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Optimization of hot air drying technology for bamboo shoots by response surface methodology

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Abstract

The drying characteristics of bamboo shoot slices were experimentally studied in a hot air drying system. The individual and combined influence of air temperature, velocity, and slice thickness on the drying process was analyzed. The chromatic aberration and rehydration ratio were used as response indicators, and a 17-group experimental optimization of the drying process was carried out using a response surface methodology. According to the optimization analysis, a hot air temperature of 60.4 °C, an air velocity of 0.4 m/s, and a slice thickness of 0.2 cm were the optimal conditions for hot air drying of bamboo shoots. The predicted rehydration ratio and chromatic aberration of the dried bamboo shoot slices were 10.46 and 12.03, respectively. A validation experiment was conducted under optimum conditions to confirm the applicability of the models.

Keywords. bamboo shoots; hot air drying; optimization; response surface methodology.

1. Introduction

Bamboo (*Phyllostachys edulis*) shoots have a centuries-old history of food and culture in China. In the Tang Dynasty, people regarded it as a delicacy, and there was a saying that "Not a banquet without bamboo." In the past, bamboo shoots were mainly exported and sold in Asian countries, where they were used in soups, curries, salads, and delicious snacks. Nowadays, bamboo shoots are sold more and more not only in Asia but also in Europe, America, and Africa. According to statistics, more than 2 million tons of bamboo shoots are sold every year. They have low fat (0.41%), high dietary fiber (3.90%), and rich mineral (1.03%) content (Bhatt et al., 2005). Bamboo shoots are rich in lignin and phenolics (Gong et al., 2016; Park & Jhon, 2010), and they have health benefits from their antioxidant, hypolipidemic, and hypoglycemic effects. They have been widely accepted by people as an important crop and vegetable.

In China, most bamboo grows and distributes in remote mountainous areas. The production period of bamboo shoots is relatively dense, usually from February to May in spring. At this time, the temperature and humidity of the environment are very beneficial to the growth of bamboo shoots. The growth of bamboo shoots is strictly seasonal, and the production period of bamboo shoots is relatively concentrated, which causes the need for bamboo shoots storage. Due to its high moisture content (>90%), bamboo shoots are difficult to store and keep fresh for a long time, and the wound of fresh-cut products exhibits a specific hardening and browning (Bo et al., 2019; Luo et al., 2013), which considerably reduces the commercial quality. Therefore, cold storage or drying technology is necessary to solve these problems by prolonging the storage time of bamboo shoots (Jia et al., 2020).

Drying is one of the most important means of food preservation in the food processing industry. The purpose of drying is to remove water from the food ingredients, prevent the growth and reproduction of spoilage microorganisms, slow the action of enzymes, and minimize the many water-mediated deterioration reactions (Wu et al., 2007). However, the quality of dried products is greatly reduced during the drying because the color changes and other undesirable changes in the quality of the dehydrated products inevitably appear (Rajkumar et al., 2007).

Hot air drying has the following advantages: simple equipment, low initial investment, simple operation, and large drying capacity (Jia et al., 2021). It remains the main process for the preparation of dried foods (Eştürk, 2010). Based on the knowledge of food processing and heat and mass transfer, the drying ratio and the drying quality of horticultural products are affected by many factors including air velocity, temperature, and the size of the horticultural products.

For example, the air supply temperature has a strong influence on the drying effect. A study (Zahoor & Khan, 2021)

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on the relationship between the surface color and non-enzymatic browning of red pepper with drying temperature ranging from 60 to 80 °C showed that as the drying temperature increases, the surface color degradation and non-enzymatic browning increase. Similar findings were made by Omolola et al. (2019) in a study on the drying properties of Jew's mallow leaves. He et al. (2021) found that 45 °C is a suitable temperature for the industrial-scale hot air drying of Chinese hickory. Takougnadi et al. (2020) studied the effect of drying conditions on dried bananas and found that drying below 65 °C limited the enzymatic browning reaction at the beginning of drying and resulted in a dried product with better organoleptic quality.

Furthermore, air velocity is another important factor. Norhaida et al. (2020) concluded that at higher air velocities, more heat was supplied to the leaves of *Clinacanthus nutans*, which increased the drying power of water evaporation. Ivan Pavkov's study (Pavkov et al., 2021) on the hot air drying of apricot halves found that increasing the air velocity resulted in faster heating of apricots and greater activation energy and similar phenomena were also observed in the study of apples (Kumar et al., 2018), *Piper umbellatum* L. leaves (Dorneles et al., 2019), and raspberries (Stamenković et al., 2019).

In addition to the air supply parameters, the change in the size of the material itself will also have a certain impact on the drying results. In a study of the drying characteristics of potatoes (Azimi-Nejadian & Hoseini, 2019), it was found that with increasing slice thickness, the mean value of effective humidity increased and the mean activation energy decreased. Li et al. (2021) studied the drying of *gastrodia elata* slices and found that the drying rate increased as the thickness of the slices became thinner, as reflected in the study of purple sweet potatoes (Wang et al., 2020), pumpkin slices (Benseddik et al., 2018), purple-speckled cocoyam slices (Ndisya et al., 2020), and Chinese yam (Wang et al., 2019).

In fact, the effects of temperature, velocity, and thickness on the drying quality of bamboo shoots are coupled, and studying the influence of only a single variable is often somewhat biased in practical application. Response surface methodology (RSM) is a statistical procedure frequently used in optimization studies that use quantitative data in an appropriate experimental design to identify and simulate the simultaneous solution of multivariate problems. The effects of variables on indicators can be explored, interrelationships between variables can be determined, and the combined effect of all variables on any indicator can be represented (Erbay & Icier, 2009). Thus, RSM has been used extensively to optimize the drying process of foodstuffs such as purple cabbage (Liu et al., 2021), autumn olive berries (Ghellam et al., 2021), and Konjac (Zeng et al., 2020).

Compared with the research on other horticultural products, there are only fewer reports on the hot air drying of bamboo shoots. To obtain the optimal condition for drying bamboo shoots, experimental devices were established to analyze the effect of air temperature, velocity, and slice thickness on chromatic aberration (ΔE) and rehydration ratio (RR) of bamboo shoots by the RSM.

2. Materials and methods

2.1. Materials

Fresh bamboo shoots were from Fuzhou, Jiangxi Province, China. All products were almost uniform in size and color. The shoots were treated thoroughly to remove any adhering extraneous matter and stored in a refrigerator (5 °C±0.5 °C). Shoot samples were removed from the refrigerator before the drying experiment. The initial moisture content was measured three times by a moisture teller (HH-W420 Shanghai Instrument Technology Co. Ltd., Shanghai, China), and the mean initial wet basis was 92.43%.

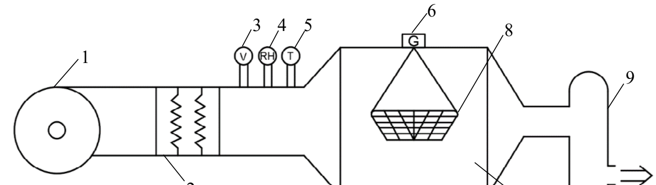
2.2. Experimental setup

The experiment was carried out in a hot air drying system shown in Figure 1. The hot air heated by the electric furnace entered the drying chamber. After heating and drying the products, the hot air was cooled and discharged. The temperature and humidity in the drying room were monitored by a temperature and humidity sensor (TH10S-B-H Pingyang Miaoguan Technology Co. Ltd., Pingyang, China). The system could automatically adjust the temperature and humidity of the heating furnace to keep the drying chamber in the desired state. The air velocity was measured by an anemometer (AL-LUGBC Tianjin Wisdom Control Technology Co. Ltd., Tianjin, China). The sample was weighed with a weighing sensor (101BH Hangzhou Yongzheng Sensor Co. Ltd., Hangzhou, China).

2.3. Hot air drying experiments

Bamboo shoots were removed from the refrigerator and put on the table until their temperature reached room temperature. Then, the shoots were blanched in water by using 0.2% citric acid for 30 min to remove the astringency, which could help to soften the shoots to avoid enzyme activity and aid drying time. Then, the materials were removed from the hot water, laid on the perforated tray to drain excess water, and wiped with a paper towel to remove surface water.

The drying equipment ran steadily after 30 min of preheating. Furthermore, the pretreated bamboo slice samples were put on a drying plate and placed in the drying chamber. The drying process ended when the final moisture content of the dried sample reached 20% (wet basis). The experiments in this work were conducted in triplicate.



1: fan; 2: electric heating furnace; 3: anemometer; 4: temperature sensor; 5: humidity sensor; 6: weighing sensor; 7: drying chamber; 8: single layer on stainless steel wire grid; 9: steam trap.

Figure 1. Schematic diagram of the drying equipment.

2.4. Evaluation indicators

2.4.1. Moisture content

The moisture content is defined as the proportion of the mass of water to the mass of the dry solid. The moisture content of the samples was defined as follows (Equation 1):

$$X_{wb} = \frac{m_t - m_s}{m_t} \quad (1)$$

Where:

X_{wb}: the wet basis moisture content (g/g, db) at time t;

m_t: the weight of material at time t;

m_s: the dry matter weight of the material;

t: the drying time (h).

2.4.2. Rehydration ratio

The dried samples were soaked in 60 °C distilled water for 30 min and drained on the blotting paper to remove free water. The rehydration ratio (RR) was represented as the ratio of the mass of rehydrated sample (m_e, g) to the mass of the dried bamboo shoot sample (m_a, g) (Equation 2) (Miraei Ashtiani et al., 2018):

$$RR = \frac{m_e}{m_a} \quad (2)$$

2.4.3. Chromatic aberration

The lightness (L^*), redness (a^*), and yellowness (b^*) were measured using an automatic whiteness meter (SC-10 Shenzhen ThreeNH Technology Co. Ltd., Shenzhen, China). The instrument was calibrated using a standard whiteboard before use. Chromatic aberration (ΔE) was estimated from the coordinates of the color by the Equation 3:

$$\Delta E = \sqrt{(L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2} \quad (3)$$

Where:

L, a, and b: the measured values of the standard sample;

L^*, a^*, and b^*: the measured values of the dried bamboo shoot samples.

2.5. Experimental protocols

2.5.1. Single-factor experiment

The hot air velocity was set at 0.8 m/s, and the slice thickness was 0.4 cm. The single-factor experiments were carried out with hot air temperatures of 40, 50, 60, 70, and 80 °C.

The hot air temperature was set at 60 °C, and the slice thickness was 0.4 cm. The single-factor experiments were carried out with hot air velocities of 0.2, 0.4, 0.6, 0.8, and 1 m/s.

The hot air temperature was set at 60 °C, and the hot air velocity was 0.8 m/s. The single-factor experiments were carried out with slice thicknesses of 0.2, 0.4, 0.6, 0.8, and 1 cm.

2.5.2. Response surface experiment

The rehydration ratio and chromatic aberration of the product were taken as the response values, and the hot air temperature (X_1), air velocity (X_2), and slice thickness (X_3) were taken as the dependent variables. The optimization of the hot air drying process variables was carried out with Box–Behnken design (BBD) using RSM (Elboughdiri et al., 2020; Gaikwad et al., 2022).

The experiment's reproducibility was evaluated to determine the experimental error, and the design included five replications of the center point. The prepared data were fitted with a quadratic equation model for predicting the optimal conditions (Rai et al., 2019), and it can be expressed as follows (Equation 4):

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ij} X_i^2 + \sum_{i \neq 1}^{3} \beta_{ij} X_i X_j \quad (4)$$

Where:

β_0, β_i, and β_{ij}: the constants, linear, quadratic, and cross-product regression coefficients;

X_i and X_j: the coded independent variables.

Regression analysis and analysis of variance (ANOVA) were performed for the model fitting and to confirm the statistical significance of the model terms. The lack of fit test and coefficient of determination (R^2) analysis were used for the determination of the adequacies of the models. The results were tested statistically at the significance level of p=0.05.

3. Results and discussion

3.1. Impact of factors on indicators

3.1.1. Drying curves

Hot air drying curves of bamboo shoot slices for different air temperatures, air velocities, and thicknesses are shown in Figures 2–4. As evident from Figures 2–4, there was a short warm-up drying period of 0–20 min. In this period, all the heat transferred from the hot air to the samples caused the temperature to rise, and the moisture content of the slices remained almost unchanged.

The drying curves for different air temperatures are shown in Figure 2. The moisture content of bamboo shoots decreased curvilinearly, and two stages, a rapid speed drying stage and a deceleration drying stage, were apparent. The moisture migrated to the surface of the slices and evaporated at a quick speed under the condition of high moisture content. When the moisture content decreased, the drying rate decreased until

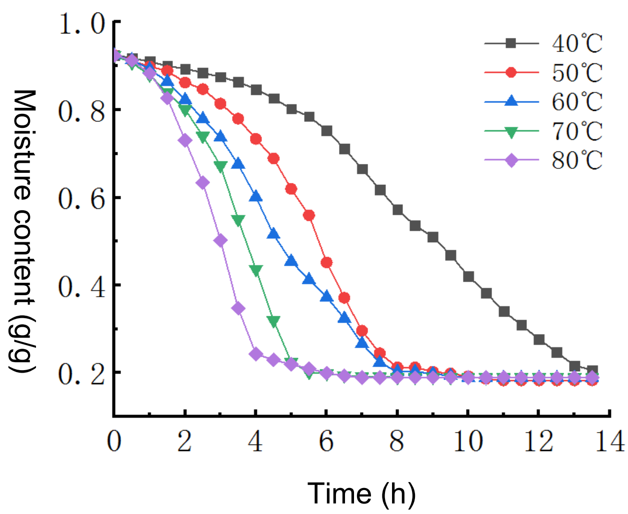


Figure 2. Drying curves for different air temperatures.

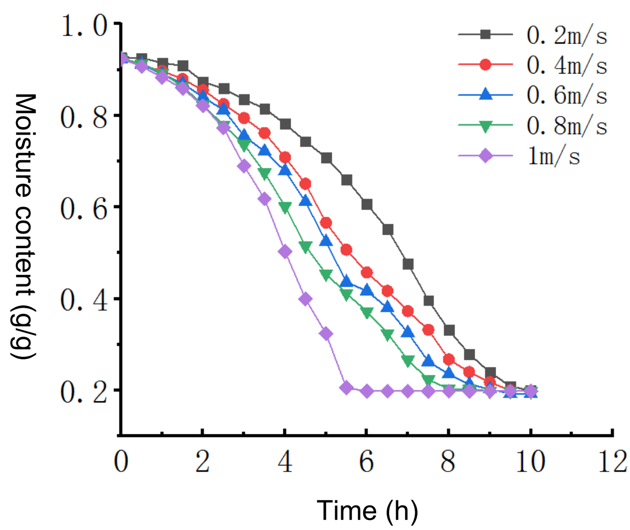


Figure 3. Drying curves for different air velocities.

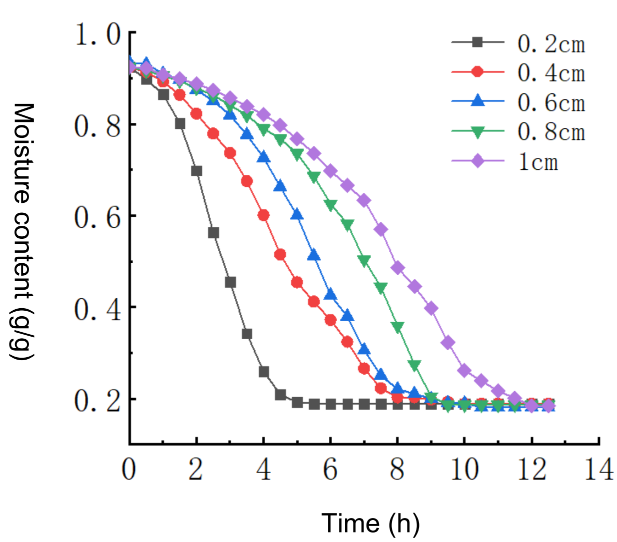


Figure 4. Drying curves for different thicknesses.

the whole drying process was completed. There was no obvious constant-speed drying stage during the drying process of bamboo shoots, which may be attributed to the high moisture content of bamboo shoots. The humidity gradient was so large that the moisture diffusion and migration ability inside the material were enhanced, thus affecting the drying rate. As shown in Figure 2, the moisture content decreased rapidly with increasing air temperature because the higher temperature led to more intense internal liquid water activity, resulting in increased drying rates.

Figure 3 shows that increasing the air velocity reduced the drying time effectively. The drying time of bamboo shoots at an air velocity rate of 0.2 m/s was approximately 4 h longer than that at a rate of 1 m/s because assumably, as the air velocity increased, the water evaporated from the surface of the slices was quickly carried away and a larger concentration difference was maintained between the interior of the slices and the dried air, which resulted in a lower evaporation pressure of water and a lower resistance to the diffusion of water in the material.

The drying curves of bamboo shoots of different thicknesses (Figure 4) show that thinner bamboo shoot slices had more rapid drying rates. When the slice thickness of samples increased from 0.2 to 1 cm, the drying time extended from 5.5 to 12 h.

3.1.2. Chromatic aberration

Chromatic aberration (ΔE) including a*, b*, and L* parameters were used for the evaluation of the color of the dried bamboo shoots (Table 1). The values of a*, b*, and L* accurately described the color changes related to enzymatic browning (Persic et al., 2017). Table 1 shows that the effect of a* on bamboo shoot slices was relatively small, and the main

Table 1. Color quality of dried bamboo shoot slices.

Normal temperature		**L***	**a***	**b***	**ΔE**
		54.63	**0.64**	**3.36**	**0**
Temperature (°C)	40	70.99	1.92	13.33	16.88
	50	68.66	2.77	16.56	17.46
	60	73.43	2.37	16.45	20.74
	70	70.28	2.86	22.20	22.91
	80	68.43	2.37	25.45	24.74
Velocity (m/s)	0.2	74.43	1.06	15.45	20.84
	0.4	68.57	3.93	20.27	20.51
	0.6	71.41	2.70	16.85	19.53
	0.8	73.43	2.37	16.45	20.74
	1	64.28	4.18	28.00	25.82
Thickness (cm)	0.2	69.27	3.20	22.51	22.65
	0.4	73.43	2.37	16.45	20.74
	0.6	69.34	3.63	22.05	22.36
	0.8	60.14	6.27	28.79	26.19
	1	60.61	4.18	31.76	28.79

parameters affecting the changes of ΔE were L* and b* during the hot air drying.

As shown in Table 1, the effect of hot air temperature on L * was not regular. The ΔE obviously increased as the temperature increased as a result of the increase in b*. Therefore, the slices turned a darker shade of yellow at a higher temperature, which might be attributed to higher surface color degradation and non-enzymatic browning resulting from the air temperature increase (Mugodo & Workneh, 2021). In addition, when the air velocity was 1 m/s, the ΔE was significantly higher than at other velocities and the b* value was also the highest among different air velocities. This meant that the high air velocity was not conducive to maintaining the color of bamboo shoots, leading to their yellow color. The ΔE of the 0.8 and 1 cm slices after drying was significantly higher than that of other thicknesses because the thicker bamboo shoot slices dehydrate at a slower rate, therefore increasing the interaction of water and enzymes. The increase in the interaction between water and enzymes caused the activity of poly oxidases; thus, the browning of bamboo shoots increased.

3.1.3. Rehydration ratio

As shown in Figures 5 and 6, the RR of the dried products became worse with the increase in air temperature and air velocity because the hot air and high air velocity could destroy the internal structure of the bamboo shoots slice. The RR decreased significantly when the air velocity was higher than 0.6 m/s. Figure 7 shows that the RR value peaked at the thickness of 0.4 cm and then fell at thicknesses greater than 0.4 cm. Easy formation of hard shells on the bamboo shoot surface as the thickness increased could result in a compacted structure and reduced rehydration. However, the rehydration ratio of bamboo shoot slices decreased slightly at 0.2 cm, which might result from a serious shrinkage phenomenon of the very thin slices, resulting in the pore structure not being restored and the rehydration being relatively low.

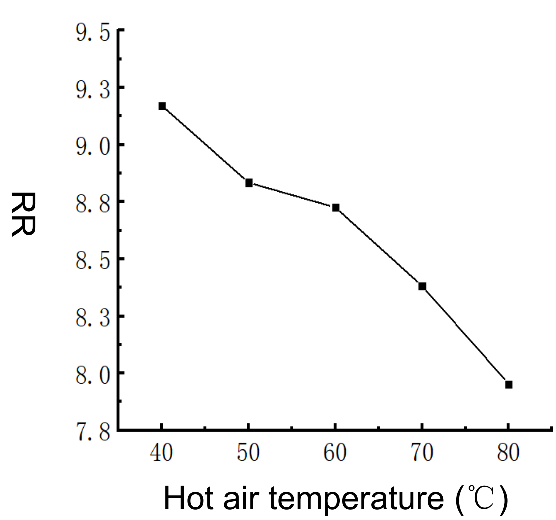


Figure 5. Rehydration ratio for different air temperatures.

3.2. Optimization of hot air drying

Based on the above experimental results, the value ranges of 50–80 °C, 0.4–0.8 m/s, and 0.2–0.8 cm were set for temperature, velocity, and slice thickness, respectively. Table 2 shows the factors and levels of experiments.

3.2.1. The experimental results of RSM

The response results were obtained in designing experiments using the BBD and Design-Expert 10.0.4 software (Table 3).

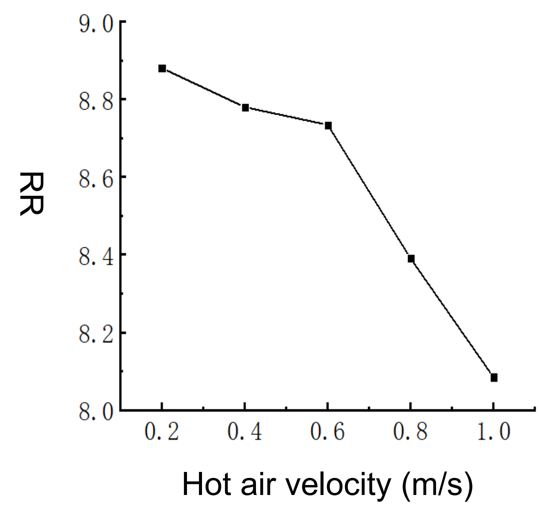


Figure 6. Rehydration ratio for different air velocities.

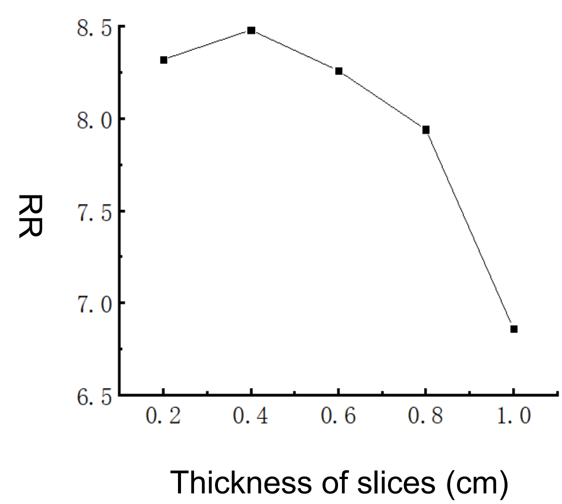


Figure 7. Rehydration ratio for different thicknesses.

Table 2. Experimental factors and levels.

Coding level	X_1 (°C)	X_2 (m/s)	X_3 (cm)
-1	50	0.4	0.2
0	65	0.6	0.5
1	80	0.8	0.8

Table 3. Results of hot air drying of bamboo shoot in RSM.

Number	X_1 Hot air temperature (°C)	X_2 Hot air velocity (m/s)	X_3 Thickness of slices (cm)	Y_1 RR	Y_2ΔE
1	1	0	-1	7.54	18.33
2	0	1	1	6.82	20.06
3	-1	1	0	7.63	21.03
4	0	0	0	8.03	17.87
5	0	0	0	7.84	22.01
6	0	0	0	7.75	20.76
7	0	-1	1	7.44	26.52
8	-1	0	1	8.23	16.32
9	-1	0	-1	9.95	12.68
10	0	-1	-1	8.37	17.28
11	1	1	0	6.41	18.12
12	0	1	-1	8.06	19.4
13	0	0	0	7.37	20.44
14	0	0	0	7.09	23.93
15	-1	-1	0	10.56	13.43
16	1	-1	0	6.31	25.12
17	1	0	1	5.64	25.25

3.2.2. Fitting the regression model

The results in Table 3 were analyzed by the Box–Behnken principle to obtain the quantitative relationships among the Y_1, Y_2, X_1, X_2, and X_3 (shown in Equations 5 and 6) by using the quadratic polynomial regression analysis in the Design-Expert 10.0.4 software:

$$Y_1=+7.62-1.31\,X_1-0.47\,X_2-0.72\,X_3+0.76\,X_1X_2-0.045\,X_1X_3-0.078\,X_2X_3+0.14\,X_1^2-0.028\,X_2^2+0.085\,X_3^2 \quad (5)$$

$$Y_2=+21+2.92\,X_1-0.47\,X_2+2.56\,X_3-3.65\,X_1\,X_2+0.82\,X_1\,X_3-2.14\,X_2\,X_3-2.12\,X_1^2+0.55\,X_2^2-0.73\,X_3^2 \quad (6)$$

Since the R^2 values of Equation 5 and Equation 6 were 0.9437 and 0.8901, respectively, the model correlations were superior. The coefficients of variation (CV) of Equation 5 and Equation 6 were 5.63 and 9.88%, respectively, which means that the model had high accuracy for predicting RR and ΔE. Thus, this model could be used to find the optimal hot air drying condition of bamboo shoots.

Hot air temperature affected RR ($p<0.001$) and ΔE ($p<0.05$) significantly, and the thickness of slices had a significant effect on RR and ΔE ($p<0.05$) as well. The hot air velocity had a significant effect on RR ($p<0.05$) but did not reach statistical significance for ΔE ($p>0.05$). In addition, the interaction between hot air temperature and air velocity also had a significant effect on the RR ($p<0.05$). The interaction between hot air temperature and slice thickness and the interaction between the hot air temperature and the air velocity had a significant impact on chromatic aberration ($p<0.05$).

By comprehensive consideration of the significance of the three factors on RR and ΔE, the effects of the three factors were ordered as hot air temperature>slice thickness>hot air velocity.

3.2.3. Response surface analysis

Figure 8 shows the interactive response surface of drying conditions on the rehydration ratio. An increase in the velocity and the temperature had a negative influence on the rehydration ratio (Figure 8A); the RR decreased significantly with the interaction of temperature and velocity. In addition, the increase in the thickness and temperature had an adverse impact on the rehydration ratio (Figure 8B). However, the relatively flat surface in Figure 8C indicates that the interaction of thickness and velocity has no significant influence on RR.

The interactive response surface of air temperature, velocity, and slice thickness to ΔE is shown in Figure 9. The interaction of temperature and air velocity had a positive effect on ΔE of the dried bamboo shoots slices (Figure 9A), which indicates that the lower drying temperature and air velocity conditions contributed to maintaining the color of bamboo shoots slices. Although there was a significant effect of temperature and thickness on the ΔE values (Table 4), the ΔE did not change significantly with thickness when the temperature was 50–65 °C (Figure 9B), indicating that the interactive effect of temperature and thickness was not significant when the temperature was low. The change in thickness had almost no effect on ΔE as the wind speed increased (Figure 9C), and combined with Table 4, we found that the interaction between air velocity and thickness did not show any significant effect.

3.2.4. Process optimization

Our purpose was to find the optimal hot air drying condition for bamboo shoots. From the response surface analysis, the optimized processing parameters of bamboo shoot slices by hot air drying were 60.407 °C, 0.404 m/s, and 0.2 cm thickness. Based on the practical operability, the drying processing parameters of 60.4 °C, 0.4 m/s, and 0.2 cm thickness were selected to carry out three verification experiments. The results showed that the RR and ΔE of the dried bamboo shoot slices for each parameter were 10.57 and 12.35, 9.98 and 11.68, and 10.72 and 12.21, respectively. The errors were less than 5% from the predicted values of 10.46 and 12.03. In summary, the processing parameters for hot air drying of bamboo shoot slices as identified in this work were exact, authentic, and of high utility value.

4. Conclusions

In this study, it was experimentally possible to ascertain that the hot air drying of bamboo shoot slices is a slow drying process. The increase in hot air temperature and velocity had

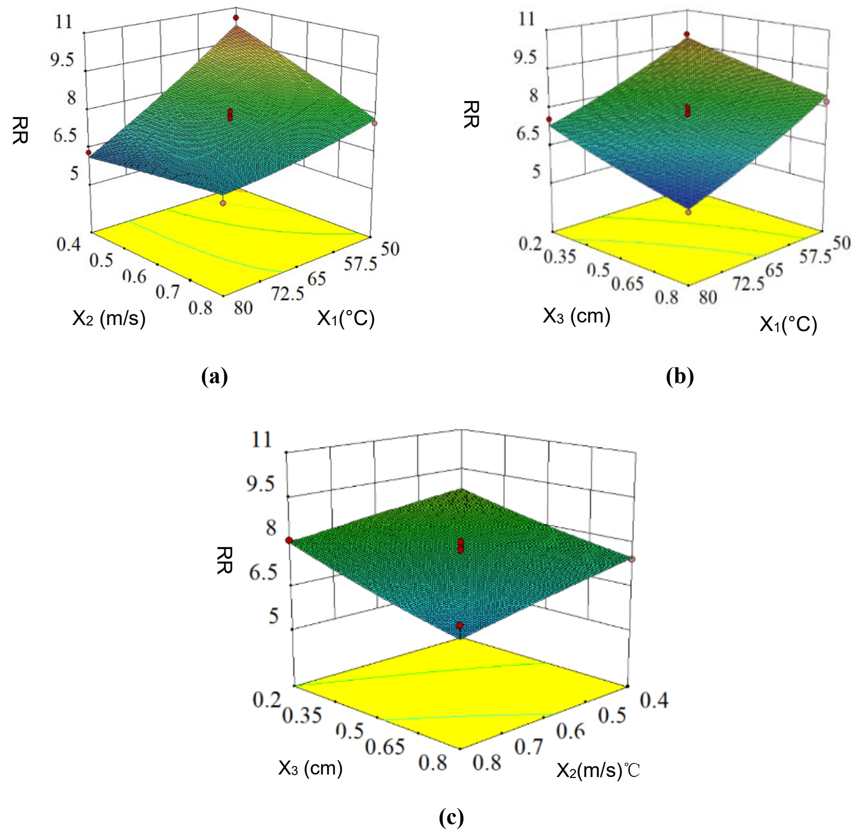


Figure 8. Response surface plots showing the combined effect of (A) hot air temperature, (B) velocity, and (C) the thickness of slices on RR.

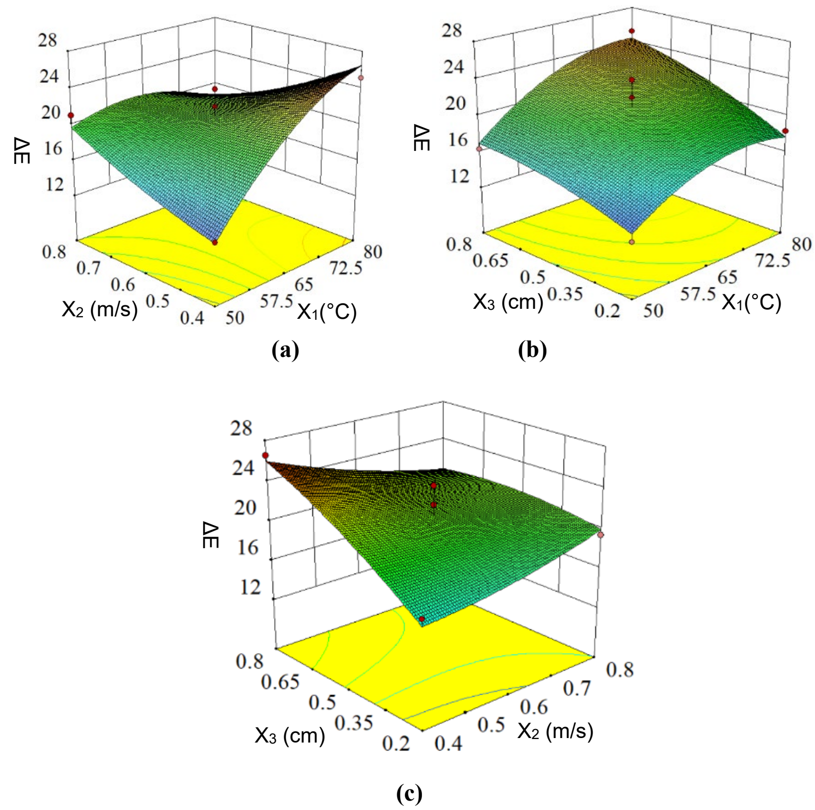


Figure 9. Response surface plots showing the combined effect of (A) hot air temperature, (B) velocity, and (C) the thickness of slices on ΔE.

Table 4. Analysis of variance (ANOVA) of the fitted polynomial model for sundry responses.

Source	df	RR				df	ΔE			
		Sum of squares	Mean square	F value	p-value		Sum of squares	Mean square	F Value	p-value
Model	9	22.11	2.46	13.04	0.0013	9	219.31	24.37	6.30	0.0120
A	1	13.70	13.70	72.75	<0.001	1	68.21	68.21	17.63	0.0040
B	1	1.77	1.77	9.38	0.0182	1	1.75	1.75	0.45	0.5230
C	1	4.19	4.19	22.25	0.0022	1	52.33	52.33	13.52	0.0079
AB	1	2.30	2.30	12.19	0.0101	1	53.29	53.29	13.77	0.0075
AC	1	0.01	0.01	0.04	0.8416	1	2.69	2.69	0.70	0.4319
BC	1	0.02	0.02	0.13	0.7315	1	18.40	18.40	4.76	0.0655
A^2	1	0.08	0.08	0.44	0.5306	1	18.99	18.99	4.91	0.0623
B^2	1	0.00	0.00	0.02	0.8984	1	1.26	1.26	0.33	0.5864
C^2	1	0.03	0.03	0.16	0.7014	1	2.27	2.27	0.59	0.4692
Residual	7	1.32	0.19			7	27.08	3.87		
Lack of fit	3	0.74	0.25	1.71	0.3012	3	7.31	2.44	0.49	0.7062
Pure error	4	0.58	0.14			4	19.77	4.94		
Cor total	16	23.42				16	246.39			
R^2		0.9437					0.8901			
R^2_{adj}		0.8714					0.7488			
PRESS		12.77					147.85			
CV/%		5.63					9.88			

a positive effect on the drying process, whereas the increase in slice thickness had a negative effect on the drying process.

The hot drying process of bamboo shoots was optimized by RSM. The optimized parameters were as follows: the air temperature of 60.4 °C, air velocity of 0.4 m/s, and slice thickness of 0.2 cm. Under these conditions, the rehydration ratio and chromatic aberration of the dried bamboo shoot slices were 10.46 and 12.03, respectively.

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