HOT-AIR DRYING CHARACTERISTICS AND QUALITY EVALUATION OF BITTER MELON SLICE
/
苦瓜片热风干燥特性及品质评价

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ABSTRACT

Hot-air drying experiments and quality evaluation were conducted to obtain drying characteristics and overall evaluation of hot-air drying of bitter melon slice in this study. The evaluation indexes included effective moisture diffusivity, total colour difference, retention rate of vitamin C and mass fraction of total saponins, etc. Results showed that: drying rate decreased with decrease of moisture content, and moisture removal was mainly processed during the falling rate drying stage; Page model and Modified Page model gave the best fit to experimental data of moisture ratio, and Page model was preferred for hot-air drying of bitter melon slice for convenience of process control and optimization; Air temperature had the highest level of influence on the synthetic evaluation index, and it was followed by air velocity, layer thickness and initial mass, sequentially, and the confidence levels of air temperature, air velocity and layer thickness were 99.6%, 98.1%, and 96.5%, respectively.

摘要

本文以有效水分扩散系数、色差、维生素 C 保留率和总皂苷质量分数等为评价指标，进行了苦瓜片的热风干燥实验，得到了苦瓜片的热风干燥特性和干燥质量的总体评价。研究结果表明：干燥速率随着含水率的降低而降低，水分的去除主要发生在降速干燥阶段；Page 模型和修正 Page 模型对苦瓜片水分比实验数据的拟合性能最好，但是基于工艺控制和优化的方便性，优选 Page 模型；热风温度对苦瓜片热风干燥综合性能的影响最显著，其次是热风速度和物料厚度，初始质量影响最小，热风温度、热风速度和物料厚度的置信度分别为99.6%、98.1%和96.5%。

INTRODUCTION

Bitter melon (*Momordica charantia* L.), also known as bitter gourd (named because of its special bitterness), is a member of the Cucurbitaceae family and mostly cultivated for its edible fruits as well as medicinal usages. Bitter melon originated in India and was introduced into China in the 14th century, and it is planted worldwide at present (*Horax et al., 2010*). In Chinese and Western cuisine, bitter melon is valued for its bitter flavour, and it is consumed by means of dishes, soups, dim sum, and herbal teas. The ingredients of bitter flavour are cucurbitane-type triterpenoids. Cucurbitane-type triterpenoids are primarily sub-divided into types of sapogenin and saponin which possess medicinal values to human beings, such as bacteriostasis and relief of diabetes (*Donya et al., 2007; Cui et al., 2015*). The nutrients of bitter melon mainly include amino acid, folic acid, carotenoid, vitamin A, vitamin C (Vc), magnesium, calcium and other microelements (*Xiang et al., 2000*). Vc is an important and essential nutrient and it is often taken as an index of nutrient quality of processes. Fresh bitter melon has Vc content of 56-120 (mg/100g), ranking the first in gourd vegetables (*Zhu et al., 2015*).

Bitter melon, as an economic crop, has been widely cultivated in Chongqing, China. The production of bitter melon is seasonal, and the fresh bitter melon is easy to become ripped and rotten after harvest. Timely dehydration or drying is crucial for bitter melon so as to guarantee the yearly supply and consumption. Dried bitter melon slice is usually consumed as dishes or bitter tea after rehydration. At present, several drying methods are available for drying of bitter melon slice, and some examples are solar/sun drying, hot-air drying, microwave drying, freeze drying, vacuum drying, infrared drying, and some of their combinations (*Santos and Silva, 2008*). Hot-air drying is the most commonly employed method to dry bitter melon slice, because of such advantages as good convenience in operation, low invest in equipment, and high efficiency in process (*Yu et al., 2013*). But for hot-air drying, if inappropriate process parameters are adopted, quality of dried bitter melon slice may be degraded, especially resulting in loss of ingredients of bitter flavour and nutrients of bitter melon. Currently, the study of hot-air drying of bitter melon slice is mainly focused on drying characteristics, and mathematical models to fit its moisture ratio change (*Mudgal and Vishakha, 2009*). As to ingredients of bitter flavour and nutrients of bitter melon, few published studies were available for good reference.

This study aimed to investigate the effects of process parameters on hot-air drying characteristics of bitter melon slice, to compare applicability of different mathematical models to the drying process, and to evaluate effective moisture diffusivity (EMD), total colour difference, retention rate of Vc, and mass fraction of total saponins, etc., in order to provide a fundamental basis for drying process optimization and quality improvement of the final product.

MATERIALS AND METHODS

Materials

Sample preparation

Fresh bitter melon (*Momordica charantia* L.) of 70-80% maturity was bought from local market. It was washed with clean water and blotted with absorbing paper. The average initial moisture content was 95%w.b. (wet basis), namely 1900%d.b. (dry basis), as determined by direct drying method (Dryer DHG-9140A, Shanghai Jing Hong Laboratory Instrument Co., Ltd.), according to Chinese standard GB 5009.3-2016 “Determination of moisture in foods” (*China National standardizing committee, 2016a*) as follows: sliced fresh bitter melon (slice thickness 3mm) of 5-10g were dried at 105±1°C for 4h first; then, the bitter melon was weighed every 1h, sequentially; finally, the drying process was ended when neighbour mass change was less than 2mg. Other bitter melon was stored in a refrigerator at 4±1°C for the later use.

Thin-layer drying test-bench

Thin-layer drying test-bench (BC-2, Changchun Jida Science instrument Equipment Co., Ltd.) was adopted for hot-air drying of bitter melon slice. The test-bench consisted of cubic drying chamber, hot-air tunnel, heating unit, draft fan, airflow control set, sensors of air temperature and velocity, and control unit, etc. Air temperature and air velocity were adjustable, and their stable control ranges were 20-80°C and 0.1-1.5m/s, respectively. Detailed information of the test-bench can be found in the published literature (*Yang, 2014*).

Methods

Experimental arrangement

Orthogonal Factorial Experiment Design technique based on Taguchi methodology was adopted to arrange experiments (*Yang et al., 2017*). Main control factors affecting hot-air drying of bitter melon slice were defined as: factor A: air temperature; factor B: layer thickness; factor C: air velocity; factor D: initial mass. Levels of each control factor were defined, as shown in Table 1. Experimental arrangement was detailed in accordance with appropriate orthogonal array $L_9(3^4)$, a 3-level 4-factor array with 9 runs, as shown in Table 2, with EMD, total colour difference, retention rate of Vc, and mass fraction of total saponins of bitter melon as evaluation indexes.

Table 1

Levels of control factor

Level	Air temperature A [°C]	Layer thickness B [mm]	Air velocity C [m/s]	Initial mass D [g]
1	45	3	0.6	30
2	55	6	0.9	40
3	65	9	1.2	50

The bitter melon slice of required thickness was prepared using a small-scale cutter. The slice thickness was adjustable. The samples of bitter melon slice were weighed every 5 min during the 1st hour of hot-air drying, every 10 min during the 2nd and 3rd hour, and every 30 min by the end of drying. The drying process was ended when neighbour mass change was less than 5mg for each drying experiment. All experiments were replicated three times. The mass of bitter melon slice was measured by a digital balance (AL204 electronic balance, Mettler Toledo) with accuracy of ±0.1mg.

Moisture ratio (MR) and drying rate (DR) were calculated by expressions as:

$$MR = \frac{M_t - M_e}{M_0 - M_e}\text{, [dimensionless]} \quad (1)$$

where MR – moisture ratio, [dimensionless]; M_t – instantaneous moisture content, [%d.b.]; M_e – equilibrium moisture content, [%d.b.]; M_0 – initial moisture content, [%d.b.].

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t}\text{, [%d.b./min]} \quad (2)$$

where DR – drying rate, [%d.b./min]; t – time elapsed, [min].

Equilibrium moisture content could be determined only under conditions of constant temperature and air humidity. Due to low values of equilibrium moisture relative to M_0 or M_t and due to change of temperature and air humidity during drying, the moisture ratio neglecting equilibrium moisture content was expressed as $MR = M_t / M_0$.

EMD at each corresponding moisture ratio and time was calculated by the expression as (*Falade and Solademi, 2014*):

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2}\text{, [dimensionless]} \quad (3)$$

where D_{eff} – effective moisture diffusivity, [m²/s]; L – half of layer thickness, [m]; t – time elapsed, [s].

The average EMD was calculated from all positive EMD values by the expression as (*Singh and Gupta, 2006*):

$$D_{ave} = \frac{\sum_{i=1}^{n} D_{eff\_i}}{n}\text{, [m}^2\text{/s]} \quad (4)$$

where D_{ave} – average EMD, [m²/s]; D_{eff_i} –positive EMD, [m²/s]; n – number of positive D_{eff_i} values of each experiment, [dimensionless].

Mathematical modelling of drying curve

Moisture ratio vs. drying time were fitted to five drying mathematical models of hot-air drying of bitter melon slice. The models for the fit were Page model, Modified Page model, Logarithmic model, Henderson and Pabis model, and Two term exponential model (*Xin et al., 2018; Doymaz, 2004*). Nonlinear regression equations were adopted for the fit by using software Origin 8.0. Coefficient of determination (R^2), reduced Chi-square (χ^2) and root mean square error (RMSE) were applied to evaluate appropriateness of the fit.

Method for quality analysis

Chromatic aberration. The colour of dried bitter melon slice was measured using a colorimeter with 8 replications (UltraScan PRO, USA). The chromatic aberration, defined by total colour difference (ΔE), was determined by the expression as (*Deng et al., 2017*):

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}\text{, [dimensionless]} \quad (5)$$

where ΔE – total colour difference; ΔL – deviation value of black and white; Δa – deviation value of red and green; Δb – deviation value of yellow and blue. ΔL, Δa, Δb are dimensionless.

Retention rate of Vc. Vc content of bitter melon slice was measured by the 2, 6-dichloro-indophenol titration method, according to regulations described in Chinese standard GB 5009.86-2016 “Determination of ascorbic acid in foods” (*China National standardizing committee, 2016b*). Vc content and retention rate of Vc were calculated by expressions (*Zhu et al., 2015*):

$$X = \frac{VT}{m_0} \times 100\text{, [mg/100g]} \quad (6)$$

where X – Vc content, [mg/100g]; V – dyestuff volume used in titration, [ml]; T – Vc content that can be oxidized by one millilitre of dyestuff, [mg/ml]; m_0 – mass of bitter melon sample used in the titration measurement, [g].

$$R_C = \frac{C_1}{C_0} \times 100, \text{ [\%]} \quad (7)$$

where R_C – retention rate of Vc, [%]; C_1 – Vc content of dried bitter melon slice, [mg/100g]; C_0 – Vc content of fresh bitter melon, [mg/100g].

Total saponins. To obtain total saponins of bitter melon slice, main steps were normally followed as: determination of wavelength for maximum absorption, establishment of regression equation of standard momordicoside A, and measurement of total saponins of bitter melon slice. The momordicoside A was bought from Cheng Du Purechem-Standard Co., Ltd, China.

(1) Determination of wavelength for maximum absorption. Wavelength for maximum absorption of momordicoside was measured by spectrometric method (*Xu and Dong, 2005*), using UV-spectrometer (Shimadzu UV-2550, Japan). The wavelength for maximum absorption of momordicoside A was measured as 551nm. The UV-spectrometer pattern of Momordicoside A was plotted within wavelength 440-700nm, as shown in Fig. 1. The wavelength for maximum absorption of total saponins of bitter melon slice was tested and ranged from 549nm to 586nm, which demonstrated that the wavelength for maximum absorption of momordicoside A, namely 551nm, was acceptable for measurement of total saponins of bitter melon slice.

(2) Establishment of regression equation of Momordicoside A. In order to obtain total saponins of bitter melon slice, it was indispensable to establish an equation of absorption of the Momordicoside A with mass. Standard solutions of Momordicoside A of 40, 100, 160, 220 and 280μL were used for measurement of absorption, and their corresponding mass were 40, 100, 160, 220 and 280μg, respectively. Standard curve of Momordicoside A (namely curve of absorption vs. mass of Momordicoside A) was plotted, as shown in Fig. 2. The regression equation, with coefficient of determination 0.9975, was obtained as expressed:

$$A = 0.0035m - 0.099, \text{ [dimensionless]} \quad (8)$$

where A – absorption, [dimensionless]; m – mass of Momordicoside A, [μg].

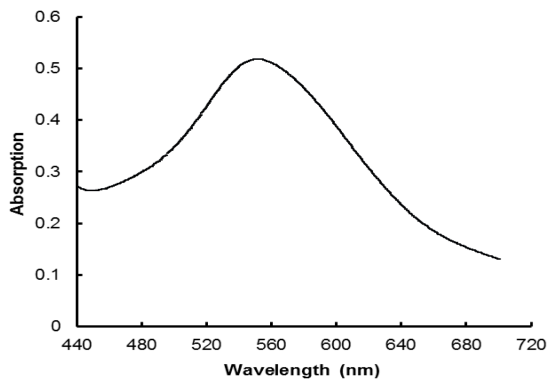


Fig. 1 - UV-spectrometer pattern of Momordicoside A

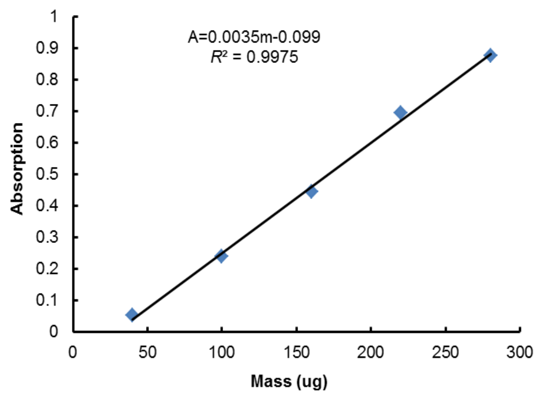


Fig. 2 - Standard curve of Momordicoside A

(3) Measurement of total saponins of bitter melon slice. The procedures for preparation of solution of bitter melon slice were outlined as follows: sample of dried bitter melon slice was powdered, and 1g of the powder, with precision of ±1mg, was placed in 500 ml round flask; 60% ethanol was used as solvent, and reflux extraction of 3 times was conducted at 60°C for 3h; the solution of extraction was fully evaporated, and the substance of extraction was dissolved into distilled water; by adding water saturated n-butanol into the resultant solution, total saponins were extracted 3 times by method of liquid-liquid extraction; the n-butanol solution of total saponins was obtained, and it was concentrated to dried saponins by reduced pressure concentration method; total saponins were dissolved with methanol, centrifuged with 3000rpm, and moved to 10mL volumetric flask; it was available to measure the absorption of total saponins of bitter melon slice (*Xu and Dong, 2005*). Then, mass fraction of total saponins of bitter melon slice was calculated by:

$$M_s = \frac{m}{m_0} \times 100, \text{ [\%]} \quad (9)$$

where M_s – mass fraction of total saponins, [%]; m – mass of total saponins of bitter melon slice, [μg]; m_0 – mass of bitter melon powder, [μg].

RESULTS

Drying Characteristics

The moisture ratio vs. drying time and drying rate vs. moisture content were obtained, as shown in Figs. 3 and 4, respectively. The EMD values of bitter melon slice of different runs were listed in Table 2.

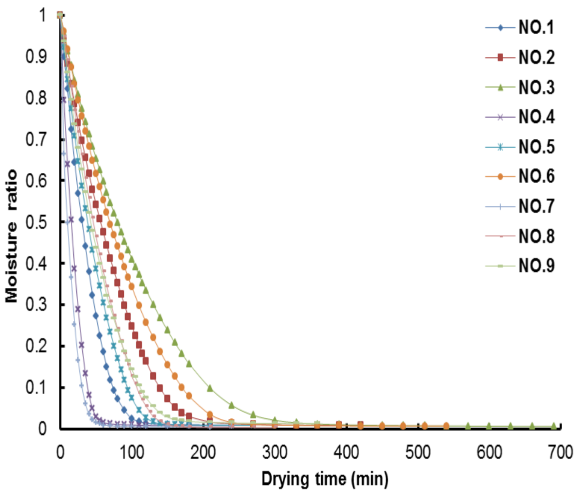


Fig. 3 - Moisture ratio vs. drying time

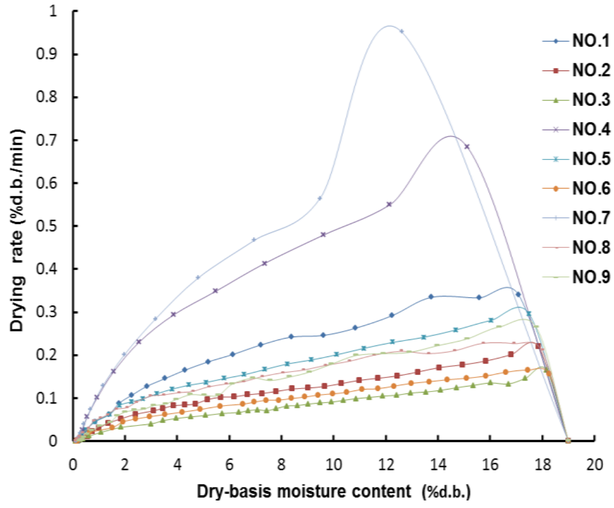


Fig. 4 - Drying rate vs. moisture content

Table 2

Experimental arrangement and results of experiment

No.	Factor A	Factor B	Factor C	Factor D	Effective moisture diffusivity	Total colour difference	Retention rate of Vc	Mass fraction of total saponins	Synthetic evaluation index
					[10^{-10}m^2/s]	/	[%]	[%]	/
1	1	1	1	1	3.55	26.31	35.69	2.28	0.3237
2	1	2	2	2	7.00	26.45	30.80	2.35	0.4103
3	1	3	3	3	10.14	26.72	29.99	2.43	0.5246
4	2	1	2	3	6.44	24.14	45.38	2.50	0.7961
5	2	2	3	1	11.58	25.46	28.69	2.55	0.7214
6	2	3	1	2	12.59	25.36	31.33	2.45	0.7138
7	3	1	3	2	8.43	24.99	35.52	2.18	0.4820
8	3	2	1	3	10.70	27.71	19.01	2.22	0.2248
9	3	3	2	1	11.91	26.49	27.90	2.32	0.4955

Moisture ratio of each run in the experiment decreased rapidly in the early stage of hot-air drying of bitter melon slice, it decreased with a gradually slower downward trend in the following stage and it approached to a relatively low value in the final stage, as shown in Fig. 3. The drying rate of each run decreased with the decrease of moisture content, except for the early stage which had a lower drying rate. During the early stage of the hot-air drying, the heat was mainly used to heat samples of bitter melon slice to levels of air temperature, which resulted in the lower drying rate in this stage, as shown in Fig. 4. Moreover, no constant drying rate stage was observed during hot-air drying of bitter melon slice, and moisture removal was mainly processed during the falling rate drying stage; the time to heat the bitter melon slice in the early stage was short, which had small effect on the change of moisture ratio during the early stage.

The result of variance analysis of EMD was listed in Table 3. The control factor with the lowest sum of squares was treated as error column while computing *F*-ratio. According to variance analysis, layer thickness had the highest level of influence on the EMD during hot-air drying of bitter melon slice, and it was followed by air temperature, air velocity, and initial mass, sequentially; the *F*-ratio of each control factor was compared to a critical value corresponding to a certain pre-selected probability, resulting in probabilities, namely confidence levels, of 99.6%, 99.3%, and 95.9% that control factors were in fact due to chance because of layer thickness, air temperature, and air velocity, respectively. The mean EMD of all runs in Table 2 was 9.15×10^{-10}m^2/s.

Table 3

Variance analysis

Experiment indexes	Source of variance	Degree of freedom	Sum of squares	Mean sum of squares	*F*-ratio	Critical *F*-ratio
Effective moisture diffusivity	Factor A	2	22.857	11.429	131.396	$F_{0.007}(2,2)$=131.396
	Factor B	2	45.529	22.764	261.726	$F_{0.004}(2,2)$=261.726
	Factor C	2	4.024	2.012	23.132	$F_{0.041}(2,2)$=23.132
	Factor D	2	0.174	0.087	Error	/
	Total	8	72.584	/	/	/
Total colour difference	Factor A	2	4.257	2.128	7.165	$F_{0.122}(2,2)$=7.165
	Factor B	2	3.162	1.581	5.323	$F_{0.158}(2,2)$=5.323
	Factor C	2	1.124	0.562	1.892	$F_{0.346}(2,2)$=1.892
	Factor D	2	0.593	0.297	Error	/
	Total	8	9.136	/	/	/
Retention rate of Vc	Factor A	2	89.398	44.699	18.311	$F_{0.052}(2,2)$=18.311
	Factor B	2	257.209	128.605	52.685	$F_{0.019}(2,2)$=52.685
	Factor C	2	54.462	27.231	11.155	$F_{0.082}(2,2)$=11.155
	Factor D	2	4.882	2.441	Error	/
	Total	8	405.951	/	/	/
Mass Fraction of total saponins	Factor A	2	0.10196	0.05098	15.881	$F_{0.059}(2,2)$=15.881
	Factor B	2	0.00996	0.00498	1.551	$F_{0.392}(2,2)$=1.551
	Factor C	2	0.01029	0.00514	1.601	$F_{0.384}(2,2)$=1.601
	Factor D	2	0.00642	0.00321	Error	/
	Total	8	0.12863	/	/	/
Synthetic evaluation index	Factor A	2	2231.628	1115.814	252.161	$F_{0.004}(2,2)$=252.161
	Factor B	2	244.576	122.288	27.636	$F_{0.035}(2,2)$=27.635
	Factor C	2	456.420	228.210	51.573	$F_{0.019}(2,2)$=51.573
	Factor D	2	8.850	4.425	Error	/
	Total	8	2941.474	/	/	/

The experimental drying data of bitter melon slice moisture ratio of each run were fitted into the selected drying mathematical models, and the corresponding model parameters and evaluation indexes of appropriateness of the fit were shown in Table 4. The higher the R^2 values and the lower the χ^2 and *RMSE* values, the better the fit appropriateness *(Wang et al., 2007)*. As shown in Table 4, Page model and Modified Page model gave the best fit to experimental data of moisture ratio, with R^2 0.99782, χ^2 0.0002, and *RMSE* 0.01360, and they were followed by Two-term Exponential model, Logarithmic model, Henderson and Pabis model. Although Page and Modified Page model had the same R^2, χ^2, and *RMSE*, in view of simplicity of mathematical model, convenience of process control and optimization, Page model was preferred for hot-air drying of bitter melon slice.

Overall Evaluation of Drying Process

Total colour difference, retention rate of Vc, mass fraction of total saponins, and their synthetic evaluation index were employed as indexes to evaluate the quality of dried bitter melon slice. The results of evaluation indexes were shown in Table 2, and their variance analysis were shown in Table 3.

Total colour difference

Air temperature had the highest level of influence on total colour difference during hot-air drying of bitter melon slice, and it was followed by layer thickness, air velocity, and initial mass sequentially; the confidence levels of air temperature, layer thickness and air velocity were 87.8%, 84.2%, and 65.4%, respectively. The mean total colour difference of all runs in Table 2 was 25.96.

The colour of bitter melon was largely showed as green, which was mainly influenced by chlorophyll. Chlorophyll easily oxidized and decomposed by heating, and the higher the temperature, the faster the oxidization and decomposition. While at the same temperature, the degree of oxidization and decomposition of chlorophyll became severe with the increase of layer thickness or the decrease of air velocity. Therefore, air temperature and layer thickness had some high significant levels of influence on the total colour difference of bitter melon slice. Moreover, with increase of temperature, enzymatic browning and non-enzymatic browning intensified during the drying process, which made colour of bitter melon slice changed from green to yellowish brown. The visual observation of dried bitter melon slice under different drying conditions was shown in Fig. 5.

Retention rate of Vc

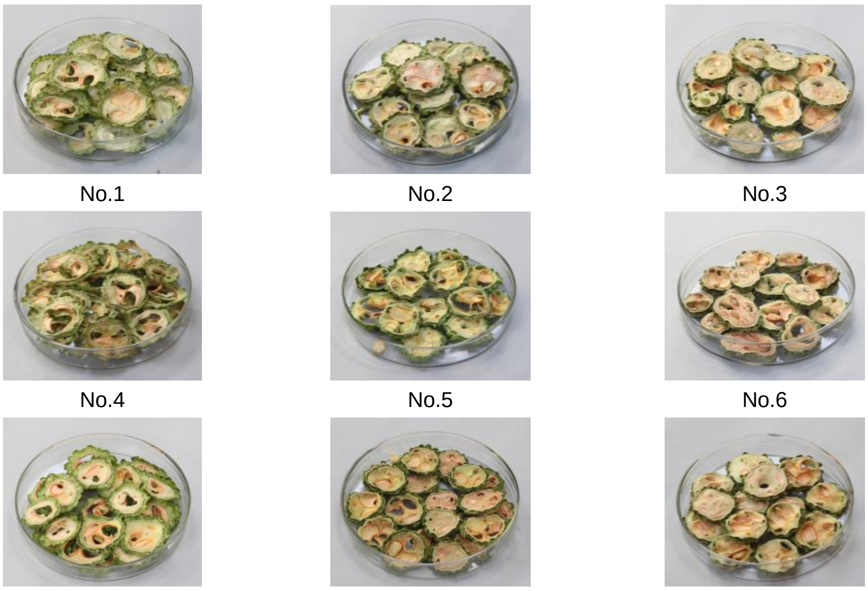
Layer thickness had the highest level of influence on retention rate of Vc during hot-air drying of bitter melon slice, and it was followed by air temperature, air velocity, and initial mass sequentially; the confidence levels of layer thickness, air temperature and air velocity were 98.1%, 94.8%, and 91.8%, respectively. The mean retention rate of Vc of all runs in Table 2 was 31.59%.

Table 4

Statistical analysis of mathematical models

Model	Parameter									Mean value
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	
1 Page：MR=exp(-kt^n)										
k	0.01012	0.00605	0.00521	0.02667	0.00809	0.00433	0.07019	0.00421	0.00849	/
n	1.24894	1.18601	1.12269	1.21018	1.23016	1.20487	1.00988	1.33875	1.17770	/
R^2	0.99819	0.99717	0.99859	0.99758	0.99738	0.99836	0.99719	0.99738	0.99851	0.99782
χ^2	0.000179	0.000267	0.000144	0.000200	0.000249	0.000173	0.000194	0.000261	0.000134	0.000200
RMSE	0.01284	0.01593	0.01174	0.01350	0.01530	0.01282	0.01328	0.01571	0.01127	0.01360
2 Modified Page：MR=exp[-(kt)^n]										
k	0.02529	0.01348	0.00925	0.05004	0.01993	0.01092	0.07200	0.01681	0.01743	/
n	1.24894	1.18601	1.12268	1.21018	1.23016	1.20486	1.01184	1.33876	1.17770	/
R^2	0.99819	0.99717	0.99859	0.99758	0.99738	0.99836	0.99719	0.99738	0.99851	0.99782
χ^2	0.000179	0.000267	0.000144	0.000200	0.000249	0.000173	0.000194	0.000261	0.000134	0.000200
RMSE	0.01284	0.01593	0.01173	0.01350	0.01530	0.01282	0.01328	0.01571	0.01127	0.01360
3 Logarithmic：MR=$a$exp(-kt)+c										
a	1.07771	1.05930	1.03639	1.04213	1.0806	1.06664	0.99484	1.12721	1.06074	/
k	0.02549	0.01341	0.00913	0.0 257	0.01955	0.01086	0.07164	0.01637	0.01771	/
c	-0.03015	-0.02502	-0.01519	-0.00758	-0.03969	-0.02413	-0.00086	-0.06181	-0.02026	/
R^2	0.99152	0.99317	0.99693	0.99200	0.99284	0.99436	0.99705	0.98942	0.99481	0.99357
χ^2	0.000836	0.000644	0.000313	0.000661	0.000682	0.000594	0.000203	0.001060	0.000467	0.000607
RMSE	0.02713	0.02441	0.01714	0.02397	0.02486	0.02347	0.01325	0.03112	0.02072	0.02290
4 Henderson and Pabis：MR=$a$exp(-kt)										
a	1.05716	1.04222	1.02592	1.03715	1.05559	1.04982	0.99432	1.08651	1.04821	/
k	0.02740	0.01422	0.00946	0.05368	0.02158	0.01147	0.07184	0.01890	0.01864	/
R^2	0.98980	0.99196	0.99644	0.99203	0.98976	0.99328	0.99719	0.98331	0.99395	0.99197
χ^2	0.00101	0.000758	0.000364	0.000658	0.000975	0.000709	0.000194	0.001670	0.000544	0.000765
RMSE	0.03042	0.02683	0.01866	0.02451	0.03023	0.02597	0.01326	0.03968	0.02269	0.02581
5 Two-term exponential：MR=$a$exp(-kt)+(1-a)exp(-kat)										
a	1.78403	1.70686	1.62603	1.73317	1.75879	1.73545	1.35196	1.86710	1.70306	/
k	0.03616	0.01837	0.01199	0.06948	0.02807	0. 1513	0.07928	0.02531	0.02370	/
R^2	0.99787	0.99730	0.99887	0.99744	0.99709	0.99835	0.99734	0.99591	0.99855	0.99764
χ^2	0.000210	0.000255	0.000116	0.000211	0.000277	0.000174	0.000183	0.000408	0.000131	0.000218
RMSE	0.01389	0.01556	0.01053	0.01388	0.01612	0.01286	0.01290	0.01964	0.01111	0.01405

Notes: k, n, a and c are model constants.



No.1 No.2 No.3
No.4 No.5 No.6
No.7 No.8 No.9

Fig. 5 - Visual observation of dried bitter melon slice under different drying conditions

Vitamin C was a thermal sensitive substance, and it easy oxidized and decomposed by heating, which showed a similar trend as the change of total colour difference. The higher the temperature, the faster the oxidization and decomposition of Vc. While at the same temperature, the degree of oxidization and decomposition of Vc also became severe with increase of layer thickness or decrease of air velocity. Under the dual influence of temperature and air velocity, retention rate of Vc first increased and then decreased.

Mass fraction of total saponins

Air temperature had the highest level of influence on mass fraction of total saponins during hot-air drying of bitter melon slice, and it was followed by air velocity, layer thickness, and initial mass sequentially; the confidence levels of air temperature, air velocity and layer thickness were 94.1%, 61.6%, and 60.8%, respectively. The mean mass fraction of total saponins of all runs in Table 2 was 2.36%. There was a trend that mass fraction of total saponins first increased and then decreased as well, with the increase of air temperature.

Synthetic evaluation

To obtain the overall influence of control factors on hot-air drying of bitter melon slice, it was necessary to give weights to different factors. Normalization was applied to all evaluation indexes since these indexes had different units. The equation of normalization was expressed as (*Li et al., 2007*):

$$q' = \frac{q - q_{\min}}{q_{\max} - q_{\min}}, \text{ [dimensionless]} \tag{10}$$

where q' – the characteristic parameters after normalization, [dimensionless]; q – characteristic parameters before normalization, [dimensionless]; q_{max} – the maximum value in the corresponding parameters, q_{max}=max(q), [dimensionless]; q_{min} – the minimum value in the corresponding parameters, q_{min}=min(q), [dimensionless].

Same weight of 0.25 was given to each evaluation index, and synthetic evaluation index was expressed as:

$$E_s = 0.25D_e' + 0.25(1 - C_r') + 0.25R_c' + 0.25M_s', \text{ [dimensionless]} \tag{11}$$

where E_s – synthetic evaluation index, [dimensionless]; D_e', C_r', R_c', and M_s' – normalized values of EMD, total colour difference, retention rate of Vc, and mass fraction of total saponins, respectively, [dimensionless].

According to variance analysis, air temperature had the highest level of influence on synthetic evaluation index during hot-air drying of bitter melon slice, and it was followed by air velocity, layer thickness, and initial mass sequentially; the confidence levels of air temperature, air velocity and layer thickness were 99.6%, 98.1%, and 96.5%, respectively. The mean synthetic evaluation index of all runs in Table 2 was 0.5214.

Range analysis was applied to synthetic evaluation indexes of all runs and analysis results were shown in Table 5. The values in cells of each level of control factors in Table 5 represent synthetic evaluation index of the corresponding levels and factors. The delta values of each factor represent the biggest change of synthetic evaluation index of the factor, namely the impact level of each factor. The numbers in the rank row indicate the impact significance sequence of control factors. According to range analysis, there were same sequences of influence significance on synthetic evaluation index as variance analysis; the optimal combination for the highest synthetic evaluation index was A2B3C3D2 which showed a value of synthetic evaluation index 0.7490, according to optimal engineering average strategy (*Wang, 2004*). But it was less than the maximum value 0.7961 of synthetic evaluation index of run 4, namely A2B1C2D3, with a relative difference 5.92% which might result from experimental errors during the multi-factor multi-index drying process.

Table 5

Range analysis of synthetic evaluation index

Level	Factor A	Factor B	Factor C	Factor D
1	0.4195	0.5339	0.4208	0.5135
2	0.7438	0.4521	0.5673	0.5353
3	0.4007	0.5780	0.5760	0.5152
Delta	0.3430	0.1258	0.1552	0.0218
Rank	1	3	2	4

CONCLUSIONS

In this study, effects of process parameters on hot-air drying characteristics of bitter melon slice were investigated, applicability of different mathematical models to the drying process was compared, and overall evaluation was conducted by using synthetic evaluation index. Main conclusions were drawn as follows:

- Moisture ratio of bitter melon slice decreased rapidly in the early stage of hot-air drying of bitter melon slice. Drying rate decreased with decrease of moisture content. No constant drying rate stage was observed during the drying process, and moisture removal was mainly processed during falling rate drying stage.
- Page model and Modified Page model gave the best fit to experimental data of moisture ratio, with coefficient of determination 0.99782, reduced Chi-square 0.0002 and root mean square error 0.01360. For convenience of process control and optimization, Page model was preferred for hot-air drying of bitter melon slice.
- Air temperature had the highest level of influence on synthetic evaluation index during hot-air drying of bitter melon slice, and it was followed by air velocity, layer thickness, and initial mass sequentially; the confidence levels of air temperature, air velocity and layer thickness were 99.6%, 98.1%, and 96.5%, respectively. The optimal combination for hot-air drying of bitter melon slice was obtained, with synthetic evaluation index 0.7490.

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REFERENCES

[1] Cui J.J., Li B., Cheng J.W., and Hu K.L., (2015), Progress on bitter principles and its biosynthesis in bitter gourd (*苦瓜苦味物质及其生物合成研究进展*), *Acta Horticulturae Sinica*, vol. 42, issue 9, pp. 1707-1718, Ed. Chinese Society for Horticultural Science, Beijing/P.R.C.;

[2] Deng Y.Y., Tang Q., Zhang R.F., Zhang Y., Liu L., Wei Z.C., Ma Y.X., and Zhang M.W., (2017), Effects of different drying methods on the nutrition and physical properties of *Momordica charantia* (*不同干燥方式对苦瓜营养与品质特性的影响*), *Scientia Agricultura Sinica*, vol. 50, issue 2, pp. 362-371, Ed. Chinese Academy of Agricultural Sciences, Beijing/P.R.C.;

[3] Donya A., Hettiarachchy N., Liyanage R., Lay J., Chen P.Y. and Jalaluddin M., (2007), Effects of processing methods on the proximate composition and momordicosides K and L content of bitter melon vegetable, *Journal of Agricultural and Food Chemistry*, vol. 55, issue 14, pp. 5827-5833, Ed. American Chemical Society, Washington, D.C./U.S.A.;

[4] Doymaz I., (2004), Effect of dipping treatment on air drying of plums. *Journal of Food Engineering,* vol. 64, issue 4, pp. 465-470, Ed. Elsevier Sci Ltd, Oxford/England;

[5] Falade K.O., Solademi O.J., (2010), Modelling of air drying of fresh and blanched sweet potato slices, *International Journal of Food Science and Technology*, vol. 45, issue 2, pp. 278-288, Ed.Wiley Blackwell Publishing, Inc., Malden/U.S.A.;

[6] Horax R., Hettiarachchy N., Kannan A., and Chen P.Y., (2010), Proximate composition and amino acid and mineral contents of *Mormordica charantia* L. pericarp and seeds at different maturity stages, *Food Chemistry*, vol. 122, issue 4, pp. 1111-1115, Ed. Elsevier Sci Ltd, Oxford/England;

[7] Li X.W., Yang M.J., Xie S.Y., and Yang S.Z., (2007), Wear condition monitoring of helical cutters based on neural network information infusion method (*基于神经网络信息融合的铣刀磨损状态监测*), *Transactions of the Chinese Society for Agricultural Machinery*, vol. 38, issue 7, pp. 160-163, Ed. Chinese Society for Agricultural Machinery, Beijing/ P.P.C.;

[8] Mudgal, V.D., Vishakha, K.P., (2009), Thin-layer drying kinetics of bitter gourd (*Momordica charantia* L.). *Journal of Food Science and Technology - Mysore*, vol. 46, issue 3, pp. 236-239, Ed. Association of Food Scientists and Technologists of India, Mysore/India;

[9] Santos P.H.S., Silva M.A., (2008), Retention of Vitamin C in drying processes of fruits and vegetables-a review, *Drying Technology*, vol. 26, issue 12, pp. 1421-1437, Ed. Taylor & Francis Inc, Philadelphia/U.S.A.;

[10] Singh B., Gupta A.K., (2006), Mass transfer kinetics and determination of effective diffusivity during convective dehydration of pre-osmosed carrot cubes, *Journal of Food Engineering*, vol. 79, issue 2, pp. 459-470, Ed. Elsevier Sci Ltd, Oxford/England;

[11] Wang W.Z., (2004). Design of experiments and analysis (*试验设计与分析*), Higher Education Press, Beijing / P.R.China;

[12] Wang Z.F., Sun J.H., Liao X.J., Chen F., Zhao G.H., Xu J.H., and Hu X.S., (2007), Mathematical modelling on hot air drying of thin layer apple pomace, *Food Research International*, vol. 40, pp. 39-46, Ed. Elsevier Science Bv, Amsterdam/Netherlands;

[13] Xiang C.P., Wu C.Y., and Wang L.P., (2000), Analysis and utilization of nutrient composition in bitter gourd (*苦瓜营养成分分析及利用评价*), *Journal of Huazhong Agricultural University*, vol. 19, issue 4, pp. 388-390, Ed. Huazhong Agricultural University, Wuhan/P.R.China;

[14] Xin Y.N., Zhang J.W., and Li B, (2018). Drying kinetics of tobacco strips at different air temperatures and relative humidities, *Journal of Thermal Analysis & Calorimetry*, vol. 132, issue 2, pp. 1347-1358, Ed. Springer, Dordrecht/Netherlands;

[15] Xu B., Dong Y., (2005), Determination on total saponins of *Momordica charantia* L. by spectrophotometry (*分光光度法测定苦瓜总皂甙含量*), *Food Science*, vol. 26, issue 10, pp. 165-169, Ed. Beijing Academy of Food Science, Beijing/P.R.China;

[16] Yang L., (2014), *Heat & Mass transfer characteristics and model of hot-air drying for seed of rape* (*Brassica napus* L.) (*甘蓝型油菜籽热风干燥传热传质特性及模型研究*), PhD dissertation, Southwest University, Chongqing / P.P.China;

[17] Yang M.J., Liu B., Yang Z.R., Ding Z.Y., Yang L., Xie S.Y., and Chen X.B., (2017), Development and experimental study of infrared belt dryer for rapeseed, *INMATEH - Agricultural Engineering*, vol. 53, issue 3, pp. 71-80, Ed. INMA, Bucharest/Romania;

[18] Yu M.J., Zhang X.J., Mu G.L., Yan J.S., Zhang H., and Shi Z.L., (2013), Research progress on the application of hot air-drying technology in China (*我国热风干燥技术的应用研究进展*), *Agricultural Science & Technology and Equipment*, issue 8, pp. 14-16, Ed. Liaoning Provincial Institute of Agricultural Mechanization, Shenyang/ P.R.China;

[19] Zhu X.Y., Zhang J., He Y.Y., and Deng F.M., (2015), Effects of hot air and far-infrared drying temperatures on quality of bitter gourd (*Momordica charantia* L.) powder (*热风与远红外干燥温度对苦瓜全粉品质的影响*), *Modern Food Science and Technology*, vol. 31, issue 7, pp. 265-269, 325, Ed. South China University of Technology, Guangzhou/P.R.China;

[20] *** China National standardizing committee, (2016a), *Determination of moisture in foods, GB 5009.3-2016* (*食品安全国家标准食品中水分的测定, GB 5009.3-2016*), Chinese Standard Press, Beijing / P.R.China;

[21] *** China National standardizing committee, (2016b), *Determination of ascorbic acid in foods, GB 5009.86-2016* (*食品安全国家标准食品中抗坏血酸的测定, GB 5009.86-2016*), Chinese Standard Press, Beijing / P.R.China.