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Experimental study on fluidized bed drying process of Maca (*Lepidium meyenii* Walp.) tuber

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ABSTRACT

In this study, the fluidized bed drying method of maca tuber was adopted. Through single factor test, the influence of three main factors including air inlet temperature, air flow and material particle size on the glucosinolate content and the saturation value of the maca tuber were investigated. Setting the glucosinolate content as the response value, the response surface methodology (RSM) and optimization were performed, to establish the regression model for the influence of fluidized bed drying of maca tuber on its glucosinolate content. The results showed that, when the air inlet temperature was 65 ℃, air flow was 150 m³/h and material particle size was 3 mm, the highest glucosinolate content of maca with good sensory quality was achieved.

Key words: maca; fluidized bed; drying; rehydration rate; glucosinolate

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INTRODUCTION

Maca (*Lepidium meyenii* Walp.), a kind of *Lepidium* herb that can be used for food and medicine, was originated in the area of Andean alpine mountains with an altitude of 3500m. It has been extensively used in the Peruvian highland for thousands of years. The latest research showed that, it was not only rich in nutritious, but also had good effects in sexual health, anti-fatigue and fertility improvement, *etc*.. As a result, it has always enjoyed the reputation of being "Peruvian treasure" or "Peruvian ginseng"[1-4].

The moisture content of fresh maca tuber is about 80% (relatively high). If it is not dried timely, it will be easily getting browning, enzymatic hydrolysis and deterioration, which will seriously affect its quality. Besides, the moisture content is also a critical factor in the foods preservation, which can directly affect the stability quality. At present, fruit and vegetable dehydration methods mainly include hot air drying, vacuum freeze drying, infrared drying, microwave drying, and so on. In general, the dehydrated products without high quality requirements for the appearance and quality can be produced by the hot-air drying method, while other drying methods, due to large investment in equipment and high operating costs, are rarely applied in actual production. However, glucosinolates, the most important bio-active ingredient in maca tuber, is very unstable under acid-base, heat conditions or when it is in contact with the mustard enzymes, which can be easily decomposed into products with pungent odor. Moreover, unpleasant changes to the quality of the maca also will happen when it is exposured to high-temperature drying for a long time[5-8].The fluidized bed drying can provides large contact surfaces for the materials and drying medium, which helps achieve uniform temperature distribution, better effect of heat transfer and short drying time. Fluidized bed are suitable for many fruits and vegetables drying, such as potato[9], sunflower seeds[10], wheat germ[11], blueberries[12], carrot slices[13], cabbage[14] and garlic slices[15] etc.. In the present study, the fluidized bed was adopted on fresh maca tuber dying. The influence of the air inlet temperature, air flow and other operating parameters on the product quality was investigated to determine the optimal operating conditions of the drying of maca tuber by the fluidized beds through the response surface optimization test. Then a comparative study was performed among maca tuber products with fluidized bed drying , hot air drying and vacuum freeze drying.

EXPERIMENTAL SECTION

Fresh chilled maca tuber, provided by the Mid-Yunnan Highland Experiment Station, the experiments were conducted at the Research Center of Engineering and Technology on Forest Resources with Characteristics, State Forestry Administration, the Research Institute of Resources Insects, Chinese Academy of Forestry.

FLUIDIZED BED DRYING PROCESS OF MACA TUBER

Firstly, the tuber was taken out from a -5□ refrigerator(moisture content of 78.6%). After naturally thawing for 20 min, it was evenly diced with a slicing machine under low temperature, and placed in a refrigerator at 4□ constant temperature for 2h for future use. About 1g of sample was fetched to determine its initial moisture content with a fast halogen moisture analyzer. In the drying test, (200±0.5)g of samples was weighed from each portion, and placed in a fast drying instrument evenly spread it (ambient temperature 19°C, humidity 50%). The parameters set were according to the experimental design requirements, Then the machine was turned on, and samples should be taken out from the dry container every 5min. The samples were weighed, recorded the change of weight, and calculated the change of moisture content according to the initial moisture content. According to the instructions for the new resource foods of maca powder of the Ministry of Health of the People's Republic of China, when the moisture content of the materials reduced to about 10% of drying endpoint, record the final drying time was recorded. The reliability of data was guaranteed by three repeat trials, and the average of the three replicates was taken as the final result.

HOT AIR DRYING AND VACUUM FREEZE-DRYING PROCESS THE MACA TUBER

The maca tubers were diced into pieces with the particle size of 3 mm. The moisture content was measured by a Halogen Moisture Analyzer. About 200g of materials was weighed and put into a tray, and then placed to a oven with temperature of 65□, air flow of 288m^3/h for drying. In addition, 200g of material was placed in a glass dish, and dried in a freeze dryer at the drying condition of -40□, 0.09mba. When the moisture content of the material was or below 10%, it was the drying endpoint. The final drying time should be recorded at this time. The test was repeated for three times, the average of the three replicates was taken as the final result.

DETERMINATION OF TOTAL GLUCOSINOLATE CONTENT SAMPLES

The procedures was modified with reference to the method of La et al.[16]. 10g of the maca tuber sample was fetched and placed in a glass dish, freeze-dried, and crushed into powder with a freezing mixed ball mill to examine the moisture content of the powder. 0.1g of powder was taken, added with 3mL of 70% methanol to extract for 15 min in 75□ water bath condition, centrifuged (4□, 4000rpm) for 10min. Then the supernatant was precipitated for extracting twice according to the procedures above. The extracting solution was combined with 0.1 mL of 0.375mol/L lead acetate solution, placed for 15 min, and then centrifuged for 15 min (4□, 10000rmp). The supernatant was set to the volume 10mL. 2mL of extracting solution was fetched to determine the absorbance at 540nm wavelength according to the developing method in standard curve, which was compared with that in the standard curve to calculate the glucosinolate content of the samples.

ANALYTICAL TEST METHOD OF DRIED PRODUCTS

The test method of moisture content: The moisture content of maca tuber was determined with a fast halogen moisture test apparatus. The acceptable value of moisture content of the dried products was set as ≤10%, with reference to the description of the Ministry of Health of the People's Republic of China for the maca powder new resource foods.

Determination of saturation value: The three colors of red, green, blue of the dried maca tuber were determined with a portable colorimeter for nine times by parallel test and the average was taken. To make the data close to the human eye visual effect, the quality analysis of the saturation value was performed with HIS system and the RGB color difference coordinates were transformed: $I=(R+G+B)/3$, $S=1-[\min(R,G,B)]/I$; when the saturation value S=0, expressed as white; when S=1, expressed as black[17]

Determination of rehydration rate: approximately 2g of dried product was placed in a 200ml beaker, added with clear water of 20 times of the sample volume; soaked for 2h at room temperature before taken out. the mass of the sample was determined after its surface water was absorbed by a filter paper. The rehydration rate R was calculated as follows: $R=G_2/G_1$, where, G_2 is the mass of dried product after dehydration; G_1 is the mass of the dried product.

Three parallel tests were performed for each sample, and its average was taken as the test result[18].

Scanning electron microscopy (SEM) characterization: the maca samples with hot air drying, vacuum freeze-drying and fluidized bed drying processed were observed, examined and imaged with different multiples under the scanning electron microscope. The appropriate and clear pictures were selected for the comparative analysis[19].

DATA PROCESSING AND ANALYSIS

The Origin 8.0 and the Design-expert 8.0 software were adopted for the test data processing, to establish the regression equation and the surface chart. This group of charts was used for the analysis and evaluation of the any two kinds of interaction effect and determination of the optimum operating conditions.

RESULTS AND DISCUSSION

The influence of the fluidized bed drying temperature on the glucosinolate saturation value of the maca tubers was shown in Fig.1. As shown in the figure, the content of glucosinolates in maca tuber firstly rose and then dropped with the temperature, When the temperature was 70°C, its content reached the peak value. The maca contains a substrate enzyme system: glucosinolate- myrosinase system[1]. The myrosinase that decomposed the glucosinolate has reached its maximum activity at 50°C[20]. If the maca was dried at about 50°C, the reaction of myrosinase to decompose the glucosinolate would be intensified, Consequently, the maca glucosinolate content would be correspondingly low after drying. The myrosinase activity gradually decreased with the temperature rose, and the glucosinolate content of the dried product increased correspondingly. However, when the temperature was iabove 70°C, it might intensify the thermal decomposition of glucosinolates, and thus decreasing the glucosinolate content in the dried products. When the temperature was over 70°C, the maca tuber color saturation value will significantly increased with the rise of temperature, suggesting that maca might be subject to severe browning when drying under high temperature; Therefore, the drying of maca tuber should be controlled within a low temperature. Under comprehensive consideration, the optimal temperature was 65°C.

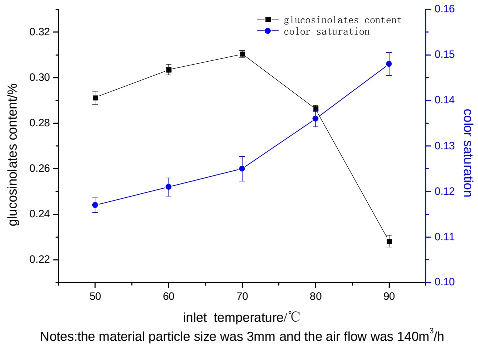


Fig.1 Effect of intake air temperature on glucosinolates content and color saturation of maca

The influence of air flow on the maca tuber glucosinolate content and the saturation value were shown in Fig.2. As displayed in the figure, the content of glucosinolates in maca tuber gradually increased and the saturation value decreased with the increase of air flow. When the air flow exceeded $140m^3/h$, the glucosinolate content increased slowly and the saturation value curve decreased slowly, but the influence was not very significant, the energy consumption gradually increased. Therefore, by comprehensive consideration, the optimal air flow was $140m^3/h$.

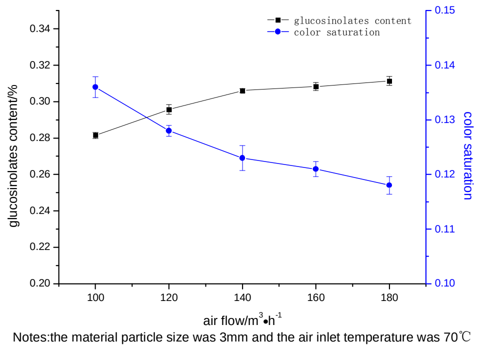
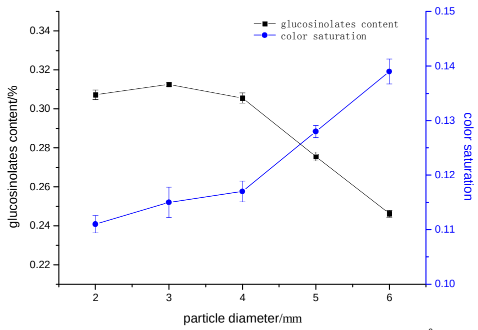


Fig.2 Effect of air flow on glucosinolates content and color saturation of maca

The influence of the material particle size on the maca tuber glucosinolate content and the saturation value were shown in Fig.3. As shown in the figure, the glucosinolate content preset increased and then decreased with the material particle size. When the size was 3mm, it reached the maximum value. It was possible that when the particle size was more than 3mm, the drying time increased dramatically, which caused the treatment of tuber at high temperature for a long time and accelerated the decomposition of glucosinolates; When the particle size was less than 3mm, the mechanical damage in the slicing process more likely happened comparing to the particle size was larger, which promoted the contact of glucosinolates and myrosinase to generate the hydrolytic reaction, lowering the glucosinolate content. The saturation value gradually increased with the increase of the particle size, which might result from the increased drying time. Therefore, under comprehensive consideration, the optimal material particle size was selected to be 3mm.



Notes:the air inlet temperature was 70℃ and the air flow was 140m^3/h

Fig.3 Effect of the particle diameter on glucosinolates content and color saturation of maca

OPTIMIZATION OF THE FLUIDIZED BED DRYING PROCESS CONDITIONS

The fluidized bed drying has some influence on the maca tuber nutrients and appearance. The glucosinolates is a very important and effective ingredient of maca tubers, which has the anticancer activity. It is necessary to minimize the losses and decomposition of glucosinolates in the drying process[21]; Moreover, the appearance quality of the dried product is also very critical, especially the color of the product[22]. In this test, the lustre of tuber was characterized by the color saturation value. Therefore, in the single factor test, two representative indicators were selected to assess the maca tuber product dried by fluidized bed. Using the glucosinolate content as the main index, color saturation value as the secondary reference index, the single factor test conditions were selected. On the basis of single factor test, with the Design-expert8.0 software, central composite experimental design (Box-Behnken Design, BBD) was adopted. The three main factors of air inlet temperature (□), air flow(m^3/h) and material particle size (mm) were used as the responsible variables, expressed as A, B and C, and the content of glucosinolates Y as the response value, to optimize the response surface. The test factor level design was shown in Table 1.

Table 1. Factors and levels for RSM

Factors	Coded variables		
	-1	0	1
Intake air temperature /□	60	65	70
Air flow /m^3•h^{-1}	130	140	150
Particle diameter /mm	2	3	4

In combination with the single-factor test results, a three-factor and three-level test was conducted according to the Box-Behnken test procedures with the maca tuber glucosinolate content as the response value. The codes and values of all test groups were shown in Table 2. There were 15 test sites in total, including 12 factorial sites and three zero test sites. The zero test was carried out for three times and error estimation was made. The multiple regression fitting of the obtained test data was made by Design Expert software to obtain the quadratic polynomial regression equation with the maca tuber glucosinolate content as the objective function:

$$Y=0.30+0.013A+3.51\times10^{-3}B-8.75\times10^{-4}C+3.75\times10^{-4}AB+3.50\times10^{-4}AC+2.00\times10^{-4}BC-2.75\times10^{-3}A^2+2.54\times10^{-4}B^2-4.07\times10^{-3}C^2 \quad (1)$$

In the Eqs.1, the absolute value of the coefficients reflected the degree of influence of various factors on the index value and the negative or positive value of coefficient reflected the direction of influence. As seen from the regression equation, the two linear terms of the air inlet temperature and air flow and the quadratic term of material particle size had greater influence on the glucosinolate content.

Table 2. Arrangement and results of the three-level, three-variable Box-Behnken experimental design

Run	Variable levels			Response values
	A	*B*	*C*	Glucosinolates content/%
1	-1	0	1	0.2825
2	0	0	0	0.3039
3	0	-1	-1	0.2976
4	1	-1	0	0.3109
5	0	1	-1	0.3047
6	-1	1	0	0.2917
7	0	0	0	0.3041
8	1	0	1	0.3103
9	1	1	0	0.3182
10	0	1	1	0.3035
11	0	0	0	0.3045
12	-1	-1	0	0.2859
13	1	0	-1	0.3115
14	0	-1	1	0.2956
15	-1	0	-1	0.2851

In order to test the validity of equation, ANOVA was conducted for the regression models (Table 3.). The results showed that there was significant difference among the models ($P<0.0001$), indicating that the significance and reliability of the regression equation were extremely high. The lack-of-fit test (LOF) of the regression equation showed that the P value was more than 0.05 ($P=0.1704$), which indicated that the influencing factors were comprehensive for this test, without other factors that can not be ignored and the degree of fitting of the models was good. The coefficient of determination of the regression model was 0.9990 and the adjusted coefficient of determination was 0.9972, both of which were more than 90%, indicating that the measured value and the predicted value fitted well. Therefore, the regression equation could predict the change rules of the glucosinolate content of maca after fluidized bed drying with the air inlet temperature, air flow, material particle size and other parameters.

Table 3. Variance analysis for the fitted regression model

Source	Sum of Squares	Degree of freedom	Mean square	*F* value	*P*-value Prob>b
Model	1.588×10^{-3}	9	1.764×10^{-4}	553.34	<0.0001**
Residual	1.594×10^{-6}	5	3.188×10^{-7}		
Lack of Fit	1.408×10^{-6}	3	4.692×10^{-7}	5.03	0.1704
Pure Error	1.867×10^{-7}	2	9.333×10^{-8}		
Cor Total	1.589×10^{-3}	14			

*Notes: *.P<0.05, significant difference, **.P<0.01, extremely significant difference.*

As seen from the regression equation coefficient test in Table 4, the influence of the linear terms A, B, and C and the quadratic terms A^2, C^2 in model (1) were extremely significant; that of the interaction term AB was significant, while the influence of the interaction terms BC, AC, and quadratic term B^2 were not significant. There was no simple linear relation between the test factor and response value. The quadratic and interaction terms had relation with the response value. Therefore, it can be concluded that the response surface equation are fitting well.

Table 4. Significance test for regression coefficients of the fitted regression model

Factor	Coefficient Estimate	df	Standard Error	95%CI Low	95%CI High	*P*-value
Intercept	0.30	1	3.260×10^{-4}	0.30	0.31	
A	0.013	1	1.996×10^{-4}	0.013	0.014	< 0.0001**
B	3.513×10^{-3}	1	1.996×10^{-4}	2.999×10^{-3}	4.026×10^{-3}	< 0.0001**
C	-8.750×10^{-4}	1	1.996×10^{-4}	-1.388×10^{-3}	-3.618×10^{-4}	0.0071**
AB	3.750×10^{-4}	1	2.823×10^{-4}	-3.507×10^{-4}	1.101×10^{-3}	0.0415*
AC	3.500×10^{-4}	1	2.823×10^{-4}	-3.757×10^{-4}	1.076×10^{-3}	0.2701
BC	2.000×10^{-4}	1	2.823×10^{-4}	-5.257×10^{-4}	9.257×10^{-4}	0.5103
A^2	2.746×10^{-3}	1	2.939×10^{-4}	-3.501×10^{-3}	-1.990×10^{-3}	0.0002**
B^2	2.542×10^{-4}	1	2.939×10^{-4}	-5.012×10^{-4}	1.010×10^{-3}	0.4266
C^2	-4.701×10^{-3}	1	2.939×10^{-4}	-4.826×10^{-3}	-3.315×10^{-3}	< 0.0001**

The response surface and contour of the model made according to the regression equation were shown in Fig.4-6. The three groups of figures intuitively predicted the influence of the fluidized bed drying on the glucosinolate content of the maca tuber. As seen from the figure, the influence of the air inlet temperature on the retention of glucosinolate content of the maca tuber in the fluidized bed drying process was the maximum. Since the increased air inlet temperature intensified the gas-solid mass transfer, heat transfer driving force, the dehydration rate of the material had increased significantly throughout the drying period, The shortened drying time and the contact time between the glucosinolates and myrosinase facilitated its retention. When the air flow rose, the retention rate of the glucosinolates increased. But when the air flow exceeded a certain value, its influence was not very significant, but the energy consumption and equipment costs rose, reducing the economic efficiency. The glucosinolate content slowly increased and then decreased with the increase of the particle size, it reached the maximum value when the particle size was about 3mm. Besides, there was interaction between the factors. Through software analysis, the optimal drying condition was obtained: air inlet temperature 65℃, air flow 150m^3/h, material particle size 2.96mm, at this time, the retention of maca glucosinolates reached the maximum value 0.3188%.

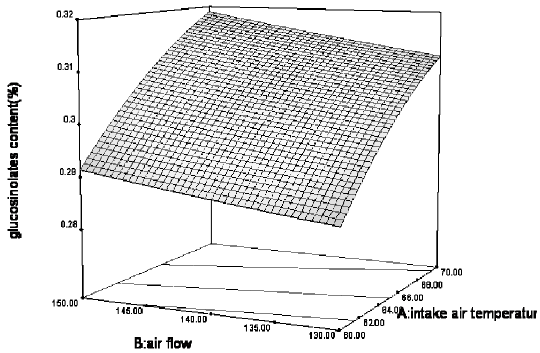


Fig.4 Response surface plots showing the pairwise interactive effects of intake air temperature and air flow on glucosinolates content of maca

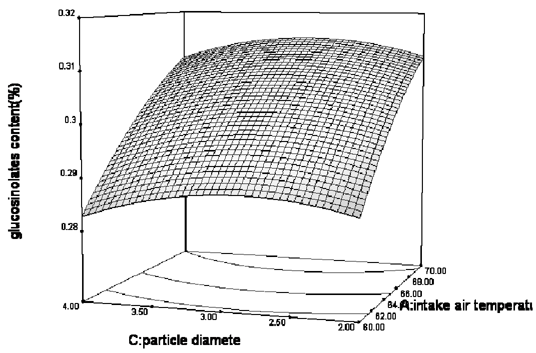


Fig.5 Response surface plots showing the pairwise interactive effects of intake air temperature and the particle diameter on glucosinolates content of maca

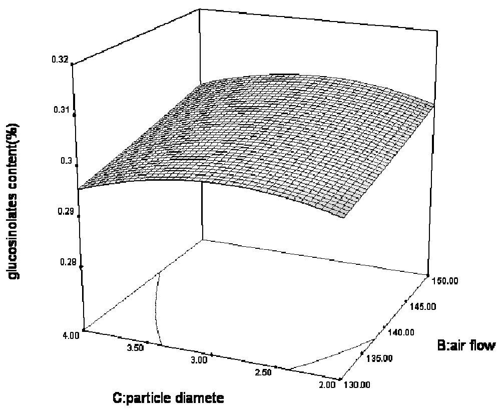


Fig.6 Response surface plots showing the pairwise interactive effects of air flow and the particle diameter on glucosinolates content of maca

To test the reliability of the results obtained by RSM, three times of validation test were carried out under the condition of air inlet temperature of 65℃, air flow of 150m^3/h and material particle size of 3mm. The average glucosinolate content measured was 0.3192% and its theoretical value was 0.3188%, with the error only 0.125%, indicating that the equation predicted values fitted well with the actual situation. It proved that it was feasible to predict the influence of the fluidized bed drying of maca tuber on its functional component glucosinolate with the RSM. Under the optimal condition, the average velocity of the air inlet of the fluidized bed was 1.33m/s and the observed minimum floating air velocity of maca was 1.16m/s. During the whole drying process, the temperature and humidity recorder recorded the changes of the temperature and humidity of the dried tail gas of the fluidized bed, It showed that the temperature ranged from 61 □ to 19 □, humidity ranged from 76% to 7%, drying time was 65 minutes, the air consumption of unit mass of maca (on wet basis, moisture content 72%) was 1048kg/kg (wet material). The drying curve of fluidized bed drying of maca tuber under the optimal conditions was indicated in Fig.7. As seen from the figure, during the early drying period, the water loss rate of maca tuber was high and then it gradually decreased. There was no obvious drying stage of constant rate. But in the later drying stage, the water loss rate of maca tuber water loss rate became very low and relatively stable.

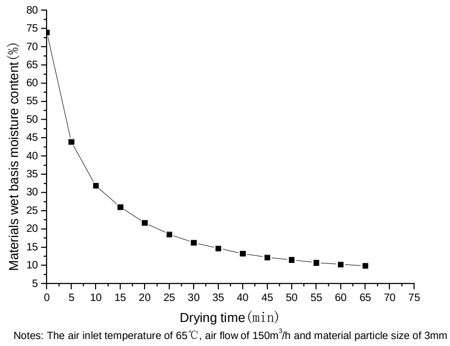
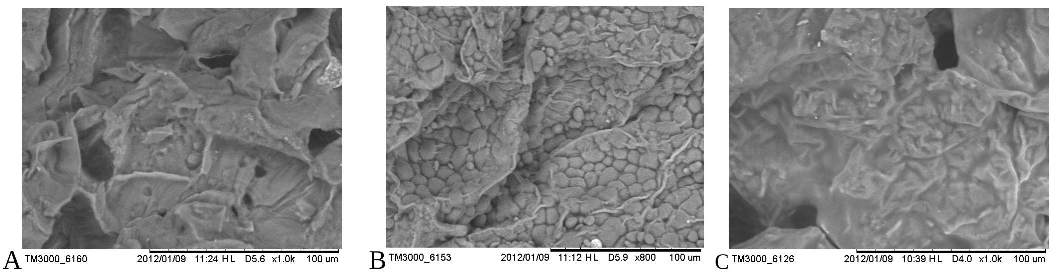


Fig.7 Drying curves of maca root under fluidized bed drying

COMPARISON TEST BETWEEN THE HOT AIR DRYING AND VACUUM FREEZE-DRYING



Notes: 15KV , ×1000, 100μm

Fig.8 The SEM picture of the dried maca samples

The maca tuber samples obtained by different drying methods were observed with the scanning electron microscope and their microscopic internal structures were shown in Figure 8. For the hot air drying, due to intense drying condition, the maca tuber surface became shrinkage with the collapse of internal structure and hard texture, irregular appearance and poor color. The maca texture through fluidized bed drying formed the porous, loose-like structure, whose gap distribution could be clearly seen with poor appearance and color; while the vacuum freeze-dried maca texture was relatively dense, strong, with relatively smooth surface and the best color and appearance.

Table 5 Comparison of the effects of hot air drying and vacuum freeze-drying on the quality of maca

Samples Treatment conditions	Hot air drying 65□, 288m^3/h, 3mm	Fluidized bed drying 65□, 150m^3/h, 3mm	Vacuum freeze-drying -40□, 0.09mba	Raw material(DM)
Drying time(min)	330	65	1200	
Glucosinolate content(mg/g)	2.136	3.192	3.627	3.695
Residual rate of glucosinolate (%)	57.81	86.34	98.16	
Rehydration rate	2.18	2.73	2.96	
Color saturation	0.141	0.121	0.107	0.102
Final moisture content(%)	9.86%	9.73%	9.13%	

The effects of hot air drying, vacuum freeze-drying and fluidized bed drying on the quality of maca were shown in Table 5. Among the three methods, the hot air drying process was featured by processing of a large amount of equipment one time, small equipment input and easy to operate. But the quality of tuber after drying was not high, and the retention of functional ingredient glucosinolates is small, and the appearance and color and rehydration were poor. For the vacuum freeze-drying, maca tuber quality is the best and the retention rate of glucosinolates was highest, the appearance and color and rehydration were good, but the cost of equipment was high with great one-time investment, and the process operation is relatively complex, reducing the economic benefit. The measured glucosinolate content of fresh maca tuber before drying was 3.695mg/g; after fluidized bed drying, its retention rate rechieved 86.34%, which was much higher than that of the hot air drying. Among the three methods, the fluidized bed drying took the shortest time used the least energy, but keep relatively good appearance and color, and rehydration performance of maca tuber.

CONCLUSION

1) The air inlet temperature, air flow and material particle size did have certain influence on the retention of glucosinolates and the saturation value of the maca tuber through fluidized bed drying. Among which, the air inlet temperature has the greatest influence, and there was certain interaction among various factors. Through optimization by response surface methodology, the mathematical regression model equation of the influence of fluidized bed drying on the glucosinolate content was established. This model fitted well, which could predict the change rules of glucosinolate content after fluidized bed drying. The optimal drying condition was as follows: air inlet temperature 65, air flow 150m^3/h, and material particle size 3mm, at this point, the glucosinolate content reached the maximum value 3.192mg/g. Moreover, the fluidized bed drying could quickly dry the maca tubers within a very short time, retain the most glucosinolate content, and obtain better appearance, color, and rehydration performance of maca tuber.

2) In this test, the application of fluidized bed drying technology in maca tuber drying was studied. The fluidized bed drying had the advantages of simple equipment, uniform heating distribution and fast drying, *etc.*. When applied in the drying of maca tubers, it could dry maca tuber within a very short time. Meanwhile, the functional ingredient glucosinolates could be retained at a maximum content, and the appearance such as saturation value, rehydration ratio, *etc.* was better.

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