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Drying Ginseng Slices Using a Combination of Microwave and Far-Infrared Drying Techniques

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Abstract

Purpose: This study was performed to improve the drying quality and drying rate of ginseng slices by combining microwave and far-infrared drying techniques. **Methods:** Based on single-factor experiments and analyses, a quadratic regression orthogonal rotation combination design was adopted to study the effects of the moisture content at the conversion point between the microwave and far-infrared techniques, the ginseng slice thickness and the far-infrared drying temperature on the chip drying time, the surface color difference value, the nutritional composition and the surface shrinkage rate index. **Results:** Compared to the far-infrared drying alone, the combined microwave and far-infrared drying resulted in an increase in the saponin content of the ginseng slices and reductions in the drying time, surface color difference, and shrinkage rate. **Conclusions:** We established a mathematical model of the relationships between the surface shrinkage rate index and the experimental factors using the multi-objective nonlinear optimization method to determine the optimal parameter combination, which was confirmed to be the following: microwave and far-infrared moisture contents of 65%, a ginseng slice thickness of 1 mm, and a far-infrared drying temperature of 54°C.

Keywords: Combined process, Drying characteristics, Far-infrared, Ginseng, Microwave

Introduction

Ginseng has the following characteristics: tastes sweet, belongs to the genus Panax of the family Araliaceae, helps to improve eyesight, benefits heart function, enriches the mind, pacifies spirit and soul, prevents fright, removes pathogens, and can be taken for a long time to prolong lifespan and reduce body weight (Feng, 1996). Ginseng is a precious Chinese herbal medicine that has the reputation of being the "king of all herbs" (Xv, 2001; Zhang, 2009). The moisture content of fresh ginseng is more than 70%, and it is difficult to store. If ginseng is stacked in a hot environment, the enzyme activity is enhanced and catabolism is increased, which leads to the hydrolysis of the oligosaccharides in fresh ginseng to monosaccharides, and the monosaccharides being oxidized into alduronic acid. The color of the ginseng is also altered. Glycolysis reactions increase and release heat, which can easily lead to mold contamination and subsequent decay. In addition, the chemical reactions of ginseng's internal starch, maltose, etc. also cause damage to ginseng (Liu and Du, 1994). Therefore, fresh ginseng needs to be dried before storage. The traditional method of drying ginseng is sun drying (Feng, 1986). This traditional processing method causes the loss of great quantities of nutrient components, substantial surface color changes, and relatively substantial deformation and shrinkage. In recent years, there have been developments in the ginseng processing methods. The main processing methods include microwave drying, vacuum freeze-drying, hot-air drying, far-infrared drying, etc. (Xv and Li, 1994).

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The combination ginseng drying method is a new technology that combines the advantages of different methods and has been widely used in recent years (Figiel, 2001; Xv et al., 2005; Zhang et al., 2005). Maskan (2011) used hot air and microwave methods to dry kiwifruits, and the vitamin C content and rehydration rate of the products after drying were significantly higher than those of carrots exposed to microwave drying alone. However, the application of microwave and far-infrared techniques to the drying of ginseng has not been reported. The water content of fresh ginseng is high, and water molecules have strong ability to absorb microwaves. The use of the microwave method to dry ginseng can result in the generation of ginseng products with very high energy levels in a short period of time because the water rapidly overflows while the space occupied by the raw water cannot be filled quickly. Thus, the appearance of the fresh ginseng is maintained. The microwave drying method can save time and energy, while also exerting a bactericidal effect.

To exploit the advantages of microwave drying and far-infrared drying for drying ginseng slices and to overcome the shortcomings of either method used in isolation, this article reports a study on the combination drying of ginseng slices using different microwave and far-infrared modes. The drying characteristics were analyzed in terms of factors including drying time, surface color changes, nutritional composition, and surface shrinkage. The results were compared to those from using far-infrared drying alone. It is identified that the new methods improve ginseng slice's drying quality and reduce the drying time.

Materials and Methods

Materials

Ginseng samples collected from the South Five ginseng wholesale market of Shenyang were used as the experimental materials in this study. The origin of the ginseng was Fusong County in Baishan City. The initial average moisture content of the plant material was 74.83%. The initial average color values were 81.27 (lightness), -0.93 (redness) and 16.70 (yellowness). The initial average saponin content of the raw material was 0.35 mg g^{-1}. The initial average surface area was 225 mm^2.

Experimental equipment

The following instruments were used in the experiments: an electronic balance (DJ-5002, Huazhi Scientific Instrument Co., Ltd., Fuzhou), a multi-function traditional Chinese medicine slicing machine (DYQ-838B, Yongli Pharmaceutical Machinery Co., Ltd., Ruian, Zhejiang), a microwave oven (Galanz WD-850, Galanz Group, Shunde, Guangdong), a far-infrared drying oven (HY-1B, Tongli Xinda Instrument Factory, Tianjin), a color-difference meter (CR-400, Konica Minolta Holdings Inc., Japan), an electrically heated constant-temperature water-bath (DK-S26, Jinghong Experiment Equipment Co., Ltd., Shanghai), a desktop high-speed centrifuge (H-1650, Xiangyi Centrifuge Instrument Co., Ltd), and an ultraviolet visible spectrophotometer (TU-1810, Purkinjie General Instrument Co., Ltd., Beijing). A digital camera was also used to assess the combined microwave and far-infrared drying.

Experimental methods

We washed the fresh ginseng in clean water, gently brushed the surface, and ensured that no dirt was on the surface. Next, after removing the head and the root, the ginseng was sliced for the combination drying experiments. Approximately 50 g of ginseng was used in each drying condition.

Drying time

Every 10 min, the samples were quickly placed on the electronic balance and weighed to ensure that the samples were dried to a final moisture content of 13.0±0.5% (w. b) to obtain the drying times.

Surface color measurement

The colors of both fresh and dried ginseng slices were measured with a color-difference meter (JX777; C.T.S. Co., Tokyo, Japan). According to the CIELAB (Zhu et al., 2002) color system, also known as the L*a*b* color system, the surface colors of six treated and untreated ginseng samples were measured in terms of L [black (0) to white (100)], a [red (60) to green (-60)] and b [yellow (60) to blue (-60)]. According to the L*a*b* system, the color difference between two samples (ranging from 1 to 2 ΔE*ab) was taken as the distance in color space as follows:

$$\triangle E^{*}ab = \sqrt{(L1^{*}-L2^{*})^2+(a1^{*}-a2^{*})^2+(b1^{*}-b2^{*})^2} = \sqrt{(\triangle L^{*})^2+(\triangle a^{*})^2+(\triangle b^{*})^2} \quad (1)$$

ΔL^*, Δa^*, and Δb^* indicate the D-values in three coordinates. ΔE^*ab indicates the corresponding color difference between two conditions, and larger values indicate greater color differences.

Saponin measurement

Approximately 0.5 g of finely ground samples was mixed with 50 mL of water and then the mixture was heated in an electrically heated constant-temperature water bath for 15 min at 60°C. The reagents were cooled, centrifuged, and mixed with 0.5 mL of color rendering agent; subsequently, 5 mL of sulfuric acid was added. Next, the extracted saponin solution was dried at 50°C and then mixed with 10 mL of methanol. The saponin content was analyzed according to the absorption value as assessed with an ultraviolet visible spectrophotometer at a wavelength of 544 nm.

Surface shrinkage measurement

The shrinkage rate of the actual area during the ginseng slice drying process is relatively complex. In the present paper, the projection area contraction ratio was used as the test index.

$$R = \left(1 - S'/S\right) \times 100\% \quad (2)$$

where S' indicates the projection area of any condition after drying, and S indicates the initial projection area.

In this paper, we used the MATLAB image processing function to measure the ginseng slice area. First, the ginseng slice was fixed on a standard plate, and the original image and background image were obtained, as shown in Figure 1(A) and 1(B). The background image was removed using MATLAB as shown in Figure 1(C). Figure 1(D) was then obtained by applying the binarization process in MATLAB. Using the MATLAB program, the total proportions and sizes of the ginseng slices were obtained.

Quadratic regression rotatable orthogonal design

Determination of the factor levels

This experiment investigated the effects of the moisture contents, ginseng slice thicknesses and far-infrared drying temperatures on chip drying times, surface color differences,

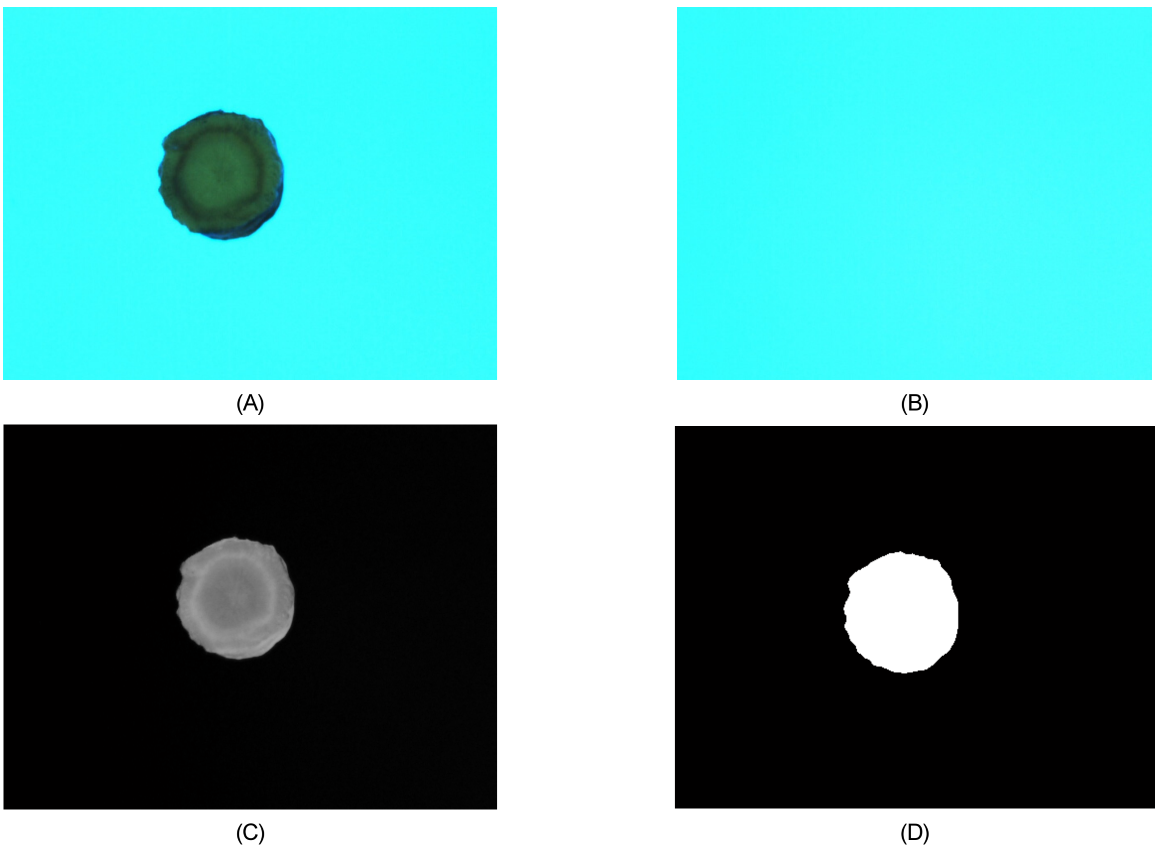

Figure 1. Illustration of the ginseng slice area measurement by MATLAB image processing function.

nutritional compositions and surface shrinkage rates under the microwave and far-infrared drying process. Regarding the ginseng slice thickness, Yan (2007) and others reported that the thickness of ginseng slices on the market is 3 mm. Moreover, these authors demonstrated that ginseng slices less than 1 mm in thickness deform easily and the drying times for slices whose thickness is greater than 5 mm are too long and uneven (Yan, 2007); therefore, the thicknesses of the ginseng slices used in this study were 1 - 4 mm (Guo, 2012). Regarding the far-infrared drying temperature, higher temperatures result in shorter drying times and faster dehydration rates. However, high temperatures can cause ginseng slices to overheat, which reduces the nutrient contents of the samples. If the selected temperature is too low, the ginseng slice drying time is prolonged, and the dehydration rate obviously decreases; thus, far-infrared temperatures of 50 to 65°C were selected for the present study based on previous experiments. Regarding the moisture content at the conversion point, the shape and color of the ginseng slices change significantly prior to microwave drying, if the moisture content at the conversion point is too low. If the moisture content at the conversion point is too high, the far-infrared drying time will be too long. For all microwave drying experiments, the moisture contents at the conversion points were set to 50 - 65% (Wang et al., 1999).

Scheme of the quadratic regression rotatable orthogonal design

The experiment was completed using a three-factor quadratic regression rotatable orthogonal design. Each factor was coded according to its level and value, and a factor-level coding table was obtained as shown in Table 1.

The design theory of the three-factor quadratic regression rotatable orthogonal design was arranged and tested 23 times (Zhu, 1981; Li and Hu, 2004). The test scheme and results are shown in Table 2.

Results and Discussion

Drying curves

Figure 2 shows the changes in moisture content according to the drying time. The drying times for ginseng slices to reach final moisture content at a moisture content at the conversion point of 62% and slice thickness of 3.5 mm with far-infrared drying temperatures of 62°C and 54°C are 69.6 min, and 72 min, respectively. The drying times at a moisture content at the conversion point of 54% with the same slice thickness and far-infrared drying temperatures are 75 min, and 69.6 min, respectively. The drying times for ginseng slices to reach final moisture content at a moisture content at the conversion point of 62% and slice thickness of 1.5 mm with far-infrared drying temperatures of 62°C and 54°C are 61.2 min, and 55.8 min, respectively. The drying times at a moisture content at the conversion point of 54% with the same slice thickness and far-infrared drying temperatures are 27.6 min, and 13.8 min, respectively. The minimum drying time (13.8 min) was observed at a conversion point of 54% with a slice thickness of 1.5 mm and a drying temperature of 54°C. The maximum drying time (75 min) was observed at a conversion point of 54% with a slice thickness of 3.5 mm and a drying temperature of 62°C. As expected from these drying curves, moisture content at the conversion point, slice thickness, and far-infrared drying temperature have effected on the drying rate of ginseng slices. It can be seen from Figure 2 that a decrease in moisture content at the conversion point and slice thickness and an increase in far-infrared temperature result in a decrease in drying time.

Table 1. Coding of the factors and levels of the optimal ginseng drying parameters

Factors	The moisture content at the conversion point (%, w.b.)	Slice thickness (mm)	Far-infrared drying temperature (°C)
Variable	x_1	x_2	x_3
Zero lever (0)	58	2.5	58
Change interval (Δ)	4	1	4
Upper level (1)	62	3.5	62
Lower level (-1)	54	1.5	54
Upper asterisk arm (γ)	65	4	65
Lower asterisk arm (-γ)	50	1	50

Table 2. Experimental project and results of the optimal ginseng drying parameters

Test number	z_1	z_2	z_3	Drying time y_1 (h)	Surface color value y_2 (ΔE)	Saponin content y_3 ($mg \cdot mL^{-1}$)	Surface shrinkage rate y_4 (%)
1	1	1	1	1.16	1.10	0.06	16.66
2	1	1	-1	1.20	3.33	0.14	17.34
3	1	-1	1	1.02	1.23	0.14	14.66
4	1	-1	-1	0.93	3.23	0.18	13.34
5	-1	1	1	1.25	1.67	0.15	18.00
6	-1	1	-1	1.16	1.78	0.19	16.66
7	-1	-1	1	0.46	1.67	0.22	6.66
8	-1	-1	-1	0.23	2.05	0.25	3.34
9	1.682	0	0	1.71	0.33	0.08	24.66
10	-1.682	0	0	0.65	3.33	0.25	9.34
11	0	1.682	0	0.60	1.13	0.06	8.66
12	0	-1.682	0	0.56	1.21	0.12	8.00
13	0	0	1.682	0.56	1.09	0.05	8.00
14	0	0	-1.682	1.02	3.33	0.16	14.66
15	0	0	0	0.32	1.67	0.07	4.66
16	0	0	0	0.46	1.10	0.07	6.66
17	0	0	0	0.56	1.10	0.01	8.00
18	0	0	0	0.18	1.10	0.15	2.66
19	0	0	0	0.69	1.23	0.03	10.00
20	0	0	0	0.28	1.10	0.05	4.00
21	0	0	0	0.37	1.23	0.09	5.34
22	0	0	0	0.42	1.67	0.04	6.00
23	0	0	0	0.37	1.10	0.06	5.34

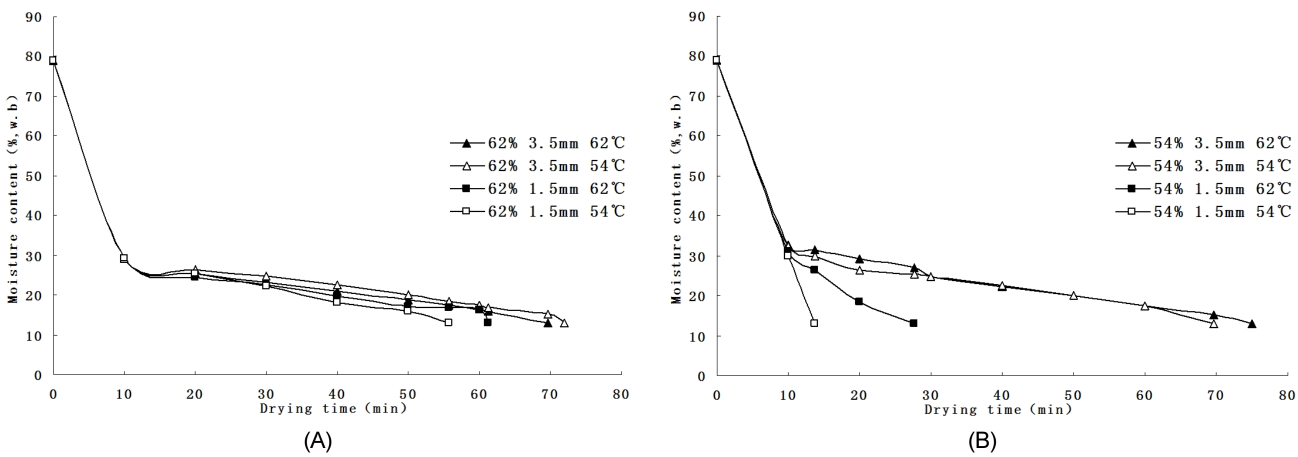

Figure 2. Illustration of the change of moisture content of ginseng slices with drying time.

Establishment of the mathematical model

According to the results of the three-factor quadratic regression rotatable orthogonal model, a mathematical model was established. Through analysis of the data, an index test of the regression equation and a previously reported test of the data fit (Li and Hu, 2004) revealed that the factors z_2, z_3, z_1z_2, z_1^2, z_2^2, z_3^2 are more significant. The remaining factors are non-significant to some extents. The non-dimensional factor coding regression equation for ginseng slice drying time is expressed as follows:

$$y_1=0.405161+0.161533z_2-0.03001z_3-0.16198z_1z_2+0.284141z_1^2+0.071324z_2^2+0.144963z_3^2 \quad (3)$$

According to the partial regression coefficients of the non-dimensional factor coding regression equation, we determined the order of the influences of the test factors on the drying time of the ginseng slices as follows: the thickness of the ginseng, the far-infrared drying temperature, and the moisture content at the conversion point between the microwave and far-infrared drying. The regression equation of the drying time and the factors related to the ginseng slice is as follows:

$$y_1=24.31781-0.0422x_1+0.845729x_2-0.80193x_3-0.00578x_1x_2-0.00031x_1x_3-0.00864x_2x_3+0.000393x_1^2+0.087696x_2^2+0.007341x_3^2 \quad (4)$$

The regression equations for the surface color difference, saponin content and shrinkage area of the ginseng slices were obtained using the same method. The non-dimensional factor coding regression equation for ginseng slice surface color difference is as follows:

$$y_2=1.250261-0.03182z_2-0.62143z_3+0.03z_1z_2+0.253163z_1^2+0.019875z_2^2+0.38748z_3^2 \quad (5)$$

According to the partial regressions coefficient of the non-dimensional factor coding regression equation, we determined the order of the influences of the test factors on the surface color of the ginseng slices as follows: the thickness of the ginseng, the far-infrared drying temperature, and the moisture content at the conversion point between the microwave and far-infrared drying. The regression equation of the surface color difference and the factors related to the ginseng slice is as follows:

$$y_2=50.60182-0.151528x_1-0.5148x_2-1.798x_3+0.001071x_1x_2-0.00417x_1x_3-0.00125x_2x_3+0.000378x_1^2+0.05924x_2^2+0.01805x_3^2 \quad (6)$$

The non-dimensional factor coding regression equation for ginseng slice saponin content is as follows:

$$y_3=0.17913-0.01611z_2-0.005091z_3+0.025z_1z_2-0.03424z_1^2-0.00419z_2^2-0.00949z_3^2 \quad (7)$$

Similarly, we determined that the order of the influences of the test factors on the saponin content of the ginseng slices is as follows: the far-infrared drying temperature, the thickness of the ginseng, and the moisture content at conversion point between the microwave and far-infrared drying. The regression equation describing the saponin content and the factors of the ginseng slice is as follows:

$$y_3=0.423689-0.00534x_1-0.1491x_2-0.011304x_3+0.000893x_1x_2-0.000201x_1x_3-0.00125x_2x_3-0.000048x_1^2-0.00695x_2^2-0.0003x_3^2 \quad (8)$$

The non-dimensional factor coding regression equation for ginseng slice shrinkage area is as follows:

$$y_4=5.834321+2.326076z_2-0.43213z_3-2.3325z_1z_2+4.091624z_1^2+1.027071z_2^2+2.08747z_3^2 \quad (9)$$

The order of the influences of the test factors on the surface shrinkage rate of the ginseng slices is as follows: the thickness of the ginseng, the far-infrared drying temperature, and the moisture content at the conversion point between the microwave and far-infrared drying. The regression equation of the shrinkage area and the factors related to the ginseng slice is as follows:

$$y_4=350.1764-0.60763x_1+12.1785x_2-11.54784x_3-0.0833x_1x_2-0.00449x_1x_3-0.12437x_2x_3+0.005666x_1^2+1.262824x_2^2+0.105704x_3^2 \quad (10)$$

Drying performance analysis

The analysis of the experimental factors revealed that the effects of the moisture content at the conversion point between the microwave and far-infrared drying on the ginseng slice drying time, saponin content, surface color difference and shrinkage area were minimal. The moisture content at the conversion point between the microwave and far-infrared was reduced to zero using the dimension reduction method, and the effects of the other two factors on drying time, surface color difference, saponin content, and surface shrinkage rate were analyzed. To assess the relationships between each test index and the test factor, a 3D contour map was plotted using the MATLAB software, and the results are shown in Figure 3.

With increasing ginseng slice thickness z_2, the ginseng slice drying time increases slightly with the increase in the far-infrared drying temperature z_3. Additionally, with the increase in the far-infrared drying temperature z_3, the

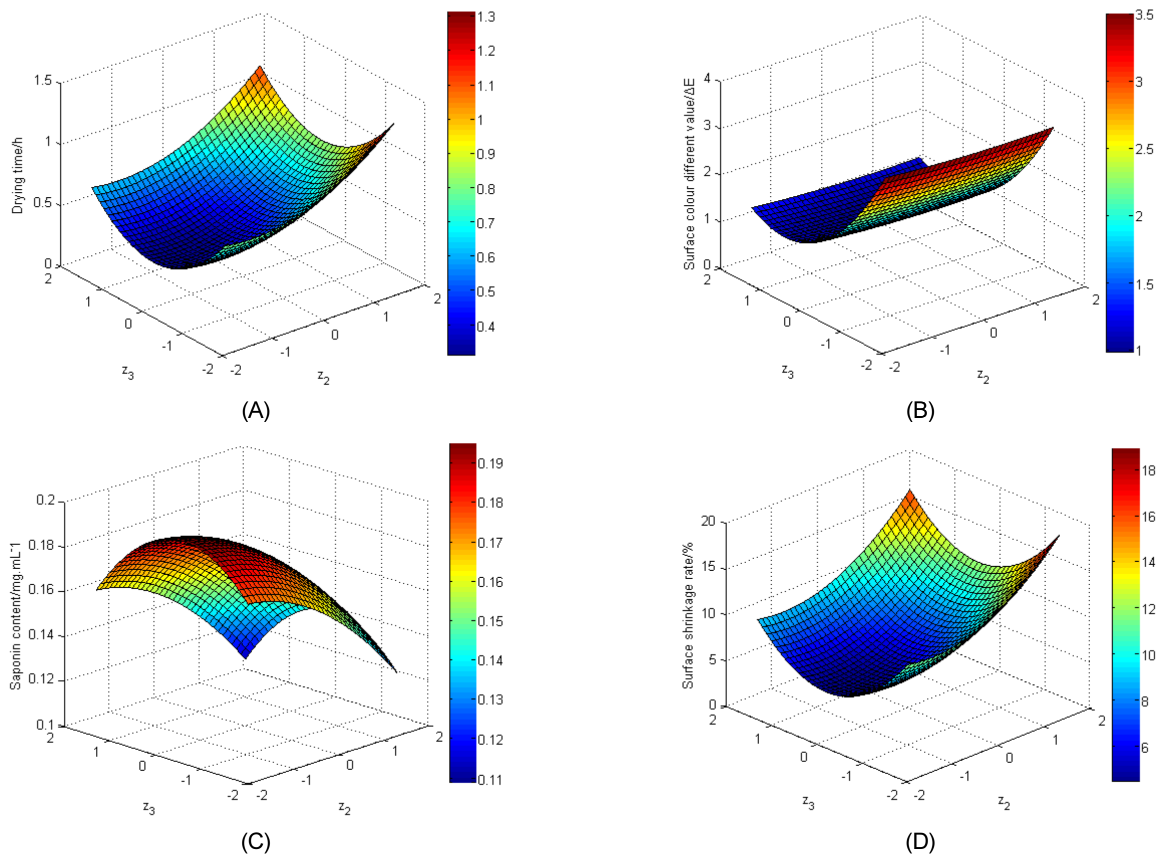

Figure 3. Illustration of interactive influences of ginseng slice thickness and drying temperature on drying performance generated by MATLAB image processing function.

ginseng slice drying time first decreases and then increases with the increase in the ginseng slice thickness z_2; $y_{min}(0, z_2, z_3) = (0, -1, 0) = 0.315$ h (Figure 3(A)).

With the increase in the ginseng slice thickness z_2, the ginseng slice surface color difference first decreases and then increases with increase in the far-infrared drying temperature z_3. Additionally, with increasing far-infrared drying temperature z_3, the ginseng slice surface color difference decreases slightly with the increase in the ginseng slice thickness z_2; $y_{min}(0, z_2, z_3) = (0, 1, 1) = 1.004$ (Figure 3(B)).

With increasing ginseng slice thickness z_2, the ginseng slice saponin content first increases and then decreases with increase in the far-infrared drying temperature z_3. Additionally, with increasing far-infrared drying temperature z_3, the ginseng slice saponin content decreases slightly with the increase in the ginseng slice thickness z_2; $y_{max}(0, z_2, z_3) = (0, -1.682, 0) = 0.194$ mg·mL^{-1} (Figure 3(C)).

With the increase in the ginseng slice thickness z_2, the ginseng slice surface shrinkage rate increases slightly with the increase in the far-infrared drying temperature z_3. Additionally, with the increasing far-infrared drying temperature z_3, the ginseng slice surface shrinkage rate first decreases and then increases with the increasing ginseng slice thickness z_2; $y_{min}(0, z_2, z_3) = (0, -1, 0) = 4.54\%$ (Figure 3(D)).

Drying performance optimization

The drying process should ensure that the saponin content of the ginseng slices is maximal and that the drying time, surface color changes, and surface shrinkage rate are minimized. Therefore, we created the objective function $F = -y1-y2+y3-y4$ and then brought the regression equation into the objective function. The objective function and the constraint conditions are as follows:

$$Constraint\,conditions \begin{cases} y_1 \geq 0 \\ 50\% \leq x_1 \leq 65\% \\ 1 \leq x_2 \leq 4 \\ 50 \leq x_3 \leq 65 \end{cases}$$

$$F_{max} = -y_1 - y_2 + y_3 - y_4 \quad (11)$$

Table 3. Best combinations of parameters and results

Theoretical value					Test value				
y_1 (h)	y_2 (ΔE)	y_3 ($mg{\cdot}mL^{-1}$)	y_4 (%)	F	y_1 (h)	y_2 (ΔE)	y_3 ($mg{\cdot}mL^{-1}$)	y_4 (%)	F
2.84	5.38	0.21	4.12	-4.91	2.83	5.44	0.19	3.98	-4.87

Table 4. Test programs and results

Drying method	Slice thickness (mm)	Drying temperature (°C)	Drying time y_1 (h)	Surface color value y_2 (ΔE)	Saponin content y_3 ($mg{\cdot}mL^{-1}$)	Surface shrinkage rate y_4 (%)
1	1.5	54	1.25	3.10	0.05	32.04
2	1.5	54	0.93	3.23	0.18	13.34
1	1.5	62	1.17	7.43	0.07	30.52
2	1.5	62	1.02	1.23	0.14	14.66
1	3.5	54	6.17	8.43	0.06	29.04
2	3.5	54	1.2	3.33	0.14	17.34
1	3.5	62	3.00	3.47	0.07	29.52
2	3.5	62	1.16	1.1	0.06	16.66

[1]FID: Far-infrared drying; [2]CD: Combined drying

Excel was used to solve the objective function, and the results of the optimization of the parameters are as follows: the moisture content at the conversion point from microwave to far-infrared drying is 65%, the thickness of the ginseng slice is 1 mm, and the far-infrared drying temperature is 54°C.

The results of the optimization, which were obtained from 3 additional tests, are shown in Table 3.

Far-infrared drying

The experiment was finished by using two-factor full factorial experimental design. The factor level is shown in Table 4.

The combined drying technique resulted in better quality, shorter drying time, smaller surface color value, higher saponin content, and smaller surface shrinkage rate, compared to the results from far-infrared drying conditions.

Conclusions

(1) Compared with far-infrared drying alone, combined microwave and far-infrared drying results in an increase in the saponin content of the ginseng slices and reductions in the drying time, surface color difference, and shrinkage rate.

(2) The relationships between the drying parameters and drying properties of the ginseng slices were confirmed from the three-factor quadratic regression rotatable orthogonal design. In the design, the moisture content at the conversion point from microwave to far-infrared drying, the ginseng slice thickness and the far-infrared drying temperature were used as the independent variables, and drying time, surface color difference, saponin content, and shrinkage rate were used as the dependent parameters.

(3) Based on the regression equation, the effects of the moisture content at the conversion point from the microwave to the far-infrared drying, the ginseng slice thickness and the far-infrared drying temperature on the ginseng slice drying time, surface color difference, saponin content and surface shrinkage rate were not the same. In order of decreasing influence, the influences of the primary and secondary factors on drying time, surface difference and area shrinkage rate are as follows: the thickness of the ginseng, the far-infrared drying temperature, and the moisture content at the conversion point between the microwave and far-infrared drying. In order of decreasing influence, the effects of the primary and secondary factors on the saponin content are as follows: the far-infrared drying temperature, the thickness of the ginseng, and the moisture content at the conversion point between the microwave and far-infrared drying.

(4) The optimum technological parameters for combined microwave and far-infrared drying are as follows: the moisture content at the conversion point between the microwave and far-infrared drying is 65%, the thickness of the ginseng slice is 1 mm, and the far-infrared drying temperature is 54°C. The drying performance of the ginseng slices was optimal under these conditions.

(5) In this study, we investigated the characteristics of far-infrared drying technique and the combined microwave and far-infrared drying technique for ginseng drying. It turned out that the results from the combined drying were better than the ones from the far-infrared drying.

Conflicts of Interest

The authors have no conflicting financial or other interests.

Acknowledgments

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