PERFORMANCE ANALYSIS AND TECHNOLOGY OPTIMIZATION OF INFRARED DRYING OF SWEET POTATO SLICE
/
甘薯片近红外干燥性能评价和工艺优化

Xie, SY[1]; Yang, ZR[2]; Yang, L[1]; Li, ST[1]; Wang, JL[3]; Yang, MJ*[1] [1]
[1] Chongqing Key Laboratory of Agricultural Equipment for Hilly and Mountainous Regions, College of Engineering and Technology, Southwest University, Chongqing 400715;
[2] Xi'an Guide Technology Co. Ltd, Xi'an 710065, China;
[3] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China;
**Correspondence: Tel: +86-13883002509; E-mail: ymingjin@swu.edu.cn*
DOI: https://doi.org/10.35633/inmateh-64-11

Keywords: *IR drying, drying performance, technology optimization, temperature-varying, analysis of variance, sweet potato*

ABSTRACT
Sweet potato (Ipomoea batatas L.) is an important tuber crop for the daily consumption. Efficient processing must be taken to reduce wastage, and to improve quality and extend shelf period of sweet potato products. Infrared (IR) drying has advantages of high drying rate, good uniformity, and high production efficiency. A laboratory infrared (IR) dryer was developed to study the drying performance of sweet potato slice and its technology optimization in this paper. Single-factor, orthogonal, and temperature-varying experiments of IR drying of sweet potato slice were conducted sequentially. Temperature, slice thickness and steaming time were defined as control factors, and effective moisture diffusivity (EMD), total color change (TCC), specific energy consumption (SEC) and drying time were defined as evaluation indexes. Same weights were applied to the synthetic evaluation index (SEI). Experiment results and statistical analysis showed that: temperature-varying IR drying technology of temperature-decrease mode, under drying conditions of 70ºC (75min) - 65ºC (to end), showed the best drying performance; the optimal combinations for temperature-constant were slice thickness 3 mm, temperature 70ºC, and steaming time 6 min; Midilli et al. model gave the best approximation to experimental data of moisture ratio, with coefficient of determination 0.99933, reduced Chi-square 0.00007, and root mean square error (RMSE) 0.00838; high temperature (75ºC) and large slice thickness (9 mm) were not suitable for IR drying of sweet potato slice. The results of this study can provide references for research on IR drying technology and design of IR dryer for sweet potato slice.

摘要
甘薯是一种日常食用的重要根茎类作物。为了降低损坏、提高品质和延长储藏期，需对甘薯进行有效的加工处理。近红外干燥具有干燥速率快、均匀性好和效率高等优点。本文开发了一套实验用近红外干燥机用于甘薯片的干燥性能和工艺优化研究。依次对甘薯片进行近红外干燥的单因素试验、正交试验和变温试验。以温度、甘薯片厚度和蒸制时间为控制因子，有效水分扩散系数、总色差、比能耗和干燥时间为评价指标。对各评价指标赋予均等权重后得到综合指标。实验结果和数据分析表明：70 ºC (75min) - 65 ºC (至结束)的降温模式变温干燥工艺具有最佳干燥性能；常温干燥工艺的最优控制因子参数组合为：甘薯片厚度 3mm、温度 70 ºC、蒸制时间 6min；Midilli 模型对水分比的实验数据具有最佳拟合近似度，其决定系数 0.99933、卡方 0.00007、平均根方误差 0.00838；高的温度（75 ºC）和大的甘薯片厚度（9mm）不适合用于甘薯片的近红外干燥。本文研究结果可为基于甘薯片近红外干燥工艺和干燥机设计提供参考。

INTRODUCTION
Sweet potato (*Ipomoea batatas* L.) is an important tuber crop of the genus Convolvulaceae and it is broadly planted in Asia, Africa, and South America (*Liu, B. et al, 2020*). According to FAO, China ranks the first in annual planting area and production, and they are 2.374×10^6 ha and 5.199×10^7 tons in 2019. Sweet potato contains enormous amount of starch, protein, minerals, dietary fibers, and vitamins (*Song, F. et al, 2019; Rashid M. T. et al, 2020*). It can be consumed as staple food, snacks or bakery products (*Hanim, A. B. M. et al, 2014*). In addition, sweet potato can regulate blood sugar, improve immunity function and prevent

[1] *SY Xie, Prof.; ZR Yang, Ms.; L Yang, Prof.; ST Li, Ms.; JL Wang, Ms.; MJ Yang, Prof.*

cancer (*Wang, S. et al, 2016*). However, sweet potato is seasonal, and fresh sweet potato is susceptible to microbial activities because of high moisture content. These microbial activities lead to degradation and spoilage (*Onwude, D. I. et al, 2019*). Timely processing or preservation operations must be taken to reduce wastage, and to improve quality and extend shelf period of products.

Drying is an important and effective operation to remove moisture from fresh agricultural products. It implies simultaneous heat and mass transfer (*Rojas, M. L. & Augusto, P. E. D., 2018; Stasiak, M. et al, 2020*). Hot-air drying is the most common method for agricultural products, with main drawbacks of undesirable changes in physics, chemics, structure, nutrition, and color (*Ren, G. et al, 2020*). Infrared (IR) drying is used to heat materials by absorption of IR energy in the form of resonance between the electromagnetic radiation frequency and inherent frequency of the moisture in the materials, with advantages of high drying rate, good uniformity, and high production efficiency (*Huang, X. et al, 2021; Li, B. et al, 2019*). IR drying has been successfully applied to sweet potato slice, but its applications were mainly combined with other drying methods, such as hot-air drying (*Onwude, D. I. et al, 2018*), freeze drying (*Song, F. et al, 2019*), and hot-press drying (*Oh, S. et al, 2017*). However, an improper drying operation also causes the quality decline of dried products (*Zhang, M. et al, 2017*).

Doymaz et al. (2012) investigated the effect of IR power levels of 104, 125, 146 and 167 W on drying kinetics and rehydration ratio of sweet potato slice. The increase in the power level decreased the drying time. The highest rehydration ratio was obtained in the power level of 146 W. Logarithmic model gave a better fit of drying kinetics. *Onwude et al.* (2019) examined the performance of different combined IR and hot-air drying strategies for sweet potato slice, including simultaneous IR and hot-air drying, two-stage sequential hot-air and IR drying, two-stage sequential IR and hot-air drying, and intermittent IR and hot-air drying. Strategy of Intermittent IR and hot-air drying was the most suitable strategy for sweet potato slice. Wu et al. (2020) evaluated the influence of ultrasonic (US) pre-treatment on drying kinetics and quality of sweet potato slice in IR freeze drying. The US pre-treatment improved the quality of dried sweet potato slice and decreased the drying time. *Onwude et al.* (2021) developed a fully coupled multiphase model for combined IR-convective drying of sweet potato slice. The multiphase model showed the advantage in swift quantification of phase change and impact of operating parameters. Nevertheless, there are few publications on the performance-based technology optimization of IR drying of sweet potato slice.

The aim of this study was to (1) determine the levels of control factors that affect performance of IR drying of sweet potato slice, (2) find the optimal combinations for temperature-constant IR drying technology for sweet potato slice, (3) select the best model to fit experimental data with good approximation, and (4) determine the best temperature-varying IR drying technology with high performance of SEI.

MATERIALS AND METHODS

Materials

Samples of fresh sweet potato (*Ipomoea batatas L.*) were handpicked and purchased. Rotten and damaged samples were removed, and physically similar samples were stored at 4-8ºC in a sealed dark bag in a refrigerator (BC/BD-195HE, Henan Xinfei Electrical Appliance Co., Ltd., China). The initial moisture content of the samples was measured in accordance with Chinese standard "Determination of moisture in foods" (*China National Standardizing Committee, 2016*). The initial moisture was found to be 72.0 % - 76.1 % w.b.

Before each experiment, the samples were taken out of the refrigerator, washed, hand peeled and sliced. The sliced samples were color-fixed with color fixative of 0.3% citric acid + 0.1% ascorbic acid + 99.6% water (w/w) for 30 min (*He, J. et al, 2013*). Then, the sliced samples were steamed at 100ºC by a thermostat water bath (DF-101S-2L, Shanghai Pailan Instrument Equipment Co., Ltd., China). A laboratory IR dryer was developed for drying the pre-treated slices. It consists of control panel, temperature sensors, IR heaters, screen mesh (material tray), mesh stand, air inlet, air outlet, and drying chamber with 500 × 260 mm in cross section and 260 mm in height, as shown in Fig. 1. The screen mesh is placed between 2 temperature sensors with precision of ± 0.5ºC (DS18B20, Dallas Semiconductor Inc., USA). Two IR heaters of carbon fiber quartz (YH-001, Jiuerbao Optoelectronics Technology Co., Ltd., China), 300 W per heater, are fixed on the ceiling of the drying chamber. Energy consumption was measured by an electric power monitor (P08S-10, Xincheng Electronic Company Introduction, China). Total color change (TCC) was measured by a colorimeter (NR60CP, Shenzhen 3nh Technology Co., Ltd., China) after dried samples being powdered by a pulverizer (FW100, Tianjin Taisite Instrument Co., Ltd., China).

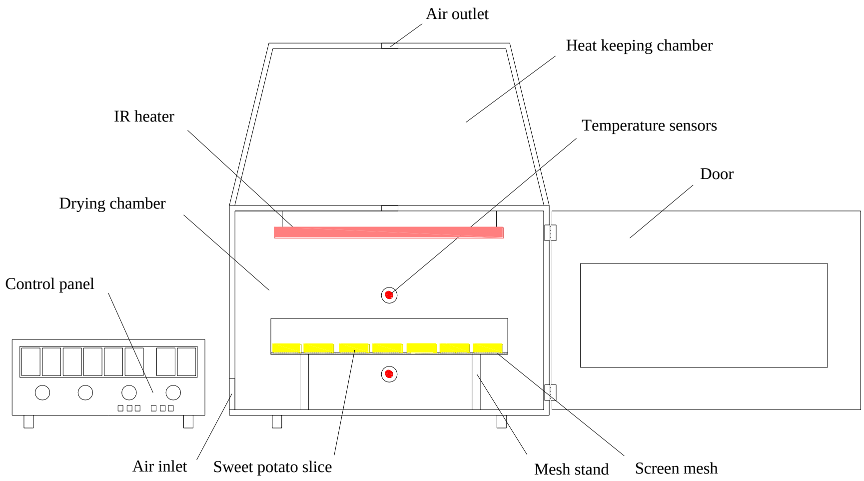


Fig. 1 - Schematic diagram of the IR dryer

Methods

Experiment arrangement

Single-factor experiment, orthogonal experiment and temperature-varying experiment were conducted in this study.

As for single-factor experiment, it was conducted to investigate the effect of individual control factor on performance of IR drying of sweet potato slice while levels of other factors remained constant, and the experiment arrangement was designed as listed in Table 1. Define temperature as factor A, slice thickness as factor B, and steaming time as factor C. No. 2, No.5 and No. 10 had the same combinations of factorial levels. Nevertheless, they kept in different rows in the table for the convenience of statistical analysis and presentation of results. Evaluation indexes included effective moisture diffusivity (EMD), TCC, Specific energy consumption (SEC), and drying time. Thereafter, normalization was applied to all evaluation indexes and equal weights were given to each evaluation index to obtain the SEI. The smaller the SEI is, the better the IR drying process is. The SEI was expressed as:

$$E_s = w_1\left(1 - D_e'\right) + w_2\Delta E' + w_3 E' + w_4 t_d' \tag{1}$$

where

E_s is SEI, [dimensionless];

D_e' – normalized EMD, [dimensionless];

$\Delta E'$ – normalized TCC, [dimensionless];

E' – normalized SEC, [dimensionless];

t_d' – normalized drying time, [dimensionless];

w_1, w_2, w_3, and w_4 – weights for EMD, TCC, SEC, and drying time, respectively, [dimensionless].

Table 1

Single-factor experiment arrangement and results

No.	Factor A [°C]	Factor B [mm]	Factor C [min]	Experiment results				SEI
				EMD [×10^{-10}m^2/s]	TCC	SEC [kJ/g]	Drying time [min]	
1	60	3	6	5.112	19.548	108.758	108.094	0.4843
2	65			6.027	19.219	102.543	75.028	0.4017
3	70			6.567	20.016	100.144	89.136	0.4248
4	75			9.888	22.829	81.537	59.057	0.3724
5	65	3	6	6.027	19.219	102.543	75.028	0.4017
6		5		12.404	16.496	127.814	136.866	0.2498
7		7		13.950	19.184	160.973	219.457	0.4144
8		9		14.566	18.646	173.761	345.967	0.5849
9	65	3	4	5.721	19.808	112.011	80.738	0.4636
10			6	6.027	19.219	102.543	75.028	0.4017
11			8	7.125	19.832	110.027	84.659	0.4258
12			10	5.008	20.891	114.354	92.778	0.5418

As for orthogonal experiment, it was conducted to investigate the significance of each factors on performance of IR drying of sweet potato slice, and to optimize process of the IR drying technology. Levels of main control factors were defined according to single-factor experiment, as listed in Table 2. Experiment arrangement was designed in accordance with an appropriate orthogonal array $L_9(3^4)$, as listed in Table 3.

Table 2

Control factors and their levels

Levels	Control factors		
	Temperature A [°C]	Slice thickness B [mm]	Steaming time C [min]
1	60	3	4
2	65	5	6
3	70	7	8

Table 3

Orthogonal experiment arrangement and results

No.	Factor A	Factor B	Factor C	Error	Experiment results				SEI
					EMD [$\times 10^{-10}$ m^2/s]	TCC	SEC [kJ/g]	Drying time [min]	
1	1	1	1	1	4.945	25.969	103.954	112.333	0.5617
2	1	2	2	2	7.539	20.116	130.074	223.117	0.6020
3	1	3	3	3	10.138	16.975	158.461	293.036	0.6595
4	2	1	2	3	6.173	20.886	97.998	89.275	0.3806
5	2	2	3	1	9.634	18.194	147.445	161.813	0.5054
6	2	3	1	2	13.013	16.706	167.346	208.887	0.5236
7	3	1	3	2	6.402	13.989	144.533	77.179	0.3814
8	3	2	1	3	12.202	15.940	136.650	127.160	0.3229
9	3	3	2	1	16.155	15.611	168.969	162.070	0.3822

As for temperature-varying experiment, it was conducted to investigate the advantages of temperature-varying drying technology in final product quality and energy consumption. Two drying modes, namely temperature-decrease mode, and temperature-increase mode, were investigated, both modes having 3 different drying conditions. The slice thickness was 3 mm, and the steaming time was 6 min. Experiment arrangement was designed based on single-factor experiment and orthogonal experiment, as listed in Table 4. Since TCC and SEC were the major factors considered for a practical IR drying process, evaluation indexes of TCC and SEC were employed to calculate the SEI.

Table 4

Temperature-varying experiment arrangement and results

No.	Drying modes	Drying conditions	TCC	SEC [kJ/g]	SEI
1	Temperature-decrease	70°C (75min) - 60°C (to end)	18.508	73.458	0.5000
2		70°C (75min) - 65°C (to end)	17.763	75.905	0.2678
3		65°C (105min) - 60°C (to end)	18.006	93.485	0.5357
4	Temperature-increase	65°C (105min) - 70°C (to end)	17.063	101.819	0.2965
5		60°C (120min) - 70°C (to end)	17.907	108.076	0.6539
6		60°C (120min) - 65°C (to end)	18.340	121.278	0.9416

Data treatment

The samples of sweet potato slice were weighed every 5 min during the 1st hour of IR drying, every 15 min during the 2nd hour, and every 30 min till the end of drying. The drying ended when neighbor weighing of mass change was less than 0.02 g. Three replications were conducted for each experiment.

Moisture ratio (MR) and drying rate (DR) are expressed as (*Chandrasekar, M. et al, 2018*):

$$MR = \frac{M_t}{M_0} \tag{2}$$

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (3)$$

where

MR is moisture ratio, [dimensionless];

DR – drying rate, [% d.b./min];

M_0 – initial moisture content [% d.b.];

M_t – instantaneous moisture content [% d.b.];

t – time [min].

EMD is expressed as (*Guine, R. P. F. et al, 2017*):

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_e t}{L^2} \quad (4)$$

where

D_e is effective moisture diffusivity, [m^2/s];

L – layer thickness, [m].

TCC between dried and fresh material is calculated as (*Pasławska, M. et al, 2020*):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (5)$$

where

Δ*E* is total color change, [dimensionless];

Δ*L**, Δ*a**, and Δ*b** – changes of lightness, greenness, and yellowness between dried and fresh material, respectively, [dimensionless].

SEC is defined as the ratio of energy consumption for removing of a unit mass of moisture in the material, and it is expressed as:

$$E = \frac{Q}{m} \times 3600 \quad (6)$$

where

E is specific energy consumption [kJ/g];

Q – energy consumed, [kW·h];

m – mass of moisture removal, [g].

Mathematical thin layer drying models were used for the approximation of moisture ratio of orthogonal experiment, as listed in Table 5. Coefficient of determination (R^2), reduced Chi-square (χ^2) and root mean square error (RMSE) were applied to evaluate accuracy of the approximation (*Yang, L. et al, 2019*). The model that gave the best approximation was employed to calculate drying time of each experiment. The drying time was defined as the time when moisture content of the sweet potato slices decreased to 10% d.b., the safe storage level of dried sweet potato slices.

Table 5

Mathematical thin layer drying models used for the approximation

Model	Model name	Equations		References
1	Page	$MR = \exp(-kt^n)$	(7)	*Page, G. 1949*
2	Two-term	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$	(8)	*Henderson, S. M., 1974*
3	Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	(9)	*Verma, L. R. et al, 1985*
4	Midilli et al.	$MR = a\exp(-kt^n) + bt$	(10)	*Midilli, A. et al, 2002*
5	Hii et al.	$MR = a\exp(-bt^c) + d\exp(-gt^c)$	(11)	*Hii, C. et al, 2009*

Note: *a*, *b*, *c*, *d*, *g*, *k*, k_1, k_2, *n* are parameters, [dimensionless].

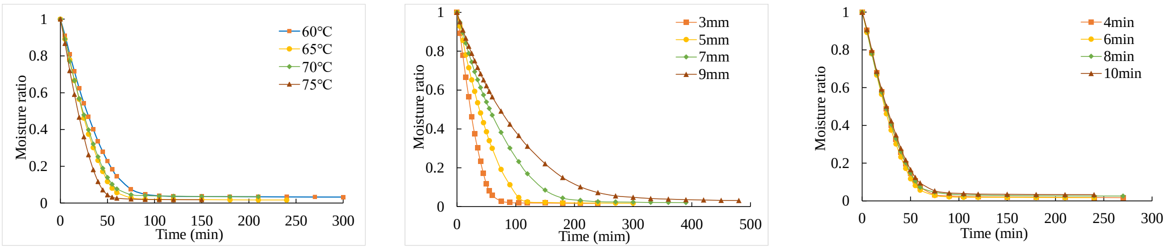
RESULTS AND DISCUSSIONS

Single-factor experiment

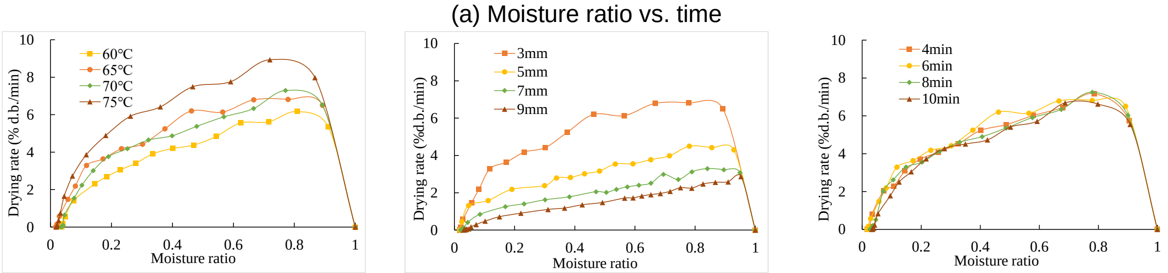
The profiles of moisture ratio and drying rate of sweet potato slice at different drying conditions by single-factor experiment were plotted, as shown in Fig. 2. The corresponding values of EMD, TCC, SEC, drying time and SEI were calculated, as listed in Table 1. The comparisons of the drying performance at different drying conditions were plotted, as shown in Fig. 3. The drying time was calculated by *Midilli et al.* model (Model 4 in Table 5) which showed the best approximation of moisture ratio during the IR drying of sweet potato slice.

As seen from Fig. 2, the moisture ratio decreased with the increase of time processed. The drying rate decreased with the decrease of moisture ratio, except for the initial drying period. During the initial drying period, the moisture ratio was high and the sweet potato slice required to be heated to drying temperature that was set for each experiment, which affected the changes of moisture ratio and drying rate in this period. There was no constant drying rate stage for sweet potato slice. The higher the drying temperature was, the shorter the drying time was required. Steaming time had little effect on the changes of moisture ratio and drying rate. Nevertheless, steaming benefited nutritious quality of the sweet potato slice (*Trancoso-Reyes, N. et al, 2016*), pre-treatment of steaming was kept in the IR drying technology of this study. As seen from Fig. 3, slice thickness had strong effects on EMD and drying time, temperature had certain effects on them, and steaming time had a small effect on them. The larger the slice thickness was, the higher the EMD and drying time were; the higher the temperature was, the higher the EMD was, and the lower the drying time was. All control factors had a small effect on TCC, except for the effect of temperature at 75ºC and slice thickness of 5 mm. Slice thickness had a strong effect on SEC, temperature had a certain effect on SEC, and steaming time had a small effect on SEC.

The larger the slice thickness was, the higher the SEC was. As for SEI, the effect of temperature was the strongest among all control factors.

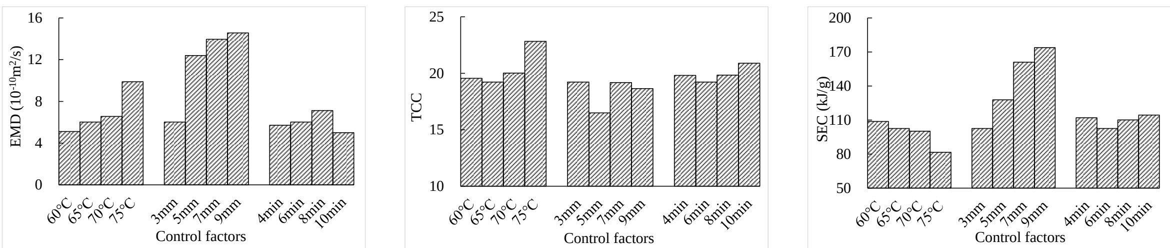


(a) Moisture ratio vs. time

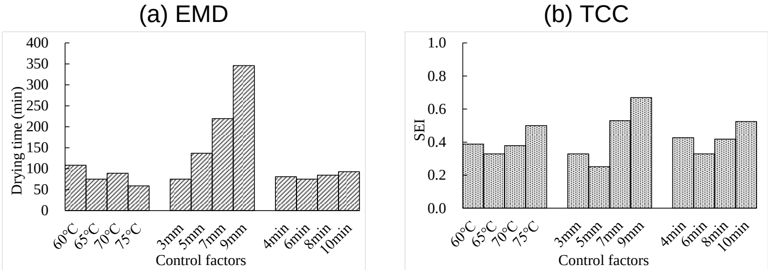


(b) Drying rate vs. moisture ratio

Fig. 2 - Drying curves of sweet potato slice by single-factor experiment



(a) EMD (b) TCC (c) SEC

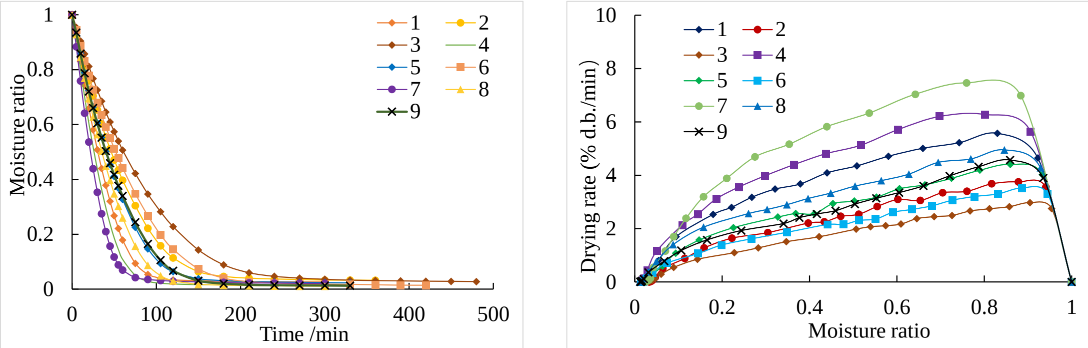


(d) Drying time (e) SEI

Fig. 3 - Drying performance of sweet potato slice by single-factor experiment

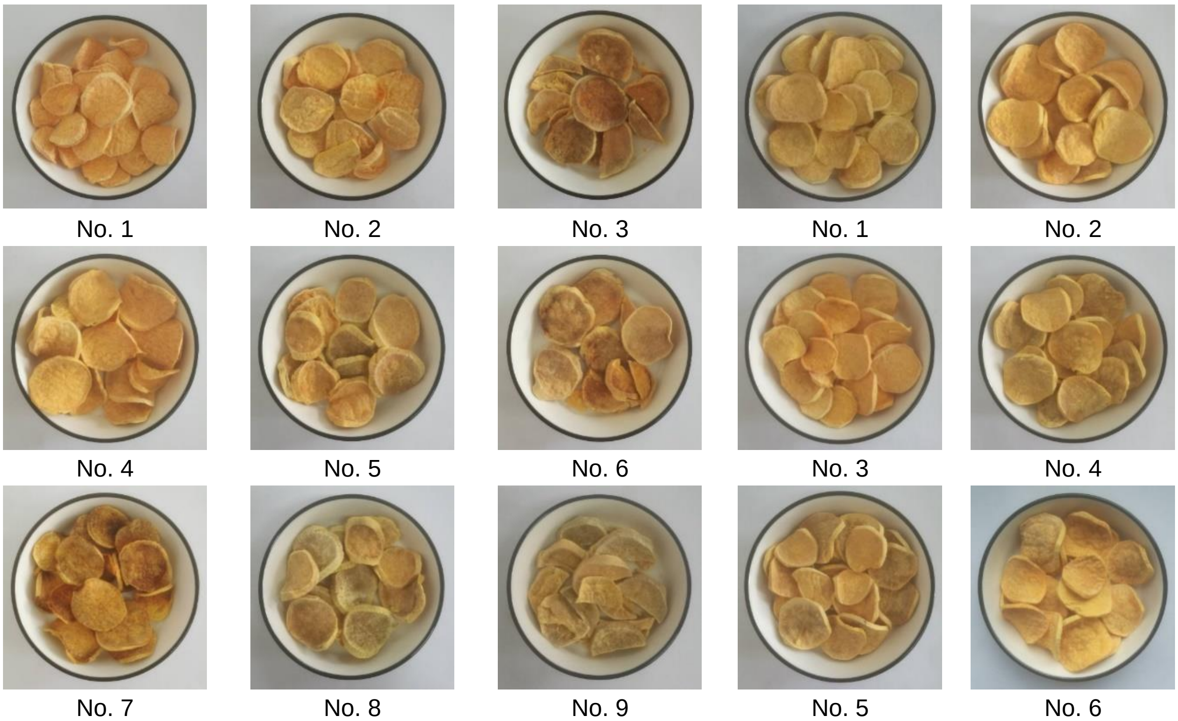
Orthogonal experiment

According to single-factor experiment results and the corresponding analysis, levels of temperature 75ºC, slice thickness 9 mm, and steaming time 10 min were not considered in the orthogonal experiment. The profiles of moisture ratio and drying rate of sweet potato slice of different runs by orthogonal experiment were plotted, as shown in Fig. 4. The corresponding values of EMD, TCD, SEC, drying time and SEI were calculated, as listed in Table 3. The visual observations of dried sweet potato slice of different runs were presented, as shown in Fig. 5 a. As seen from Fig. 4, The profiles of moisture ratio and drying rate of sweet potato slice by orthogonal experiment were similar with those by single-factor experiment.



(a) Moisture ratio vs. drying time (b) Drying rate vs. moisture ratio

Fig. 4 - Drying curves of sweet potato slice by orthogonal experiment



(a) Orthogonal experiment (b) Temperature-varying experiment

Fig. 5 - Visual observations of dried sweet potato slice of different runs

Analysis of variance (ANOVA) was performed to obtain the effects and their significance level of each control factor on the individual evaluation indexes and the SEI. The results of ANOVA were presented, as listed in Table 6. As seen from Table 6, slice thickness had a significant effect on EMD at confidence level 97.06%. Temperature had a significant effect on EMD at confidence level 91.08%. Slice thickness had a significant effect on drying time at confidence level 95.48%. Temperature had a significant effect on drying time at confidence level 90.83%. Slice thickness had a significant effect on SEC at confidence level 90.20%. As for SEI, temperature had a significant effect at confidence level 96.29%.

Table 6

Analysis of variance

Evaluation indexes	Source of variance	Degree of freedom	Sum of squares	Mean sum of square	F-ratio	Critical F-ratio
EMD	Factor A	2	24.555	12.277	10.207	$F_{0.0892}(2, 2) = 10.207$(*)
	Factor B	2	79.311	39.655	32.967	$F_{0.0294}(2, 2) = 32.967$*
	Factor C	2	3.290	1.645	1.368	$F_{0.4223}(2, 2) = 1.368$
	Error	2	2.406	1.203	/	/
	Total	8	109.561	/	/	/
TCD	Factor A	2	51.646	25.823	3.719	$F_{0.2119}(2, 2) = 3.719$
	Factor B	2	22.386	11.193	1.612	$F_{0.3828}(2, 2) = 1.612$
	Factor C	2	16.557	8.279	1.192	$F_{0.4562}(2, 2) = 1.192$
	Error	2	13.885	6.943	/	/
	Total	8	104.475	/	/	/
SEC	Factor A	2	570.327	285.163	1.428	$F_{0.4119}(2, 2) = 1.428$
	Factor B	2	3674.281	1837.141	9.199	$F_{0.0980}(2, 2) = 9.199$(*)
	Factor C	2	530.640	265.320	1.329	$F_{0.4294}(2, 2) = 1.329$
	Error	2	399.407	199.703	/	/
	Total	8	5174.654	/	/	/
Drying time	Factor A	2	11759.538	5879.769	9.900	$F_{0.0917}(2, 2) = 9.900$(*)
	Factor B	2	25098.674	12549.337	21.130	$F_{0.0452}(2, 2) = 21.130$*
	Factor C	2	1221.226	610.613	1.028	$F_{0.4931}(2, 2) = 1.028$
	Error	2	1187.819	593.909	/	/
	Total	8	39267.256	/	/	/
SEI	Factor A	2	0.091	0.045	25.928	$F_{0.0371}(2, 2) = 25.928$*
	Factor B	2	0.010	0.005	2.787	$F_{0.2641}(2, 2) = 2.787$
	Factor C	2	0.006	0.003	1.709	$F_{0.3691}(2, 2) = 1.709$
	Error	2	0.004	0.002	/	/
	Total	8	0.110	/	/	/

Notes: * indicates the significance of effect at confidence level higher than 95%; (*) indicates the significance of effect at confidence level higher than 90%.

According to statistics of range analysis (*Yang, L. et al, 2019*), the optimal combinations of control factors' levels for individual evaluation indexes and SEI were obtained as: EMD: B3A3C1; TCD: A3B3C2; SEC: B1A3C2; drying time: B1A3C1; SEI: B1A3C2. The sequence of characters in the combinations indicated the significance of the control factor with a decrease mode. The numbers in the combinations indicated the levels of the corresponding control factors. Therefore, the optimal combinations for SEI were slice thickness 3 mm, temperature 70ºC, and steaming time 6 min.

The experimental data of moisture ratio of the orthogonal experiment were fitted into the selected mathematical models (Table 5). The model parameters and accuracy of approximation were shown in Table 7. The higher the R^2 values and the lower the χ^2 and RMSE values were, the better the approximation was (*Wang, Z. F. et al, 2007*). As seen from Table 7, Midilli et al. model (Model 4) gave the best approximation to experimental data of moisture ratio, with R^2 0.99933, χ^2 0.00007, and RMSE 0.00838. To validate the effectiveness of Midilli et al. model, experiments of combinations that were different from those in Table 3 were conducted. The profiles of experimental and calculated moisture ratio at different drying conditions were plotted, as shown in Fig. 6. The experimental results agreed well with calculated data (mean coefficient of determination 0.99857, mean relative error 12.15%), and the accuracy of the approximation was presented, as listed in Table 8.

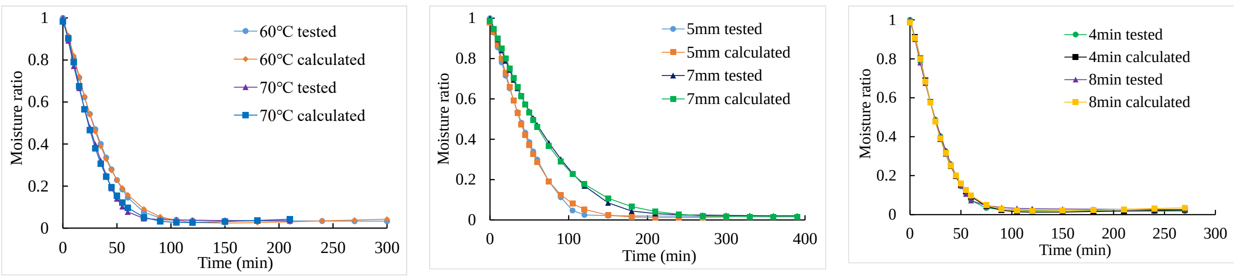
Temperature-varying experiment

The profiles of moisture ratio and drying rate of sweet potato slice at different drying conditions by temperature-varying experiment were plotted, as shown in Fig. 7. The visual observations of dried sweet potato slice of different technology were presented, as shown in Fig. 5 b. The corresponding values of TCD, SEC, and SEI were calculated, as listed in Table 4. Same weights were applied to TCD and SEC for the calculation of SEI. As seen from Table 4, drying mode of temperature-decrease, namely, No. 2 under drying conditions of 70ºC (75min) - 65ºC (to end) showed the minimum SEI 0.2678. Then, drying mode of No.2 was the optimal temperature-varying drying technology. If same weights were applied to results of No. 2 and No. 3 in Table 1, their resultant values of SEI were 0.3288 and 0.3287, respectively. Therefore, there were 18.55 % and 29.28% decrease of SEI by the optimal temperature-varying drying technology compared to the optimal traditional temperature-constant drying technologies 65ºC and 70ºC, respectively. The experiments of No. 2 and No. 3 were the temperature-constant IR drying technologies under same conditions of slice thickness 3 mm and steaming time 6 min as temperature-varying IR drying technology, while their temperatures were 65ºC and 70ºC, respectively.

Table 7

Statistical analysis of mathematical models

Model	Parameters	values									Mean values
		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	
1	k	0.00960	0.00945	0.00795	0.01072	0.00944	0.00799	0.01431	0.00897	0.01025	/
	n	1.25783	1.12191	1.08799	1.28723	1.16915	1.13689	1.26790	1.22587	1.14359	/
	R2	0.99753	0.99781	0.99855	0.99882	0.99809	0.99914	0.99686	0.99894	0.99911	0.99832
	χ2	0.00026	0.00024	0.00017	0.00012	0.00021	0.00010	0.00030	0.00012	0.00010	0.00018
	RMSE	0.01618	0.01553	0.01313	0.01117	0.01449	0.01006	0.01726	0.01087	0.00996	0.01318
2	a	-477.704	-0.24228	-0.14477	-40.3014	47.8823	-25.0392	72.8883	95.6354	27.5444	/
	b	478.699	1.23978	1.14322	41.2945	-46.8867	26.0344	-71.8932	-94.6424	-26.5473	/
	k1	0.04577	0.04909	0.04172	0.05601	0.03104	0.02339	0.06471	0.03804	0.02931	/
	k2	0.04570	0.01866	0.01325	0.05498	0.03143	0.02291	0.06537	0.03831	0.02990	/
	R2	0.99739	0.99778	0.99856	0.99873	0.99812	0.99928	0.99668	0.99900	0.99921	0.99831
	χ2	0.00028	0.00024	0.00017	0.00013	0.00021	0.00008	0.00031	0.00011	0.00009	0.00018
	RMSE	0.01661	0.01562	0.01308	0.01162	0.01438	0.00920	0.01775	0.01054	0.00934	0.01313
3	a	537.501	1.24476	1.14546	503.288	1289.708	-161.250	-124.412	-545.642	1337.069	/
	k	0.04550	0.01868	0.01326	0.05510	0.03102	0.02298	0.06494	0.03787	0.02945	/
	g	0.04556	0.04785	0.04073	0.05518	0.03104	0.02291	0.06465	0.03783	0.02946	/
	R2	0.99751	0.99788	0.99861	0.99877	0.99819	0.99930	0.99683	0.99902	0.99924	0.99837
	χ2	0.00026	0.00023	0.00016	0.00013	0.00020	0.00008	0.00030	0.00011	0.00008	0.00017
	RMSE	0.01623	0.01528	0.01283	0.01143	0.01410	0.00910	0.01734	0.01044	0.00916	0.01288
4	a	0.98850	0.98943	0.99131	0.98738	0.98525	0.98588	0.99014	0.98472	0.98880	/
	k	0.00801	0.00752	0.00640	0.00921	0.00756	0.00660	0.01253	0.00748	0.00891	/
	n	1.30785	1.18113	1.14118	1.32834	1.22499	1.18059	1.30771	1.26985	1.17707	/
	b	0.00011	0.00010	0.00006	0.00007	0.00008	0.00003	0.00017	0.00003	0.00003	/
	R2	0.99931	0.99958	0.99976	0.99928	0.99926	0.99945	0.99888	0.99913	0.99930	0.99933
	χ2	0.00007	0.00005	0.00003	0.00008	0.00008	0.00006	0.00011	0.00010	0.00008	0.00007
	RMSE	0.00854	0.00683	0.00533	0.00877	0.00904	0.00802	0.01029	0.00984	0.00879	0.00838
5	a	0.95283	0.99285	0.00730	0.90394	0.93144	0.91810	0.95821	0.87313	0.86603	/
	b	0.00629	0.00885	-0.00132	0.00464	0.00506	0.00375	0.01017	0.00275	0.00331	/
	c	1.35618	1.13585	1.13838	1.48775	1.30370	1.28985	1.35348	1.48873	1.38033	/
	d	0.04758	0.00715	0.98453	0.09550	0.06872	0.08087	0.04183	0.12488	0.13287	/
	g	0.09754	0.36186	0.00649	0.06140	0.06906	0.04594	0.20015	0.03467	0.03394	/
	R2	0.99729	0.99749	0.99974	0.99907	0.99809	0.99935	0.99650	0.99953	0.99945	0.99850
	χ2	0.00029	0.00028	0.00003	0.00010	0.00021	0.00008	0.00033	0.00005	0.00006	0.00016
	RMSE	0.01692	0.01663	0.00553	0.00993	0.01449	0.00876	0.01823	0.00721	0.00779	0.01172



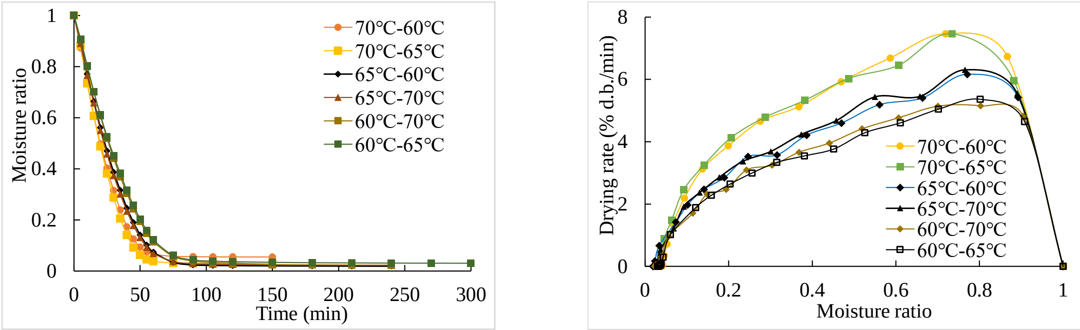
(a) Different temperature (b) Different slice thickness (c) Different steaming time

Fig. 6 - Validation of Midilli et al. model under different drying conditions

Table 8

Accuracy of the approximation of Midilli et al. model under different drying conditions

No.	Factor A [°C]	Factor B [mm]	Factor C [min]	R^2	Relative error [%]
1	60	3	6	0.99915	9.42
2	70			0.99810	10.59
3	65	5	6	0.99806	16.17
4		7		0.99899	9.87
5	65	3	4	0.99890	13.48
6			8	0.99823	13.38



(a) Moisture ratio vs. drying time (b) Drying rate vs. moisture ratio

Fig. 7 - Drying curves of sweet potato slice by temperature-varying experiment

CONCLUSIONS

A laboratory IR dryer was developed to study the drying characteristics of sweet potato slice, to investigate the effects of control factors and their significance on drying performance, and to optimize the IR drying technology. Main conclusions were drawn as follows:

- Temperature-varying IR drying technology of temperature-decrease mode, under drying conditions of 70ºC (75min) - 65ºC (to end), showed the best drying performance while considering TCD and SEC, with 18.55% and 29.28% decrease of SEI compared to temperature-varying IR drying technologies of 65ºC and 70ºC, respectively.

- The significance order of the effects of control factors on the SEI was: temperature, slice thickness and steaming time, in a sequence of decrease. Temperature was significant at confidence level 96.29%. The optimal combinations for temperature-constant were slice thickness 3 mm, temperature 70ºC, and steaming time 6 min.

- Midilli et al. model gave the best approximation to experimental data of moisture ratio, with R2 0.99933, χ2 0.00007, and RMSE 0.00838. The results of validation experiment agreed well with calculated data of Midilli et al. model, with R2 0.99857 and mean relative error 12.15%.

- Temperature of 75ºC and slice thickness of 9 mm were not suitable for IR drying of sweet potato slice because the former resulted in high TCD and the latter resulted in high SEC. Steaming time had little effect on the IR drying performance.

ACKNOWLEDGEMENTS

The study was funded by Chongqing Science and Technology Bureau (cstc2019jscx-gksbx0108); Chongqing Municipal Education Commission (kjcx2020002); Key Lab of Modern Agricultural Equipment, Ministry of Agriculture and Rural Affairs, China (ht20200705).

REFERENCES

[1] Chandrasekar M., Senthilkumar T., Kumaragurubaran B., Fernandes, J. P., (2018). Experimental investigation on a solar dryer integrated with condenser unit of split air conditioner (A/C) for enhancing drying rate. *Renewable Energy*, Vol. 122, pp. 375-381, England, DOI: 10.1016/j.renene.2018.01.109;

[2] Doymaz İ., (2012). Infrared drying of sweet potato (*Ipomoea batatas* L.) slices. *Journal of Food Science and Technology*, Vol. 49, Issue 6, pp. 760-766, New Delhi / India, DOI: 10.1007/s13197-010-0217-8;

[3] Guine R. P. F., Brito M. F. S., Ribeiro J. R. P., (2017). Evaluation of mass transfer properties in convective drying of kiwi and eggplant. *International Journal of Food Engineering*, Vol. 13, Issue 7, pp. 1-13, Berlin/Germany, DOI: 10.1515/ijfe-2016-0257;

[4] Hanim A. B. M., Chin N. L., Yusof Y. A., (2014). Physico-chemical and flowability characteristics of a new variety of Malaysian sweet potato, VitAto flour. International Food Research Journal, Vol. 21, Issue 5, pp. 2099-2107, ISSN 1985-4668;

[5] He J., Cheng L., Hong Y., Gu Z., Li Z., (2013). Optimization of compound color fixative without sulfur during sweet potato flour processing (甘薯全粉加工中无硫复合护色工艺优化). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 29, Issue 9, pp. 275-284, Chinese Society of Agricultural Engineering, Beijing/P.R.C.; DOI: 10.3969/j.issn.1002-6819.2013.09.035;

[6] Henderson S. M., (1974). Progress in developing the thin layer drying equation. *Transactions of the American Society of Agricultural Engineers*, Vol. 17, pp.1167-1172, USA, ISSN: 0001-2351;

[7] Hii C. L., Law C. L., Cloke M., (2009). Modeling using a new thin layer drying model and product quality of cocoa. *Journal of Food Engineering*, Vol. 90, Issue 2, pp. 191-198, England, DOI: 10.1016/j.jfoodeng.2008.06.022;

[8] Huang X., Li W., Wang Y., Wan F., (2021). Drying characteristics and quality of stevia rebaudiana leaves by far-infrared radiation. *LWT-Food Science and Technology*, Vol. 140, 110638, Ed. ELSEVIER, Amsterdam/Netherlands, DOI: 10.1016/j.lwt.2020.110638;

[9] Li B., Lin J., Zheng Z., Duan H.; Li D., Wu M., (2019). Effects of different drying methods on drying kinetics and physicochemical properties of Chrysanthemum morifolium Ramat. *International Journal of Agricultural and Biological Engineering*, Vol. 12, Issue 3, pp. 187-193, Beijing/PRC, DOI: 10.25165/j.ijabe.20191203.4820;

[10] Liu B., Lyu X., Wang C., Sun J., Jiang W. (2020). Process optimization of high temperature and short time hot air treatment to promote the callus formation of sweet potatoes (高温短时热空气处理促进甘薯愈伤的工艺优化). *Transactions of the Chinese Society of Agricultural Engineering*, Vol.36, Issue 19, pp.313-322, Beijing/PRC, DOI: 10.11975/j.issn.1002-6819.2020.19.036;

[11] Midilli A., Kucuk H., Yapar Z., (2002) A new model for single layer drying. *Drying Technology*, Vol. 20, Issue 7, pp. 1503-1513, USA, DOI: 10.1081/DRT-120005864;

[12] Oh S., Ramachandraiah K., Hong G. P., (2017). Effects of pulsed infra-red radiation followed by hot-press drying on the properties of mashed sweet potato chips. *LWT-Food Science and Technology*, Vol. 82, pp. 66-71, Ed. ELSEVIER, Amsterdam/Netherlands, DOI: 10.1016/j.lwt.2017.04.023;

[13] Onwude D. I., Hashim N., Abdan K., Janius R., Chen G. N., (2018). The effectiveness of combined infrared and hot-air drying strategies for sweet potato. *Journal of Food Engineering*, Vol. 241, Jan., pp. 75-87, Ed. ELSEVIER, Netherlands, DOI: 10.1016/j.jfoodeng.2018.08.008;

[14] Onwude D. I., Hashim N., Abdan K., Janius R.; Chen G.N., (2019). Experimental studies and mathematical simulation of intermittent infrared and convective drying of sweet potato (*Ipomoea Batatas* L.). *Food and Bioproducts Processing*, Vol. 114, pp. 163-174, England, DOI: 10.1016/j.fbp.2018.12.006;

[15] Onwude D. I., Hashim N., Abdan K., Janius R., Chen G. N., Kumar C., (2018). Modelling of coupled heat and mass transfer for combined infrared and hot-air drying of sweet potato. *Journal of Food Engineering*, Vol. 228, pp. 12-24, England, DOI: 10.1016/j.jfoodeng.2018.02.006;

[16] Onwude D. I., Hashim N., Chen G., Putranto A., Udoenoh N. R., (2021). A fully coupled multiphase model for infrared convective drying of sweet potato. *Journal of the Science of Food and Agriculture*, Vol. 101, Issue 2, pp. 398-413, Ed. WILEY, NJ/USA, DOI: 10.1002/jsfa.10649;

[17] Page G., (1949). Factors influencing the maximum rates of air-drying shelled corn in thin layer (MSc Thesis). Purdue University, WEST LAFAYETTE, IN/USA;

[18] Pasławska M., Sala K., Nawirska-Olszańska A., Stepien B., Plaskowska E., (2020). Effect of different drying techniques on dehydration kinetics, physical properties, and chemical composition of lemon thyme. *Natural Product Communications*, Vol. 15, Issue 2, pp. 1-12, USA, DOI: 10.1177/1934578X20904521;

[19] Rashid M. T., Jatoi M. A., Safdar B., Wali A., Aadil R. M., Sarpong F., Ma H. L., (2020). Modeling the drying of ultrasound and glucose pretreated sweet potatoes: the impact on phytochemical and functional groups. *Ultrasonics Sonochemistry*, Vol. 68, No. 105226, Ed. Elsevier, Netherlands, DOI: 10.1016/j.ultsonch.2020.105226;

[20] Ren G, Zhang L, Zeng F, Li Y. B., Li L. L., Duan X., (2020). Effects of hot air drying temperature and tempering time on the properties of maize starch. *International Journal of Agricultural and Biological Engineering*, Vol. 13, Issue 6, pp. 236-241, PRC, DOI: 10.25165/j.ijabe.20201306.3362;

[21] Rojas M. L., Augusto P. E. D., (2018). Ethanol and ultrasound pre-treatments to improve infrared drying of potato slices. *Innovative Food Science & Emerging Technologies*, Vol. 49, pp. 65-75, Ed. ELSEVIER SCI LTD, OXON/ England, DOI: 10.1016/j.ifset.2018.08.005;

[22] Song F., Xu Y., Zhang J., Qi Y., Zhang Y., (2019). Research on the effects of different drying conditions on quality of potato powder (不同干燥条件对马铃薯粉品质影响的研究). *Cereals & Oils*, Vol. 32, Issue 8, pp. 79-82, Ed. SHANGHAI INSTITUTE OF FOOD SCIENCE, SHANGHAI/PRC, ISSN: 1008-9578;

[23] Stasiak M., Musielak G., Mierzwa D., (2020). Optimization method for the evaluation of convective heat and mass transfer effective coefficients and energy sources in drying processes. *Energies*, Vol. 13, Issue 24, No. 6577, Switzerland, DOI: 10.3390/en13246577;

[24] Trancoso-Reyes N., Ochoa-Martinez L. A., Bello-Perez L. A., Morales-Castro J., Estevez-Santiago R., Olmedilla-Alonso B., (2016). Effect of pre-treatment on physicochemical and structural properties, and the bioaccessibility of β-carotene in sweet potato flour. *Food Chemistry*, Vol. 200, pp. 199-205, Ed. Elsevier SCI LTD, Oxon/ England, DOI: 10.1016/j.foodchem.2016.01.047;

[25] Verma L. R., Bucklin R. A., Endan J. B., Wratten F. T., (1985). Effects of drying air parameters on rice drying models. *Transactions of the American Society of Agricultural Engineers*, Vol. 28, pp. 296-301, USA, ISSN: 0001-2351;

[26] Wang S., Nie S., Zhu F., (2016). Chemical constituents and health effects of sweet potato. *Food Research International*, Vol. 89, pp. 90-116, Ed. Elsevier, Netherlands, DOI: 10.1016/j.foodres.2016.08.032;

[27] Wang Z. F., Sun J. H., Liao X. J., Chen F., Zhao G. H., Wu J. H. Hu X. S., (2007). Mathematical modeling on hot air drying of thin layer apple pomace. *Food Research International*, Vol. 40, Issue 1, pp. 39-46, Ed. Elsevier, Netherlands, DOI: 10.1016/j.foodres.2006.07.017;

[28] Wu X., Zhang M., Le Y., Yu, D. X., (2020). Influence of ultrasonic pretreatments on drying kinetics and quality attributes of sweet potato slices in infrared freeze drying (IRFD). *LWT-Food Science and Technology*, Vol. 131, No. 109801, Ed. Elsevier, Amsterdam/Netherlands, DOI: 10.1016/j.lwt.2020.109801;

[29] Yang L., Yin X.F., Li S.T., Wu D. K., Xie S. Y, Yang M. J, (2019). Effects of osmotic dehydration and process conditions on infrared drying: application to drying of chili pepper. *International Agricultural Engineering Journal*, Vol. 28, Issue 3, pp. 266-275, Beijing/PRC, ISSN: 0858-2114;

[30] Zhang M., Chen H., Mujumdar A. S., Tang J. M., Miao S., Wang Y. C., (2017). Recent developments in high-quality drying of vegetables, fruits, and aquatic products. *Critical Reviews in Food Science and Nutrition*, Vol. 57, Issue 6, pp. 1239-1255, USA, DOI: 10.1080/10408398.2014.979280;

[31] *** China National Standardizing Committee, (2106). GB 5009.3-2016, D*etermination of moisture in foods*. Beijing: Chinese Standard Press, PRC.