content Y_3, the weight coefficient β and Equations (5) to (7), the comprehensive evaluation response value set was obtained as shown in Equation (19). Using the Design-Expert software, the comprehensive evaluation

prediction model was calculated based on Equation (19) and prediction model Equation (4), as shown in Equation (20).

$$H=\{0.5615, 0.8981, 0.4623, 0.6784, 0.5156, 0.6684, 0.1707, 0.2934, 0.5021, 0.7597, 0.9661, 0.3921, 0.4417, 0, 0.5049, 0.5495, 0.5877, 0.3834, 0.5330, 0.5561, 0.5811, 0.5236, 0.5783\} \quad (19)$$

$$Y_{ce}= 9.25+0.035D-0.33T+2.43V0.0187TV+0.0125D^2+0.00285T^2-0.294\ V^2 \quad (20)$$

The regression analysis of the fitted comprehensive evaluation mathematical models is shown in Table 7. The table indicates that the F value of the model was 30.88 at the level of α = 0.01, $F_{0.01}(9,13)$ = 4.19. The F value of the model was considerably larger than the value of $F_{0.01}(9,13)$, indicating that the prediction model was extremely significant. The determination coefficient of model R^2 was greater than 0.8, indicating that the prediction model fits well and reasonably represents the observed values. The selection of each factor and comprehensive response desirability goal is shown in Table 8. The drying conditions and prediction results obtained by using the Design-Expert program are listed in Table 8 according to the optimal conditions and Equation (20). Table 8 shows that the desirability values of 4 predictive values are 0.978. However, in the conditions where power density was 12 W/g, hot air temperature was 55 ℃, and velocity was 1.72 m/s, the comprehensive predicted value Y_{ce} was the largest. Therefore, this drying condition was selected as the optimal drying process for hawthorn MCHA drying, that is, the power density of 12 W/g, hot air temperature of 55 ℃, velocity of 1.72 m/s, and the comprehensive prediction value Y_{ce} = 1.27126. According to Equation (7), the values of R_f, OA content, and AA content related to a comprehensive prediction value of 1.27126 were 1.303 g/g, 134.99 g/kg, and 110.9 mg/100 g, respectively.

Table 7 ANOVA for the second-order polynomial models of Y_{ce}

Source	Degree of freedom	Sum of squares	Mean square	F-value	R^2
Model	9	0.91	0.10	30.88	0.9553
Residual	13	0.04	0.003266		
Lack of Fit	5	0.011	0.00204	0.56	
Pure Error	8	0.031	0.00393		
Cor Total	22	0.95			

Table 8 Comprehensive optimization criteria for different factors and responses and optimization of process conditions

Factors or responses	Goal	Lower limit	Upper limit	Comprehensive optimization process conditions			
Power density /w g^{-1}	In the range	6	12	12	12	12	12
Hot air temperature/ ℃	In the range	55	70	55	55	55	55
Hot air velocity /m s^{-1}	In the range	1	3	1.72	1.71	1.72	1.70
Y_{ce}	Maximize	0	1.3	1.27126	1.27124	1.27122	1.27087
Desirability				0.978	0.978	0.978	0.978

3.5 Experimental validation

The test values of the rehydration ratio, OA content, and AA content were obtained under these optimum conditions, which were the average values of three tests. The test values, predicted values, and optimal test conditions are presented in Table 9. The test values were close to the predicted values, indicating that the regression model is consistent with the drying process of hawthorn slices microwave coupled with hot air. The drying process of hawthorn slices could be predicted by a regression model.

Table 9 Predicted and experimental value of comprehensive evaluation for response variable at optimum conditions

Optimum drying condition	Response variable	Experimental value	Predicted value
Microwave power 12 W/g	R_f	1.2936	1.303
Hot air temperature 55 ℃	OA	132.13	134.99
Hot air velocity 1.72 m/s	AA	109.2530	110.9

4 Conclusions

During the microwave coupled with hot air drying processing, according to the F-value, the rehydration ratio (R_f) of dried hawthorn slices got a greater impact by the initial microwave power density than the hot air temperature and the hot air velocity; the organic acid (OA) content and ascorbic acid content of dried hawthorn slices were got a greater impact by the hot air temperature than the hot air velocity and the initial microwave power density. The well fitted second-order polynomial model could be used to predict the experimental data for most responses with high values of coefficient of determination R^2 (>0.8). The comprehensive optimum condition was as follows: initial microwave power density of 12 W/g, hot air temperature of 55 ℃, and hot air velocity of 1.72 m/s, respectively. The experimental response

values and predicted values obtained from the fitted mathematic models were extremely close. The response surface methodology is applicable to effectively analyze the effect of microwave coupled with hot air drying parameters on product quality and to optimize the process.

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