

EXPERIMENTAL STUDY ON THE OPTIMAL PROCESS PARAMETERS FOR VACUUM FREEZE-DRYING OF SANBAI MELON SLICES

真空冷冻干燥三白瓜片最佳工艺参数试验研究

Lijing YAN¹⁾, Bohao SHI¹⁾, Lihong FU²⁾, Xiaobin LI^{*1)}

¹⁾ College of Agricultural Engineering, Shanxi Agricultural University, Taigu, Shanxi / China

²⁾ College of Food Science and Engineering, Shanxi Agricultural University, Taigu, Shanxi / China

Corresponding author: Xiaobin Li

Tel: +8613903446220; E-mail: lxb8008105858@163.com

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ABSTRACT

Sanbai Melon, a nationally recognized geographical indication product and a specialty agricultural product of Shanxi Province, is named for its distinctive white skin, white flesh, and white seeds. Primarily cultivated in Wanrong County, Yuncheng City, Shanxi Province, it is not only rich in various vitamins and amino acids but also boasts significant medicinal properties. Known for its ability to clear heat, detoxify the body, purify the lungs, moisten the intestines, reduce internal heat, and protect the liver, Sanbai Melon is highly valued for both its nutritional and health benefits. However, Sanbai melon is only available on the market from July to December each year. Due to this extended seasonal gap, fresh supply falls short of meeting daily consumer demand. To address this issue, processing Sanbai melon into freeze-dried powder has become essential. This study investigated the optimal freeze-drying parameters for Sanbai melon by examining the correlation between its dielectric properties and moisture content. Using a combination of single-factor tests and response surface methodology, a three-factor, three-level experimental design was implemented. Based on preliminary experiments, the vacuum levels were set at 35~40 Pa, 40~45 Pa, and 45~50 Pa; the heating plate temperatures were set at 60°C, 70°C, and 80°C; and the material thicknesses were set at 3 mm, 6 mm, and 9 mm. With drying time as the target variable, and moisture content, dielectric constant, and dielectric loss factor as response variables, response surface analysis determined the optimal freeze-drying conditions as follows: vacuum degree of 40~45 Pa, heating plate temperature of 73 °C, material thickness of 7 mm, and a total freeze-drying time of 6 hours. Under these conditions, the resulting Sanbai melon powder exhibited a moisture content of 2.9%, a dielectric constant of 2.195, and a dielectric loss factor of 1.525.

摘要

三白瓜作为全国地理标志产品、山西省特色农产品，以皮白、瓤白、籽白而得名，主要产于山西省运城市万荣县。三白瓜不仅富含多种维生素和氨基酸，而且具有显著的药用价值，能清热解毒、清肺润肠、败火护肝。然而，三白瓜的上市时间只在每年7月份到12月份，由于其供应期过长且无法满足人们的日常消费需求，将三白瓜做成冻干片势在必行。¹通过研究介电特性参数与三白瓜片含水率之间的相关关系，结合单因素试验分析和响应面分析等方法，对三白瓜片的最佳冻干工艺参数进行分析和研究。根据前期预试验结果，设定真空度为35~40 pa、40~45 pa、45~50 pa，加热板温度为60℃、70℃、80℃，物料厚度为3 mm、6 mm、9 mm。通过三因子三水平试验，研究三白瓜片最佳冻干工艺参数。以时间作为目标变量，以含水率、介电常数、介电损耗因子作为因变量，用响应面分析法得到最优真空度为40~45 pa，加热板温度为73℃，物料厚度为7 mm，冻干时间6h，在此参数下三白瓜片的含水率为2.9%，介电常数为2.195，介电损耗因子为1.525。

INTRODUCTION

Due to its highly seasonal availability, producing freeze-dried products from Sanbai melon allows consumers to enjoy it year-round, thereby meeting the continuous market demand (Yu, *et al.*, 2024). Vacuum freeze-drying effectively preserves the food's original color, aroma, taste, morphological structure, and nutritional components (Qu *et al.*, 2024; Yang *et al.*, 2024; Hay O.T. *et al.*, 2025). It corresponds to the contemporary movement toward healthier foods (Dordevic D. *et al.*, 2024; Li G. *et al.*, 2023). Furthermore, freeze-dried products are characterized by their crisp texture and excellent rehydration capacity (Fu *et al.*, 2021; Silva and Schmidt, 2022), making them ideal for use in ready-to-eat foods or as intermediates for further processing.

¹ Lijing Yan, master degree; Bohao Shi, master degree; Lihong Fu, Prof. Ph.D; Xiaobin Li, Prof. Ph.D.

Recent years have seen rapid advancements in fruit and vegetable drying technologies, driven by growing emphasis on healthy diets and increasing consumer demand for high-quality food products (Guo *et al.*, 2024; Taskin, 2025; Oznur, 2023). Vacuum freeze-drying technology was first developed in the early 19th century (Rorato *et al.*, 2025; Silambarasan *et al.*, 2022). Researchers such as Walston observed that in a vacuum environment, ice crystals within a material could sublime directly, thereby removing moisture and achieving a dried product (Erdem *et al.*, 2024; Allmendinger *et al.*, 2020). However, the high energy consumption and extended processing time associated with vacuum freeze-drying have become major limitations hindering its broader application in agricultural and food processing industries (Zhou *et al.*, 2024; Mokhova *et al.*, 2024). To enable low-energy freeze-drying, investigating the effects of optimal process parameters is essential.

The dielectric properties of agricultural materials are widely used in agricultural and food engineering, with applications including the heating and control of crop drying processes, the study of material behavior in electric fields, and the prediction of moisture content (Wang *et al.*, 2023; Díaz-Álvarez *et al.*, 2024). These properties primarily consist of three key parameters: the dielectric constant, the dielectric loss factor, and the loss tangent. Since the dielectric characteristics of fruits and vegetables are closely related to their moisture content, they can serve as an effective indicator for determining water levels in produce (Jiang *et al.*, 2024).

Through an analysis of the impact of various vacuum freeze-drying parameters, the key factors influencing the freeze-drying process were identified. Single-factor experiments were conducted to examine the effects of vacuum degree, heating plate temperature, and material thickness on the moisture content, dielectric constant, and dielectric loss factor of Sanbai melon slices. Subsequently, using the Box-Behnken experimental design method, a three-factor, three-level response surface analysis was carried out with vacuum degree, heating plate temperature, and material thickness as independent variables, and moisture content, dielectric constant, and dielectric loss factor as response variables. Nonlinear regression models were established for each of the three response indicators. The experimental outcomes were analyzed to derive final conclusions, thereby identifying the optimal parameters for the vacuum freeze-drying of Sanbai melon slices.

MATERIALS AND METHODS

The three varieties of white cucumber used in this experiment were sourced from Wanrong County, Yuncheng City, Shanxi Province. The selection criteria included freshness, appropriate maturity, uniform size, and the absence of pests, diseases, and mechanical damage. The packaging film and distilled water were supplied by the experimental procedures.

The experimental procedure was conducted as follows:

First, the Sanbai melons were washed, peeled, and deseeded. The flesh was then uniformly sliced using a precision slicer. Second, the melon slices were further cut into thin pieces measuring 20 mm × 20 mm × 3 mm. These pieces were arranged on a tray, weighed, and the initial data were recorded. Their dielectric properties were measured before pre-freezing. The samples were pre-frozen at -40 °C—below the eutectic point of Sanbai melon (-7 °C)—for 20 hours and held at that temperature until processing. Third, the cold trap of the vacuum freeze-dryer was activated and cooled to -40 °C. According to the pre-established experimental design, the heating plate temperature and vacuum level were set. The pre-frozen melon slices were then placed on the heating plate, the chamber door was sealed, and the freeze-drying process was initiated. The time was recorded, and data were logged at one-hour intervals. The drying process was considered complete when the change in sample mass was less than 5%. Each test condition was repeated in triplicate, and average values were used for analysis. Fourth, upon completion of drying, the samples were promptly transferred into pre-prepared transparent sealed bags and quickly sealed to preserve sample integrity. Finally, after sample collection, the freeze-dryer was defrosted, shut down, and disconnected from the power supply.

Apparatus and Instrumentation

The apparatus and instrumentation used for the experiment testing are presented in the Table 1.

Table 1

Number	Instrument	Testing equipment	
		Model number	Manufacturer
1	Electrically-Heated Constant-Temperature Forced-Air Oven	DHG-9023A	Sanyi Precision Electric Co., Ltd., Wuxi
2	Vacuum Freeze-Dry Test Machine	JDG-0.2	Lanzhou Kejin Lyophilization Technologies Co., Ltd.

Number	Instrument	Model number	Manufacturer
3	Haier Low-Temp Storage Cabinet	DW-40L92	Qingdao Haier Special Electrical Co., Ltd.
4	Electronic Balance	WT-C602	Hangzhou Wante Weighing Apparatus Co., Ltd.
5	Network Analyzer	E5071C	Giskos Tech Co., Ltd.

Determination of moisture content in Sanbai melon slices

The fresh Sanbai melon was peeled and sliced for moisture content determination using the constant-weight drying method in a convection oven. The specific procedure was as follows: the oven temperature was set to 100 °C, and the sliced melon pieces were placed inside to dry. Drying was considered complete when the mass change between successive weighings fell within 5%. Each experimental group was repeated three times, and the average value of the three measurements was taken to determine the initial moisture content W of the Sanbai melon slices, as expressed in Equation (1):

$$W = \frac{(m_w - m_d)}{m_w} \times 100 [\%] \quad (1)$$

where: W is the initial moisture content of the *Sanbai melon* sample, [%];

m_w - the Initial quantity of the three types of *Sanbai melon* samples, [g];

m_d - determine the constant weight mass of the sample after drying, [g].

The experimentally determined average initial moisture content of the Sanbai melon slices was 97.31%. The target moisture content of the dried product was set to be below 5%.

Measurement of dry-basis moisture content

Based on the dry matter content of the Sanbai melon, the dry-basis moisture content (W_0) was calculated to determine the moisture percentage in the sample, as expressed in Equation (2):

$$W_0 = \frac{(m_t - m_d)}{m_d} \times 100 [\%] \quad (2)$$

where: W_0 represents the dry basis moisture content of the *Sanbai melon*, [%];

m_t - the total mass of the three *Sanbai melon* at that moment, [g];

m_d - the mass of dried *Sanbai melon* after constant weight has been achieved, [g].

Assessment of drying ratio

The drying ratio (D) reflects the extent and effectiveness of dehydration achieved in the material, defined as the ratio of the mass before drying to the mass after drying. In this experiment, 36 slices of Sanbai melon constituted one sample group. The process was repeated three times, and the average value was taken to determine the drying ratio. Consistent observations of M_1 and M_2 are expressed by Equation (3) as follows:

$$D = \frac{M_1}{M_2} \quad (3)$$

where: D represents the drying ratio of the material;

M_1 - the quantity of the wet material before drying, [g];

M_2 - the quantity of the material after drying, [g].

Determination of dielectric properties

The dielectric properties were measured using a custom-built hardware system, as illustrated in Fig.1. The capacitance probe was inserted into the Sanbai melon slice, and both the sensor and the sample were placed together inside the freeze-dryer. Throughout the freeze-drying process, the probe continuously monitored the capacitance of the sample. The capacitance measurement circuit performed initial signal processing, after which the analog signal was converted to a digital signal via an A/D conversion module. The data were subsequently transmitted to a server via a WiFi connection. Upon receipt, the server computed the dielectric constant, and the results were displayed both on a digital readout and a computer interface.

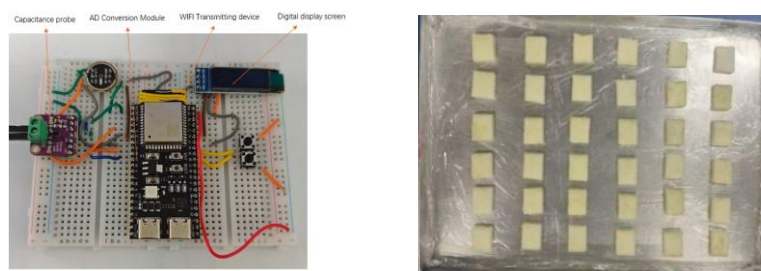


Fig. 1 - Coaxial dielectric property measurement system and Sanbai melon slices

The experimental data were analyzed using SAS software, the graphs were generated with Origin, and the response surface design was implemented in Design-Expert software (version 13).

Single-Factor experimental design and analysis

This study examined the effects of various vacuum freeze-drying parameters on the dielectric properties of Sanbai melon slices and identified the optimal ranges for three key factors, thereby establishing a theoretical foundation for optimizing the freeze-drying process of this material. The tested parameter ranges were as follows: vacuum degree (35~40 Pa, 40~45 Pa, 45~50 Pa, 50~55 Pa, 55~60 Pa), heating plate temperature (40 °C, 50 °C, 60 °C, 70 °C, 80 °C), and material thickness (3 mm, 6 mm, 9 mm, 12 mm). The response indicators included moisture content, drying ratio, dielectric constant, and dielectric loss factor. Each freeze-drying trial was conducted with a fixed duration of 6 hours.

Effect of vacuum level on the dielectric properties

The freeze-drying process generally comprises three main stages: freezing, primary drying (sublimation), and secondary drying (desorption). A higher vacuum level reduces the vapor pressure of water, typically accelerating the sublimation rate and thereby improving freeze-drying efficiency. Conversely, an insufficient vacuum may lead to incomplete drying, surface crust formation, or localized overheating, which can adversely affect product quality and process efficiency (Xu *et al.*, 2022). Therefore, precise control of chamber pressure is essential to optimize sublimation performance. Under constant conditions of heating plate temperature (70°C) and material thickness (6mm), five vacuum levels were tested: 35~40 Pa, 40~45 Pa, 45~50 Pa, 50~55 Pa, and 55~60 Pa. As shown in Fig.2, significant differences ($p < 0.05$) were observed in moisture content, drying ratio, dielectric constant, and dielectric loss factor among the treatments. However, the effect of vacuum level on moisture content was less pronounced than that of heating temperature and material thickness. As vacuum increased, moisture content initially decreased and then gradually stabilized. The drying ratio increased to an optimum point before declining with further elevation in vacuum. Both the dielectric constant and dielectric loss factor exhibited minor fluctuations around a value of 1 under increasing vacuum, eventually converging toward stability.

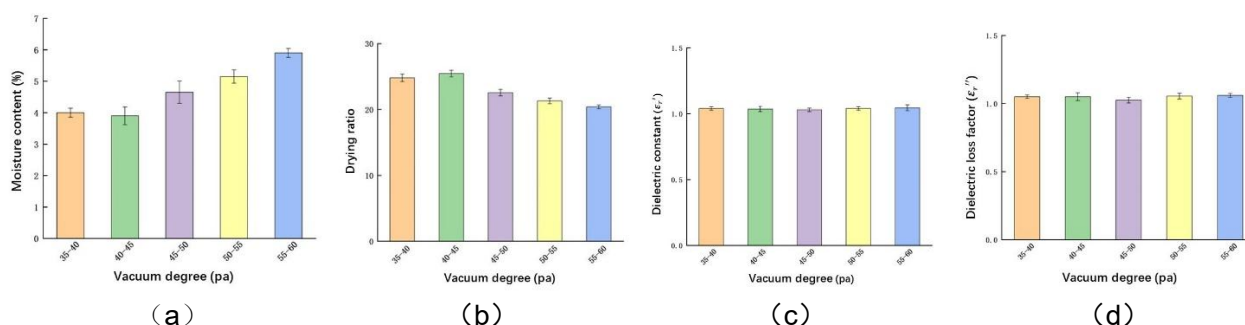


Fig. 2 - Effect of vacuum degree on dielectric properties of freeze-dried Sanbai melon slices

The effect of heating plate temperature on dielectric properties

The influence of heating plate temperature on dielectric properties is illustrated in Fig. 3. Data presented are mean values $\pm$ standard deviation. According to Duncan's multiple range test, significant differences ($p < 0.05$) were observed in the moisture content, drying rate, dielectric constant, and dielectric loss factor of freeze-dried Sanbai melon slices under the following conditions: slice thickness of 6 mm, vacuum degree of 40~45 Pa, and heating plate temperatures of 40 °C, 50 °C, 60 °C, 70 °C, and 80 °C. As the temperature increased, the moisture content of the samples gradually decreased, while the drying rate increased accordingly. This may be attributed to enhanced internal heat transfer, leading to greater driving force for moisture diffusion. When the temperature reached 70 °C, the moisture content exhibited minimal change and the drying rate stabilized, with the lowest moisture content reaching approximately 3%.

Temperature is a key factor influencing the dielectric constant. As the drying temperature rises, the dielectric constant and dielectric loss factor of Sanbai melon slices decrease, primarily due to the reduction in moisture content. At a given moisture level, higher temperatures lead to a more pronounced increase in the dielectric constant. Moreover, the effect of temperature on the dielectric constant becomes more significant with higher initial moisture content.

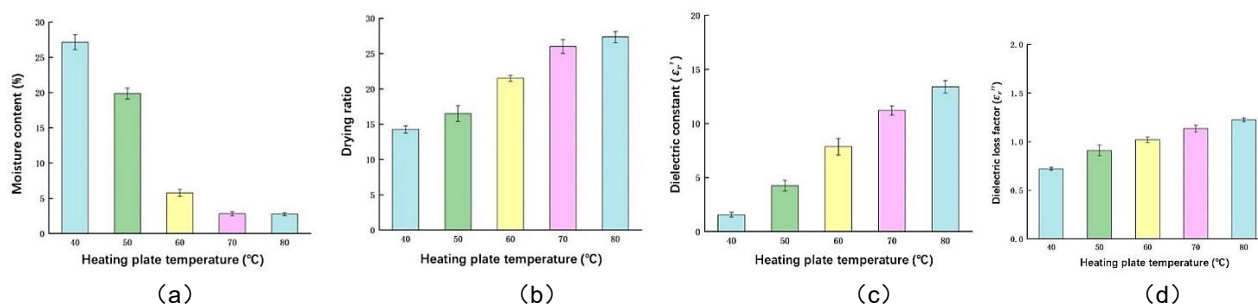


Fig. 3 - Effect of heating plate temperature on dielectric properties of freeze-dried Sanbai melon slices

Influence of sample thickness on the dielectric properties

Slice thickness significantly influences the efficiency and outcome of vacuum freeze-drying. Thicker Sanbai melon slices require extended freeze-drying time. During the process, unremoved water and soluble compounds may fuse and diffuse, leading to volume shrinkage and surface irregularities in the frozen material (Zhang *et al.*, 2025). Conversely, reduced slice thickness decreases both heat and mass transfer resistance, thereby accelerating the drying process. Thus, identifying an optimal slice thickness is essential for improving the industrial production of freeze-dried Sanbai melon and similar products.

As shown in Fig. 4, under conditions of 40~45 Pa vacuum, 70°C heating plate temperature, and slice thicknesses of 3, 6, 9, and 12 mm, significant differences ($p < 0.05$) were observed in moisture content, drying rate, dielectric constant, and dielectric loss factor of the freeze-dried Sanbai melon. Under a constant freeze-drying duration, the rate of moisture reduction slowed as slice thickness increased. Thinner samples exhibited higher drying ratios, indicating more efficient drying, whereas thicker materials resulted in lower drying ratios. Moreover, the dielectric constant and loss factor decreased more rapidly in thinner slices, with the rate of decline diminishing as thickness increased.

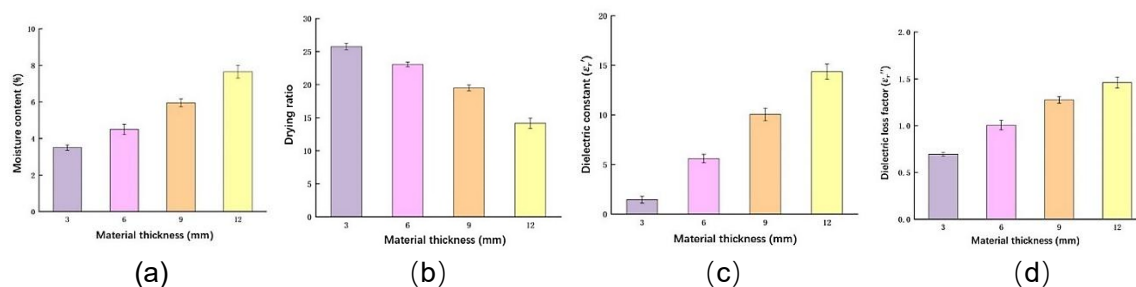


Fig. 4 - Effect of material thickness on dielectric properties of freeze-dried three white melon slices

Optimization of process parameters

Response surface methodology

Based on preliminary experiments, the factor level ranges were determined as follows: vacuum degree 35~50 Pa, heating plate temperature 60~80 °C, and material thickness 3~9 mm. A three-factor, three-level Box-Behnken experimental design was employed using three response criteria: moisture content, dielectric constant, and dielectric loss factor. The factor levels were coded as -1, 0, and +1, representing low, intermediate, and high values, respectively. This design was used to optimize and analyze the vacuum freeze-drying parameters for Sanbai melon slices, leading to the determination of the optimal parameter values. The experimental design matrix is presented in Table 2.

Table 2

Factor Levels for Response Surface Experiment on Vacuum Freeze-Drying of Sanbai Melon Slices

Level	factor		
	A Heating plate Temperature (°C)	B Vacuum degree (Pa)	C Material thickness (mm)
-1	60	35~40	3
0	70	40~45	6
1	80	45~50	9

RESULTS

Development of a regression model

Based on the Box-Behnken design results (Table 3), multivariate quadratic regression models were developed for moisture content (Y1), dielectric constant (Y2), and dielectric loss factor (Y3), as follows:

(1) Development of the Moisture Content Regression Model:

$$Y1 = 2.47 - 1.54A - 1.61B + 0.3263C + 0.0750AB + 0.1425AC + 0.2700BC + 0.6337A^2 + 0.7362B^2 + 1.35C^2$$

(2) Development of the Dielectric Constant Regression Model:

$$Y2 = 2.28 + 0.0925A + 0.1900B + 0.1375C - 0.0475AB - 0.1675AC + 0.0475BC - 0.3448A^2 - 0.4898B^2 - 0.5047C^2$$

(3) Development of a Regression Model for the Dielectric Loss Factor:

$$Y3 = 1.89 + 0.0663A + 0.1550B + 0.0763C - 0.0475AB - 0.0600AC + 0.0375BC - 0.4280A^2 - 0.3655B^2 - 0.2380C^2$$

These three models quantitatively describe the relationships among the vacuum degree, heating plate temperature, material thickness, and the moisture content, dielectric constant, and dielectric loss factor of freeze-dried white gourd slices.

Table 3

Experimental Design and Results of Response Surface Analysis for Freeze-Dried Sanbai Melon Slices

Number	A Vacuum degree / Pa	B Heating plate temperature / °C	C Material thickness / mm	Y1 Moisture content / %	Y2 Dielectric constant / pF/cm	Y3 Dielectric loss factor / dB/km
1	-1	-1	0	6.82	1.12	0.78
2	1	-1	0	3.98	1.38	1.08
3	-1	1	0	3.55	1.61	1.2
4	1	1	0	1.01	1.68	1.31
5	-1	0	-1	6.02	1.00	1.03
6	1	0	-1	2.28	1.54	1.21
7	-1	0	1	6.34	1.66	1.35
8	1	0	1	3.17	1.53	1.29
9	0	-1	-1	6.14	1.04	1.12
10	0	1	-1	2.27	1.31	1.34
11	0	-1	1	6.30	1.17	1.15
12	0	1	1	3.51	1.63	1.52
13	0	0	0	3.01	2.07	1.77
14	0	0	0	2.67	2.32	1.88
15	0	0	0	2.45	2.36	1.91
16	0	0	0	2.21	2.31	1.94
17	0	0	0	2.01	2.35	1.93

Analysis of Variance

Analysis of variance for moisture content

According to the analysis presented in Table 4, at a significance level of 0.05, coefficients A, B, C, A², B², and C² are all statistically significant, whereas the remaining coefficients are not. Overall, the model exhibits an extremely high level of significance, as indicated by a probability value (P-value) of 0.0001. Additionally, the coefficient of determination (R²) of the model is 0.9830, demonstrating a high goodness-of-fit. The P value of the misfit term is 0.6011, which is greater than 0.05, so the misfit effect is not significant. In summary, the model is both highly significant and well-fitted, confirming the effectiveness of the regression analysis. Further analysis based on the factor effect tests reveals that the order of influence of each factor on the moisture content of freeze-dried Sanbai melon slices is as follows: heating plate temperature, vacuum degree, and material thickness.

Table 4

Water content regression model variance analysis

Source of variation	Sum of Squares	Degrees of freedom	Mean Square	F value	P value
Model	53.72	9	5.97	44.91	< 0.0001
A-Vacuum degree	18.88	1	18.88	142.05	< 0.0001

Source of variation	Sum of Squares	Degrees of freedom	Mean Square	F value	P value
B- Heating plate temperature	20.80	1	20.80	156.51	< 0.0001
C- Material thickness	0.8515	1	0.8515	6.41	0.0392
AB	0.0225	1	0.0225	0.1693	0.6931
AC	0.0812	1	0.0812	0.6111	0.4600
BC	0.2916	1	0.2916	2.19	0.1821
A ²	1.69	1	1.69	12.72	0.0091
B ²	2.28	1	2.28	17.17	0.0043
C ²	7.66	1	7.66	57.63	0.0001
Residual	0.9304	7	0.1329		
Misfit error	0.3912	3	0.1064	0.6963	0.6011
Pure error	0.6112	4	0.1528		
Total sum	54.65	16			
	R ² =0.9830	R ² _{adj} =0.9611	CV=9.72%		

Note: A *p*-value ≤ 0.05 indicates statistical significance, while a *p*-value ≤ 0.01 is considered highly significant. A *p*-value > 0.05 suggests that the result is not statistically significant.

Analysis of variance for dielectric constant

As shown in Table 5, at the significance level of 0.05, coefficients A, B, C, AC, A², B², and C² are all statistically significant, while the remaining coefficients are not. The model demonstrates extremely high significance, with a probability value (P-value) of 0.0001. Moreover, the coefficient of determination (R²) is 0.9821, indicating a high goodness of fit. The P value of the misfit term is 0.9284, which is greater than 0.05, so the misfit effect is not significant. In conclusion, the model is both highly significant and well-fitted, confirming the effectiveness of the regression analysis. Further analysis based on the factor effect test results indicates that the order of influence of each factor on the dielectric constant of freeze-dried Sanbai melon slices is as follows: heating plate temperature, material thickness, and vacuum degree.

Table 5

Dielectric constant regression model analysis of variance					
Source of variation	Sum of Squares	Degrees of freedom	Mean Square	F value	P value
Model	3.51	9	0.3905	42.63	< 0.0001
A- Vacuum degree	0.0685	1	0.0685	7.47	0.0292
B- Heating plate	0.2888	1	0.2888	31.52	0.0008
C- Material thickness	0.1513	1	0.1513	16.51	0.0048
AB	0.0090	1	0.0090	0.9851	0.3540
AC	0.1122	1	0.1122	12.25	0.0100
BC	0.0090	1	0.0090	0.9851	0.3540
A ²	0.5004	1	0.5004	54.62	0.0002
B ²	1.01	1	1.01	110.24	< 0.0001
C ²	1.07	1	1.07	117.09	< 0.0001
Residual	0.0641	7	0.0092		
Misfit error	0.0063	3	0.0021	0.1440	0.9284
Pure error	0.0579	4	0.0145		
Total sum	3.58	16			
	R ² =0.9821	R ² _{adj} =0.9590	CV=5.79%		

Note: A *p*-value ≤ 0.05 indicates statistical significance, while a *p*-value ≤ 0.01 is considered highly significant. A *p*-value > 0.05 suggests that the result is not statistically significant.

Analysis of variance for dielectric loss factor

As shown in Table 6, at the 0.05 significance level, coefficients A, B, C, A^2 , B^2 , and C^2 are statistically significant, while the remaining coefficients are not. The model exhibits extremely high significance, with a *p*-value of 0.0001. Additionally, the coefficient of determination (R^2) is 0.9835, indicating a high goodness of fit. The P value of the misfit term is 0.4492, which is greater than the 0.05 significance level, so the misfit effect is not significant. In summary, the model is both highly significant and well-fitted, confirming the effectiveness of the regression analysis. Further analysis based on the factor effect test results reveals that the order of influence of each factor on the dielectric loss factor of freeze-dried Sanbai melon slices is as follows: heating plate temperature, material thickness, and vacuum degree.

Table 6

Dielectric loss factor regression model variance analysis					
Source of variation	Sum of Squares	Degrees of freedom	Mean Square	F value	P value
Model	2.05	9	0.2274	46.29	< 0.0001
A- Vacuum degree	0.0351	1	0.0351	7.15	0.0319
B- Heating plate	0.1922	1	0.1922	39.12	0.0004
C- Material thickness	0.0465	1	0.0465	9.47	0.0179
AB	0.0090	1	0.0090	1.84	0.2174
AC	0.0144	1	0.0144	2.93	0.1306
BC	0.0056	1	0.0056	1.14	0.3201
A^2	0.7713	1	0.7713	156.97	< 0.0001
B^2	0.5625	1	0.5625	114.48	< 0.0001
C^2	0.2385	1	0.2385	48.54	0.0002
Residual	0.0344	7	0.0049		
Misfit error	0.0155	3	0.0052	1.09	0.4492
Pure error	0.0189	4	0.0047		
Total sum	2.08	16			
	$R^2=0.9835$	$R^2_{adj}=0.9622$	CV=5.00%		

Note: A *p*-value ≤ 0.05 indicates statistical significance, while a *p*-value ≤ 0.01 is considered highly significant. A *p*-value > 0.05 suggests that the result is not statistically significant.

Response surface analysis

Moisture content response surface analysis

Figures 5 to 7 present the three-dimensional response surface plots and contour plots illustrating the effects of vacuum degree, heating plate temperature, and material thickness on the moisture content of freeze-dried Sanbai melon slices. These figures reveal strong interactive effects among these factors on moisture content during the freeze-drying process. As the heating plate temperature increases, the moisture content of the slices initially rises and then gradually decreases, with the rate of decline accelerating near the drying endpoint. Moisture content also decreases steadily with increasing vacuum degree.

In contrast, greater material thickness leads to an initial increase in moisture, followed by a subsequent decreasing trend. The drying performance is relatively favorable when the material thickness is between approximately 6 and 8 mm.

Among the factors investigated, heating plate temperature has the most significant effect on moisture content, followed by vacuum degree and material thickness.

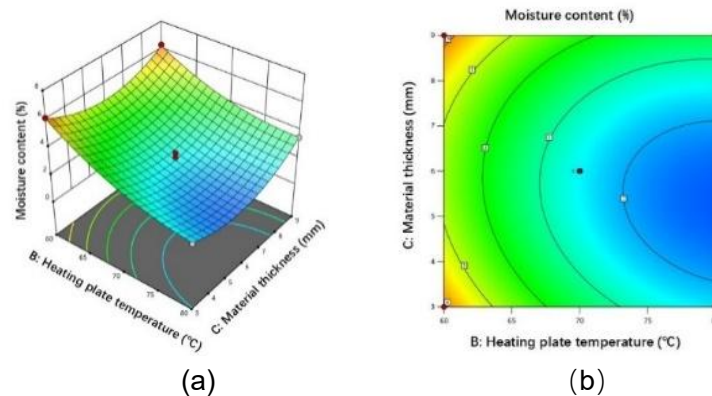
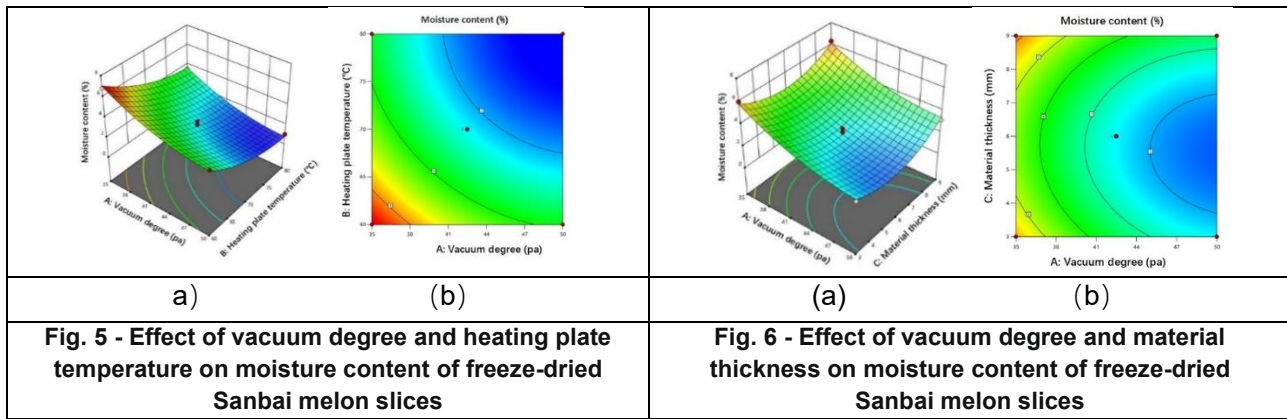


Fig. 7 - Effect of heating plate temperature and material thickness on moisture content of freeze-dried Sanbai melon slices

Dielectric constant response surface analysis

Figures 8 to 10 display the three-dimensional response surface plots and contour plots illustrating the effects of vacuum degree, heating plate temperature, and material thickness on the dielectric constant of freeze-dried Sanbai melon slices. The figures indicate that the dielectric constant initially increases and then decreases as the heating plate temperature rises, demonstrating a substantial influence of temperature during the freeze-drying process. Similarly, the dielectric constant exhibits a trend of first increasing and then decreasing with higher vacuum levels. At lower temperatures, the effect of vacuum degree on the dielectric constant becomes more pronounced. Additionally, a strong interactive effect is observed between vacuum degree and material thickness. When the vacuum degree is lower, the impact of material thickness on the dielectric constant becomes more significant.

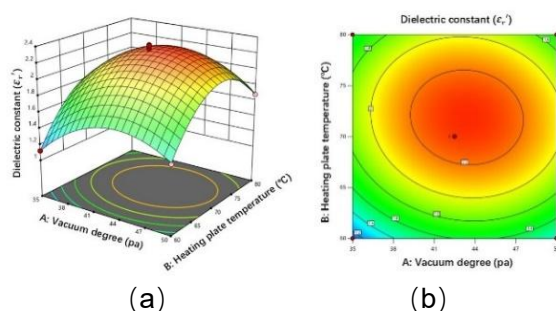


Fig. 8 - Effect of vacuum degree and heating plate temperature on permittivity of freeze-dried Sanbai melon slices

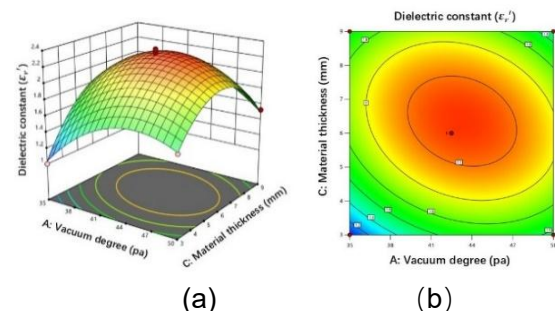


Fig. 9 - Effect of vacuum degree and material thickness on permittivity of freeze-dried Sanbai melon slices

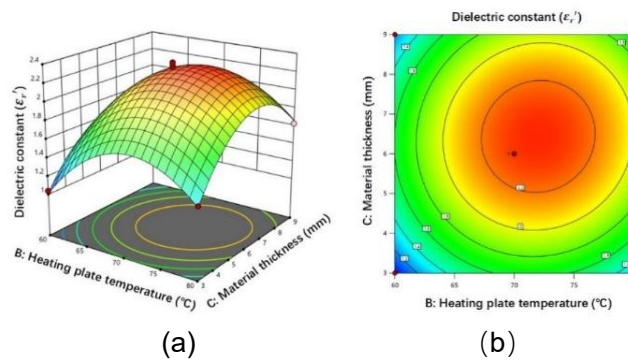


Fig. 10- Effect of heating plate temperature and material thickness on permittivity of freeze-dried Sanbai melon slices

Dielectric loss factor response surface analysis

Figures 11 to 13 present the three-dimensional response surface plots and contour plots illustrating the effects of vacuum degree, heating plate temperature, and material thickness on the dielectric loss factor of freeze-dried Sanbai melon slices. The figures reveal that the dielectric loss factor initially increases and then decreases with rising heating plate temperature, indicating a substantial influence of temperature throughout the freeze-drying process. A similar non-monotonic trend is observed with increasing vacuum degree, where the dielectric loss factor first rises and subsequently declines. The effect of vacuum degree is more pronounced at lower temperatures. Furthermore, thinner material thickness enhances the influence of vacuum degree on the dielectric loss factor. Under low vacuum conditions, material thickness exhibits a greater impact on the dielectric loss factor of the slices.

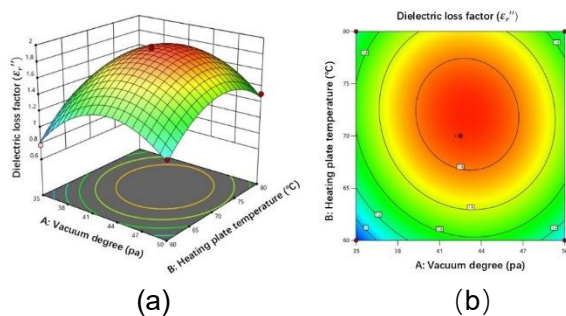


Fig.11- Effect of vacuum degree and heating plate temperature on dielectric loss factor of freeze-dried Sanbai melon slices

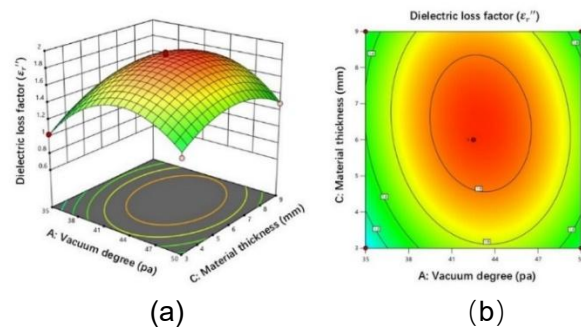


Fig.12- Effect of vacuum degree and material thickness on dielectric loss factor of freeze-dried Sanbai melon slices

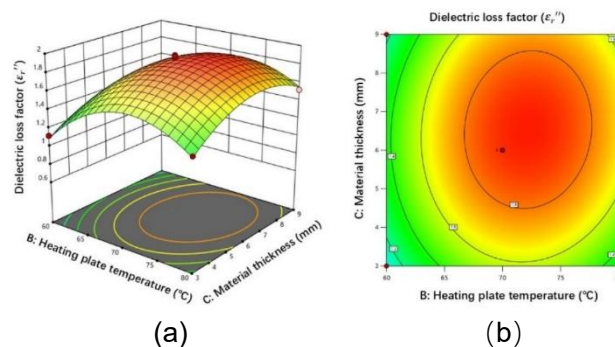


Fig.13- Effect of heating plate temperature and material thickness on dielectric loss factor of freeze-dried Sanbai melon slices

Verification test

Through analysis with Design-Expert software, the optimal parameters for vacuum freeze-drying of Sanbai melon slices were determined as follows: vacuum degree of 40~45 Pa, heating plate temperature of 73.453 °C, and material thickness of 7.061 mm. Under these conditions, the predicted values for moisture content, dielectric constant, and dielectric loss factor of the freeze-dried slices were 2.85, 2.314, and 1.912, respectively.

Considering practical experimental feasibility, a validation test was conducted using adjusted parameters: vacuum degree of 40~45 Pa, heating plate temperature of 73 °C, and material thickness of 7 mm. The measured values were 2.49 for moisture content, 2.264 for dielectric constant, and 1.865 for dielectric loss factor, all of which are close to the predicted values, demonstrating the feasibility of the regression model. Based on the optimized parameters, the freeze-drying process was carried out over 6 hours, with indicators recorded every 30 minutes. Results showed that the samples were fully dried by the end of the 6-hour period, indicating this duration represents the endpoint of the drying process. At this point, the moisture content, dielectric constant, and dielectric loss factor of the optimized Sanbai melon slices were measured as 2.90, 2.195, and 1.525, respectively, confirming that the product quality remains within an ideal range.

CONCLUSIONS

Using Design-Expert 13.0 software, the optimal parameters for the vacuum freeze-drying of Sanbai melon slices were determined through optimization and analysis. A Box–Behnken central composite design was employed, with vacuum degree, heating plate temperature, and material thickness as independent variables, and the moisture content, dielectric constant, and dielectric loss factor of the freeze-dried slices as response variables. Multiple quadratic regression models were established for each response parameter.

The analysis revealed the following order of factor influence:

For moisture content: heating plate temperature (B) > vacuum degree (A) > material thickness (C);

For dielectric constant: heating plate temperature (B) > material thickness (C) > vacuum degree (A);

For dielectric loss factor: heating plate temperature (B) > material thickness (C) > vacuum degree (A).

Based on the response surface analysis, the optimal vacuum freeze-drying parameters were determined as follows: vacuum degree of 40~45 Pa, heating plate temperature of 73 °C, material thickness of 7 mm, and a freeze-drying duration of 6 hours. Under these conditions, the moisture content, dielectric constant, and dielectric loss factor of the freeze-dried Sanbai melon slices were 2.90%, 2.195, and 1.525, respectively. The resulting product exhibited high quality and a desirable texture.

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