International Food Research Journal 30(3): 626 - 639 (June 2023)
Journal homepage: *http://www.ifrj.upm.edu.my*

Moisture diffusion modelling and effect of microwave vacuum drying on drying kinetics and quality of yam

[1,2]Zhang, F. J., [1]Wang, X., [1]Xin, L. D., [1,2]*Li, L. X., [3]Dai, J. W. and [1]Zhou, J.

[1]*Faculty of Modern Agricultural Engineering, Kunming University of Science and Technology, Kunming 650500, Yunnan, China*
[2]*Mechanization Engineering Research Centre of Yunnan Province Colleges and Universities, Kunming 650500, Yunnan, China*
[3]*College of Mechanical and Electrical Engineering, Sichuan Agricultural University, Ya'an 625000, Sichuan, China*

Article history

Received:
4 May 2022
Received in revised form:
23 August 2022
Accepted:
23 November 2022

Keywords

yam,
microwave vacuum drying,
moisture diffusion,
quality,
drying kinetics

Abstract

Microwave vacuum drying (MVD) is a rapid drying method, which can achieve a good balance between drying rate and quality. In the present work, the effects of MVD processes on the quality, drying kinetics, and moisture diffusion of yam (*Dioscorea opposita* L.) were investigated. Results indicated that the loss of moisture in the MVD of yam slices mainly occurred in the stage with a constant and decreasing speed. When the moisture content of the dry base was decreased to about 1.3 g/g (dry basis, D.B.), it began to enter the deceleration phase. The effective moisture diffusivity (D_{eff}) and mass transfer coefficient (k_m) increased following the power, loading amount at one time, and vacuum (pressure drop). The established equation of these parameters described well this variation law. Furthermore, a neural network model was established to predict the change in moisture content in the drying process, and the law of moisture diffusion was described. In terms of quality, the contribution ranked from high to low was loading, power, and pressure. Increasing the microwave power, loading, and maintaining a high vacuum degree could reduce energy consumption and ensure quality, thus improving the economic feasibility of microwave vacuum in the drying process.

Nomenclature

A_p: sample surface area (m^2); a^*: red-blue colour (+ for red, - for blue); b^*: yellow-blue colour (+ for yellow, - for blue); D_0: pre-exponential factor of the Arrhenius equation (m^2/s); D_{eff} : effective moisture diffusivity ($m^2 \cdot h^{-1}$); *DR:* drying rate (*g/(g·h)*); *E*: unit energy consumption (W·h/g); E_{ad}: activation energy for the diffusion model (W/g); E_{am}: activation energy for the mass transfer model (W/g); *i*: evaluation index, values of 1~3 (-); *j*: orthogonal test serial number, values of 1~16 (-); k_m: mass transfer coefficient (m/h); k_0 : pre-exponential factor of the Arrhenius equation (m/s); *L*: material thickness (m); L^*: lightness (0 = black, 100 = white); m_0: initial mass of sample (kg); *MR*: moisture ratio (-); M_t: moisture content (wt% db); M_0: initial moisture content (wt% db); M_e: equilibrium moisture content (wt% db); $MR_{exp,i}$: i-th experimental moisture ratio (-); $MR_{pre,i}$: i-th predicted moisture ratio (-); *N*: number of observations (-); P_1: power of microwave (W); P_2: power of vacuum machine (W); R^2: correlation coefficient (-); RMSE: root mean square error (-); R_f: rehydration rate (%); *t*: drying time (s); V_p: sample volume (m^3); W_R: w (-); W_{ij}: j-th test of the i-th index (-); W_{ijmax}: maximum measured by the i-th index test (-); and X_{ij}: index score of the j-th test of the i-th index (-).

DOI
https://doi.org/10.47836/ifrj.30.3.07

Introduction

Yam (*Dioscorea opposita* L.) is one of the traditional medicinal and food plants in China. At a normal temperature, yams are easily affected by microorganisms and enzymes, which results in decay and deterioration. Drying is thus an important approach for ensuring the nutritional value of yams,

*Corresponding author.
Email: lilixia2012@kust.edu.cn

and prolonging the industrial value of dried yam products.

At present, the methods used for drying and dehydration of yams mainly include vacuum freeze drying (FVD), hot air drying (HAD), microwave-coupled hot-air drying (MCHD), and microwave-vacuum drying (MVD) (Suriya *et al.*, 2016; Patel and Sutar, 2016; Wang *et al.*, 2019; Ojediran *et al.*, 2020). MVD is a rapid combined drying technology that combines the advantages of microwave and vacuum drying. The microwave uses the electromagnetic wave of 2,450 MHz to directly act on the moisture inside the material, thus achieving rapid heating; in the vacuum environment, the decrease in the boiling point of water is conducive to the outward diffusion of moisture, while the lack of air preserves the colour of the material. The product quality of MVD is higher than that of HAD and is close to that of FVD (Erle and Schubert, 2001; Wojdylo *et al.*, 2014). MVD can greatly shorten the drying time, improve the drying efficiency, and reduce the production cost; so, it has outstanding technical advantages (Zielinska *et al.*, 2013; Maurya *et al.*, 2018). Currently, it has been used in the drying processing of strawberries, tomatoes, and mushrooms (Borquez *et al.*, 2015; Orikasa *et al.*, 2018; Politowicz *et al.*, 2018).

For the yams, Kim *et al.* (2005) investigated the drying characteristics and quality of yam slices by drying methods, and they found that MVD achieved the shortest drying time, caused much less surface damage than HAD, and had the best overall properties in colour, shape, and drying rate. Huang *et al.* (2015) used MVD to replace the latter part of the FD of yams, and it was found that the drying quality and colour were similar to that of FD, and MVD could effectively shorten the drying time. Although much research effort has been dedicated to the drying characteristics and quality of MVD of yam, its drying moisture mass transfer law and the relationship between energy consumption and quality are less studied.

In the real situation, the drying kinetics of the Chinese yam is complicated. It needs to be simplified by mathematical equations and parameters to predict the drying behaviour and optimise the drying parameters to improve the yam quality. The calculation of mass transfer parameters is essential because it helps to understand the law of moisture transfer, and establish more complex and accurate mathematical models. Meanwhile, neural network models are developed rapidly in recent years, which can perform feedback and learning independently. The BP neural network is a multi-layer feedforward neural network, which is mainly composed of the input, hidden, and output layers. It can better predict the drying process or temperature change of materials in the drying of materials (Bai *et al.*, 2018), and help to investigate the internal mass and heat transfer methods of materials (Kaveh *et al.*, 2018). Based on the research on the mass transfer parameters, it is also important for practical production to study the relationship between energy consumption and quality due to the increasingly serious energy situation in the world. Besides, the mass transfer mathematical models can be built to reduce energy consumption while ensuring quality.

Therefore, the present work aimed to (1) study the drying kinetics of yam slices by MVD, (2) calculate the mass transfer parameters (moisture diffusivity, mass transfer coefficient, and activation energy and models) to explore the law of water transfer, and (3) optimise process (unit energy consumption, rehydration rate, and whiteness) by balancing energy consumption and product quality. Results of the present work would provide a reference for the mass drying of yam.

Materials and methods

Sample preparation and drying experiment process

Yam was purchased from Wujiaying fresh market (Kunming, China). Then, the fresh yam (fresh, without mechanical damage, and the size of the yam tablet was φ30~40 mm) was washed, and the epidermis was peeled off. Then, it was sliced into a thickness of 6 ± 0.1 mm, and evenly spread in a round glass plate (200 mm diameter). The drying experiment was conducted in the MVD equipment (H-MVD 2020, Hueray Microwave Tech. Co., Ltd., Chengdu, China) with an insulated drying chamber (50 cm length × 45 cm width × 50 cm height) as shown in Figure 1. The purpose of this was to investigate the effects of different microwave power, loading, and chamber pressure on MVD characteristics and mass transfer parameters of yam slices. Based on preliminary experiment, the test parameters were: power (250, 300, 350, and 400 W), loading pressure (50, 60, 70, and 80 g), and chamber pressure (5, 10, 15, and 20 kPa). Single-factor tests were carried out by adopting the control variable method (control power 350 W, loading 60 g, pressure 10 kPa). The initial average moisture content of the

Chinese yam was 82.6 ± 0.5% (w.b.), which was measured at 105°C for 24 h by the oven method. In the experiment, the change of sample quality was recorded every 5 min by a vacuum cavity online weighing system, and the tests were terminated when the wet base moisture content of the yam slices decreased below 12 kg water/100 kg product (Chinese Pharmacopoeia Commission, 2015). All samples were measured in triplicate. Subsequently, to further optimise the drying parameters, an orthogonal experiment with three factors and four levels (L_{16} (4^5)) was conducted with the unit energy consumption, rehydration rate, and whiteness as evaluation indices. Finally, the evaluation index scores of the optimal process parameters of the orthogonal test were obtained and compared with those of hot-air drying (60°C, 4 h) (Ju *et al.*, 2016), in terms of energy consumption and quality to determine its feasibility and applicability.

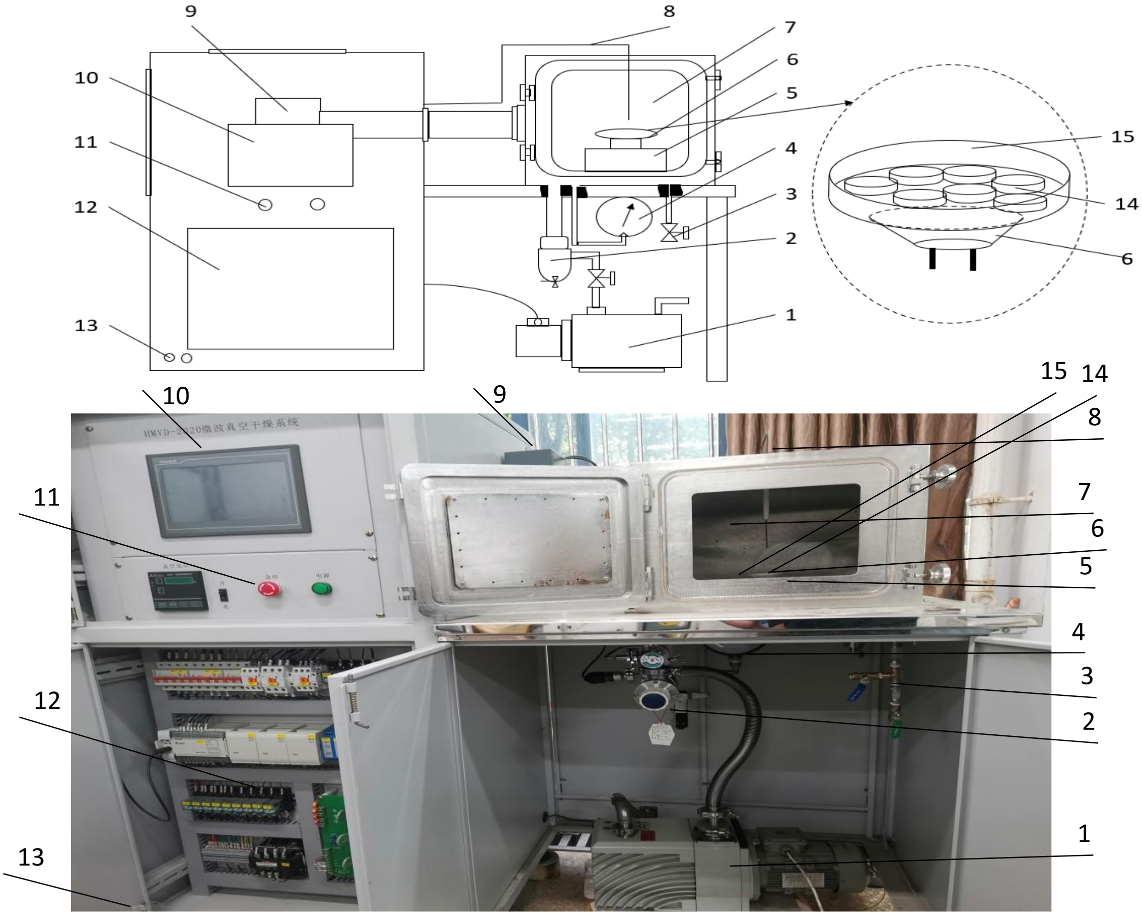

Figure 1. Schematic diagram of MVD. 1: vacuum pump; 2: condenser; 3: air solenoid valve; 4: vacuum pressure gauge; 5: metal shell electronic scale; 6: weighing plate; 7: drying chamber; 8: fibre sensor; 9: magnetron component; 10: industrial control touch all-in-one machine; 11: switch; 12: electronic control part; 13: water inlet; 14: tiled yam slices; and 15: glass tray.

Modelling of drying kinetics

During drying, moisture diffuses from the inside to the surface of the material. This leads to the mass transfer of water to the outside of the material through evaporation. During the experiment, the mass displayed by the online weighing system (with a resolution of 0.1 g) was read regularly (every 5 min), and the moisture ratio (MR) of the yam slices under different drying conditions was calculated using Eq. 1 (Kipcak and Ismail, 2020):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad \text{(Eq. 1)}$$

where, M_0 = initial dry basis moisture content, $g \cdot g^{-1}$; M_e = dry basis moisture content when the yam tablet was dried to equilibrium, $g \cdot g^{-1}$; and M_t = dry basis moisture content at any time t, $g \cdot g^{-1}$.

The drying rate (DR) of the yam slices during drying was then determined using Eq. 2.

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \quad \text{(Eq. 2)}$$

where, DR = drying rate of the yam tablet between times t_1 and t_2 during the drying process, g/(g·h); and M_{t_1} and M_{t_2} = dry basis moisture content of the material during the drying process at times t_1 and t_2, $g{\cdot}g^{-1}$.

The experimental data were processed and statistically analysed with Excel 2013 (Microsoft, Washington, USA). The neural network toolbox in MATLAB 2019 (The Math Works, MA, USA) was employed to establish and fit the model. A total of 175 groups of data were collected, where the moisture ratio (MR) of the yam slices decreased from the initial value to the drying completion under different microwave powers, chamber pressures, and loading capacities. When the BP model was used to fit the drying curve, the cross-verification method was adopted. That is, all the data were randomly selected based on the ratio of training data to verification and test data = 0.76: 0.12: 0.12. In the grouped data, the training data were used to train the BP model, and the verification data were used to verify and modify the training effect. Finally, the fitting effect was determined by the test data.

The goodness of fit and prediction accuracy of the neural network model was expressed by the coefficient of determination (R^2) and the root mean square error (RMSE). The closer the value of R^2 to 1, and the closer the RMSE to zero, the better the performance of the model (Turan and Firatligil, 2019). The calculation formulas of R^2 and RMSE are as Eq. 3 and 4, respectively:

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)\left(MR_i - MR_{\exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)^2\right]\left[\sum_{i=1}^{N}\left(MR_i - MR_{\exp,i}\right)^2\right]}} \quad \text{(Eq. 3)}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \quad \text{(Eq. 4)}$$

Mass transfer parameters

The effective water diffusion coefficient is a quantified indicator of the water migration speed during the drying process. The effective water diffusion coefficient (D_{eff}) under different drying conditions was approximately calculated using Eq. 5 (Vishwanathan *et al.*, 2010).

$$\ln M_R = ln\frac{6}{\pi^2} - \frac{\pi^2 D_{\mathrm{eff}}}{L^2}t \quad \text{(Eq. 5)}$$

where, D_{eff} = effective water diffusion coefficient of the yam tablet during the drying process, m^2/s; L = thickness of the yam tablet, *m*; and t = drying time, *s*.

The thickness of the yam slices was measured by a Vernier calliper (601-01, HMCT Group, Harbin, China) with a resolution of 0.02 mm. Three yam slices were randomly selected three times, and the average value was calculated.

The mass transfer coefficient of the yams during the drying process was determined using Eq. 6 (Kaya *et al.*, 2010):

$$k_m = -\frac{V_P}{A_p \times t}\ln(MR) \quad \text{(Eq. 6)}$$

For a symmetrically heated circular slice, V/A was equal to L. Thus, for the yam slices, Eq. 6 can be simplified as using Eq. 7:

$$k_m = -\frac{L}{t}\ln(MR) \quad \text{(Eq. 7)}$$

In MVD, the temperature was difficult to control, so the improved Arrhenius equation was adopted to calculate the activation energy (Darvishi, 2017):

$$D_{eff} = D_0 \exp\left(\frac{E_{ad} m_0}{P}\right) \quad \text{(Eq. 8)}$$

$$k_m = k_0 \exp\left(-\frac{E_{am} m_0}{P}\right) \quad \text{(Eq. 9)}$$

Quality aspects

Some yam slices (6~7 g) obtained by the orthogonal experiment of MVD were weighed and quickly placed in a beaker containing distilled water of 65°C. After 2 h, the surface was removed and weighed. The rehydration rate was calculated as using Eq. 10:

$$R_f = \frac{m_2 - m_1}{m_1} \times 100\% \quad \text{(Eq. 10)}$$

In the present work, the vacuum machine (1) had a power of 370 W, and it was turned on at the same time as the magnetron assembly (7). The energy consumption was calculated using Eq. 11:

$$E = \frac{(P_1 + P_2)t}{3600 m_0} \quad \text{(Eq. 11)}$$

Then, colour difference analysis was performed on the yam slice samples dried in the microwave vacuum by using a CR-400 colour difference meter (Konica Minolta Holdings, Inc., Tokyo, Japan), and the calibration was performed following the instructions. The yam slices were ground into a powdery mixture, and the L^*, a^*, and b^* values were measured and substituted into the Hunter whiteness formula (Eq. 12) to calculate the whiteness.

$$W_R = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \quad \text{(Eq. 12)}$$

Comprehensive score

To ensure fast drying, energy saving, and good quality, the unit energy consumption, rehydration rate, and whiteness were selected as the evaluation indices of the orthogonal test. Meanwhile, the comprehensive scoring method was employed to calculate the score of each index by weight and obtain the comprehensive score based on percentage. Considering the priority of energy consumption and rehydration performance, the colour was considered secondly, and the weights of the unit energy consumption, rehydration rate, and whiteness index were set to 0.3, 0.4, and 0.3, respectively. The index score was calculated using Eq. 13:

$$X_{ij} = \frac{w_{ij}}{w_{ij_{max}}} \quad \text{(Eq. 13)}$$

Results and discussion

Law of drying kinetics

The drying curve of the yam slices under different microwave powers, loading, and chamber pressures is shown in Figures 2a, 2c, and 2e, respectively. Under different drying conditions, the drying time ranged from 39 to 70 min. With the increase in power and vacuum, and the decrease in loading pressure, the drying time decreased by 44.3, 25.8, and 38.1%, respectively. The drying time was extremely low as compared to Duan *et al.* (2019) for MFD of yam slices (150 - 180 min), and De Vera *et al.* (2017) for HAD (100 - 260 min). So, MVD had higher efficiency than other drying methods.

As shown in Figures 2b, 2d, and 2f, the whole drying process was divided into three stages: the rapid increase, constant rate, and falling rate stage. The overall drying rate was increased by the increase in microwave power and the decrease in loading and chamber pressure. The results were consistent with those of Si *et al.* (2016). However, during the drying process, it was also found that when the microwave power was 400 W, substantial cooking would occur due to the high internal temperature of the material, which affected the quality of dried yam slices.

In the initial stage of drying, the samples in the preheating period had a high moisture content, high absorption of microwave power, and a large drying rate. With the progress of the drying process, it was found that there was a constant rate stage. In this stage, most of the water was transferred and escaped from the material. The water diffusion was mainly controlled by external diffusion, and the energy was mainly used for the evaporation of water. By increasing the microwave power, and decreasing the loading and chamber pressure, the drying rate increased in this stage; a large amount of water evaporated quickly, which shortened the overall drying time. This might have been due to the increase in microwave energy and temperature, which increased the temperature gradient with the outside, and accelerated the outward diffusion of water. At lower atmospheric pressure, the boiling point of water decreased significantly, which was beneficial to water diffusion (Monteiro *et al.*, 2018).

As the drying process continued, the resistance of mass and heat transfer increased continuously. When the moisture content of the dry base was decreased to the range of 1.2 to 1.4 g/g (D.B.), the drying process entered the falling stage. In this stage, the variation in drying rate was related to the material properties and the internal structure, and the drying loss was mainly controlled by internal diffusion. The decrease in drying rate was due to the basic removal of free water, the main removal of combined water, the inward movement of the vaporisation surface, the gradual decrease in equilibrium steam pressure, and the decrease in mass transfer driving force.

Relationship between mass transfer and process parameters

In the constant rate stage, the thickness of the material decreased from 6 ± 0.1 to 4.1 ± 0.1 mm, and the middle thickness 5.05 mm was taken as the average thickness of this stage; in the falling rate stage, the average thickness of the material was 4 mm. The variation of the mass transfer coefficient and effective moisture diffusivity (D_{eff}) under different drying conditions (power, load, and pressure) are shown in Figure 3. In the constant rate stage, the values of the mass transfer coefficient varied from

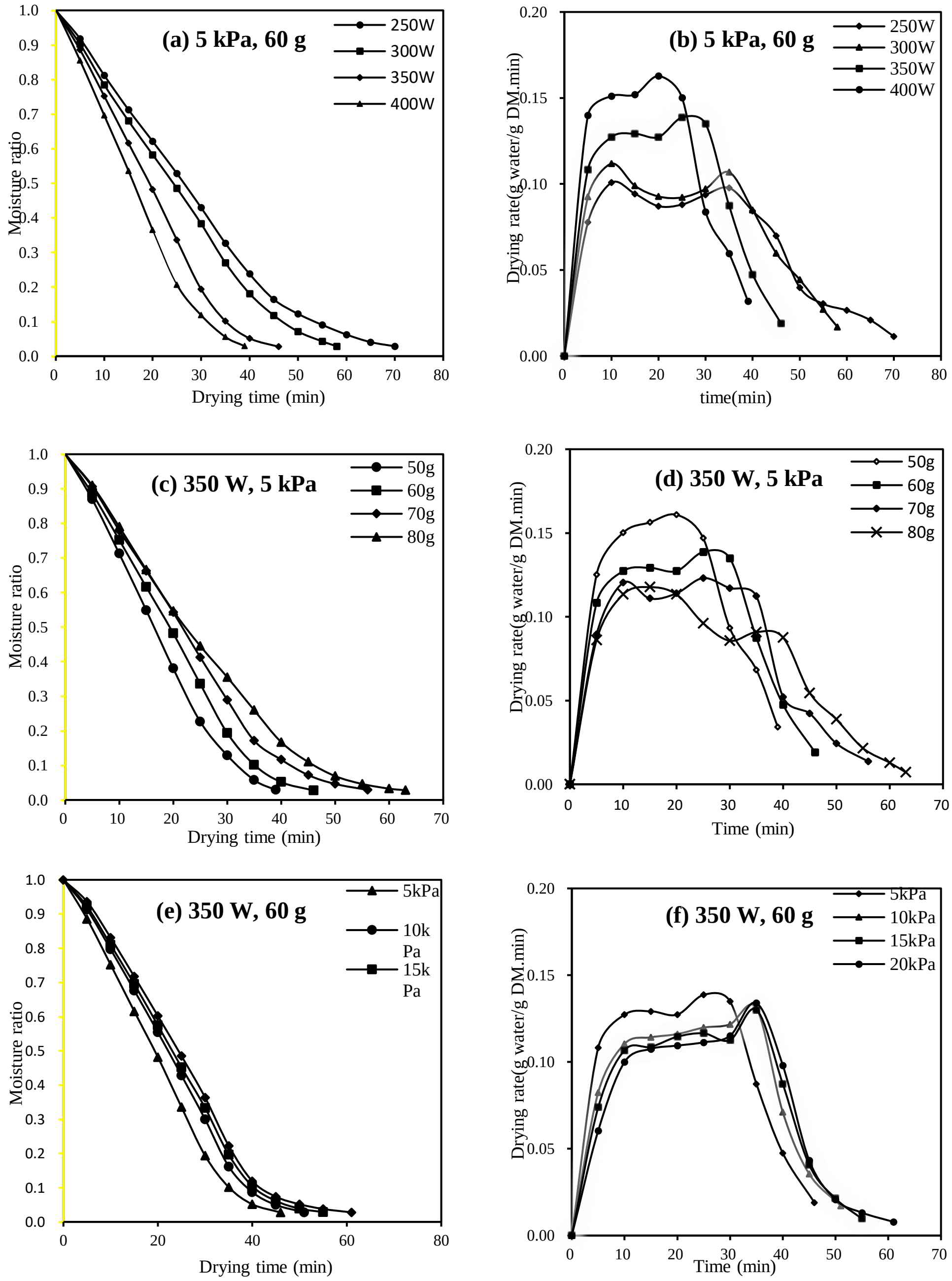

Figure 2. Drying kinetics curves of yam samples at different **(a)** power, **(c)** load, and **(e)** vacuum; the drying rate curves of yam samples at different **(b)** power, **(d)** load, and **(f)** vacuum.

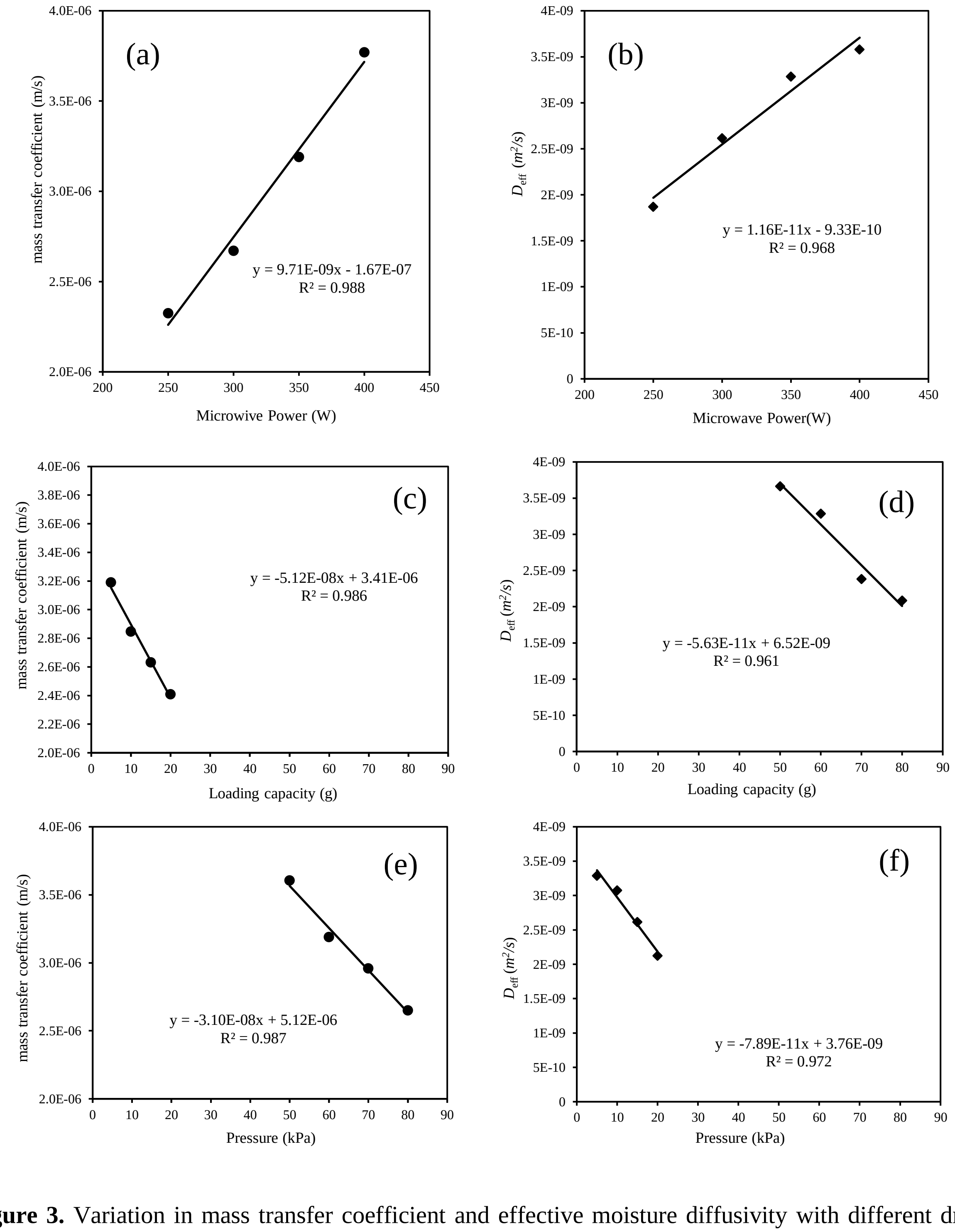

Figure 3. Variation in mass transfer coefficient and effective moisture diffusivity with different drying conditions (power, load, and pressure).

2.33 to 3.77 × 10^{-6} m/s under different drying conditions. Obviously, k_m (the mass transfer coefficient) was directly proportional to the microwave power and inversely proportional to the load and pressure. This is because when the yam slices were dried at a higher power or lower loading, the increased heating energy increased the temperature of the material and the activity of water molecules, thus leading to an increase in water evaporation and showing a higher diffusion coefficient; when the yam slices are dried under a lower chamber pressure, the vacuum affected the boiling temperature of the water and reduced the resistance of water vapour diffusion, thus leading to higher water diffusivity. Besides, these values were comparable from 2.71 to 19.98 × 10^{-6} m/s in the drying of soybean (Darvishi, 2017), and 4.68~10.06 × 10^{-7} m/s in the drying of celeriac (Beigi, 2017).

It can be seen from Figure 3 and Table 1 that the ranges of effective water diffusion coefficients (D_{eff}) in the falling rate stage of yam slices under different power (from 250 to 400 W), loading (from 80 to 50 g), and pressure (from 20 to 5 kPa) are 1.87~3.58, 2.09~3.66, and 2.12~3.29 × 10^{-9} m^2/s, respectively. The effective water diffusion coefficient of the yam slices was directly proportional to the power, and inversely proportional to the loading capacity and pressure. The reason for this phenomenon was consistent with that of the mass transfer coefficient. In the study conducted by Markowski *et al*. (2009), the effective moisture diffusivity values of potato cubes ranged between 1.17 and 4.73 × 10^{-9} m^2/s, which were consistent with the results obtained in the present work. However, it could be found that the R^2 of the effective moisture diffusivity was lower than that of the mass transfer coefficient.

Table 1. Fitting parameters of mass transfer coefficient and D_{eff}.

Condition		**Mass transfer coefficient (m/s)**
Microwave power/W	250	2.325E-06
	300	2.670E-06
	350	3.190E-06
	400	3.770E-06
Loading capacity/g	50	3.190E-06
	60	2.846E-06
	70	2.632E-06
	80	2.409E-06
Pressure/kPa	5	3.606E-06
	10	3.190E-06
	15	2.958E-06
	20	2.649E-06

Condition		**Linear regression fits the Eq**	**D_{eff} (m^2/s)**
Microwave power / W	250	lnMR = -1.153E-03t +1.33	1.86917E-09
	300	lnMR = -1.614E-03t +2.15	2.61652E-09
	350	lnMR = -2.027 E-03t+1.96	3.28605E-09
	400	lnMR = -2.208 E-03t+1.72	3.57948E-09
Loading capacity / g	50	lnMR = -2.260 E-03t+1.86	3.66378E-09
	60	lnMR = -2.027 E-03t+ 1.96	3.28605E-09
	70	lnMR = -1.456 E-03t+1.32	2.38470E-09
	80	lnMR = -1.287 E-03t+1.24	2.08641E-09
Pressure / kPa	20	lnMR = -1.310 E-03t+1.07	2.12369E-09
	15	lnMR = -1.613 E-03t+1.66	2.61490E-09
	10	lnMR = -1.897 E-03t+2.17	3.07530E-09
	5	lnMR = -2.027 E-03t+ 1.96	3.28605E-09

Law of activation energy in different drying processes

The functions expressing the variations of D_m and k_m versus the mass of sample/power are illustrated in Figure 4. The activation energy values calculated by the mass transfer coefficient and the internal diffusion mode were 5.316 and 7.406 W/g, respectively. The activation energy calculated by the D_{eff} was higher. This is related to the basic removal of free water and the removal of bound water at this stage, as it required more energy to remove bound water. These values were comparable to 5.33 W/g for soybean kernels (Darvishi, 2017), and 18.64 W/g for Trabzon persimmons (Celen, 2019).

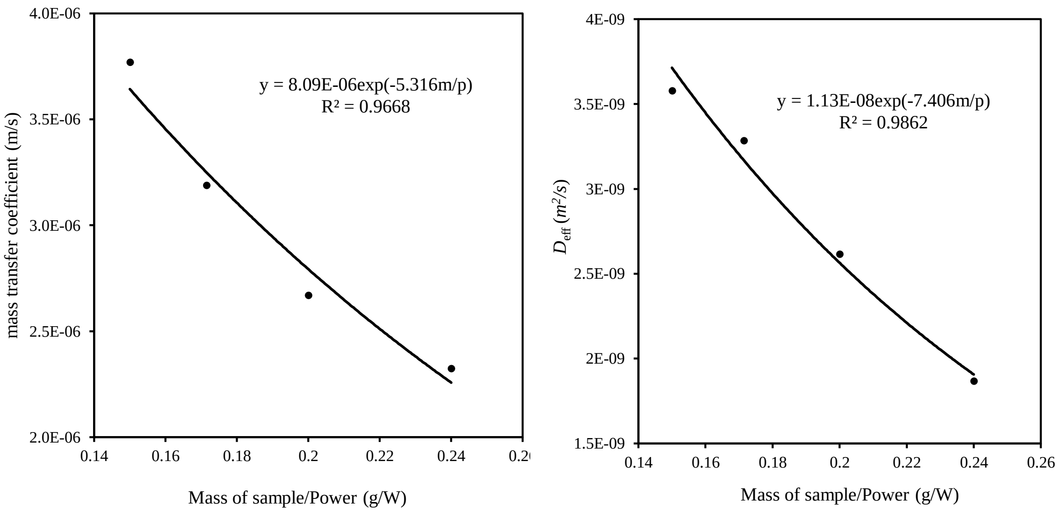

Figure 4. Fitting of experimental points to the Arrhenius relationship for the diffusion and mass transfer model.

Law of yam moisture transfer prediction

Different process parameters and drying times have important impacts on the change of moisture content of the material during the drying process. There are four neurons in the input layer of the model. Figure 5 shows the relationship between the number of different hidden layers and the fitting effect. It can be seen from the figure that the double hidden layer had a good fitting effect. When the number of nodes in the first hidden layer was 11, and the number of nodes in the second hidden layer was 2, the fitting accuracy can be ensured and over-fitting can be avoided. Based on the above analysis, the BP neural network model with a "4-11-2-1" structure was used in the present work to predict the water loss process of yam slices in MVD.

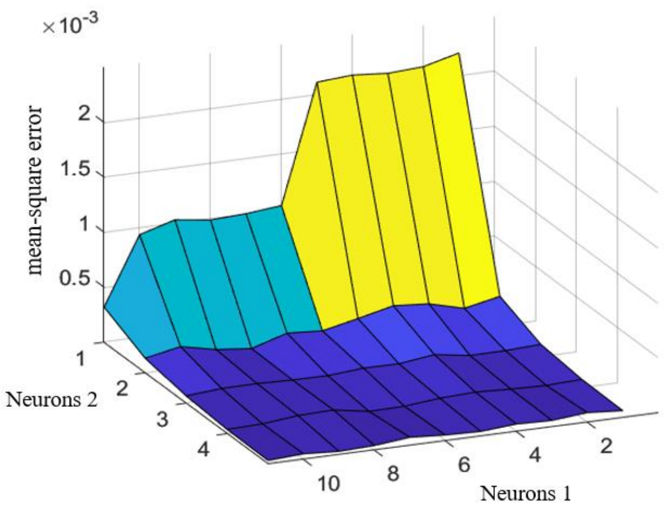

Figure 5. Relationship between the number of different hidden layers and the fitting effect.

The neural network model was trained 15 times with three common training functions: the L-M optimisation algorithm (train-lm), the scaled conjugate gradient algorithm (train-scg), and the Bayesian regularisation algorithm (train-br). After training, the smallest mean square error of train-lm was 6.55×10^{-5}. It was then used as the training function. The 76% data points randomly selected from the total samples were taken as training samples; the training stops were repeated 15 times based on the above network structure and parameters, and the optimal model with a minimum mean square error of 6.547×10^{-5} was obtained. In this model, the verification sample obtained the best root mean square error (RMSE) of 0.0104 and the determination coefficient (R^2) of 0.9993 after 21 times of training. The determination coefficient (R^2) of 0.9994 was obtained by testing the model with randomly selected test samples. The results indicated that the model described well the change of moisture ratio in the process of MVD of yam slices.

To further verify the reliability of the BP neural network model, the real-time weight in the drying process was weighed by the online weighing system under the condition of 330 W, 8 kPa, and 65 g. Then, the result was transformed into a curve of the relationship between the moisture ratio (MR) and drying time, and it was compared with the predicted value. As shown in Figure 6 and Table 2, except for the low predicted value in the early stage of the drying process, the curve in the middle and later stages basically coincided with the curve of the drying time-moisture ratio predicted by the BP neural network under this drying condition. The curve of the relationship between the drying time-moisture ratio predicted by the neural network and the measured value was fitted to obtain the coefficient of determination (R^2) of 0.9952 and RMSE of 0.0220. Therefore, the prediction curve can be taken as the curve of the real drying process; meanwhile, D_{eff} = 3.91×10^{-9} m^2/s and k_m = 3.23×10^{-6} m/s can be calculated respectively, thus indicating that they were the real D_{eff} and k_m under the conditions of 330 W, 8 kPa, and 65 g. It can be seen that the neural network model achieved good prediction accuracy, and could well predict the change of moisture ratio in the process of MVD of yam slices.

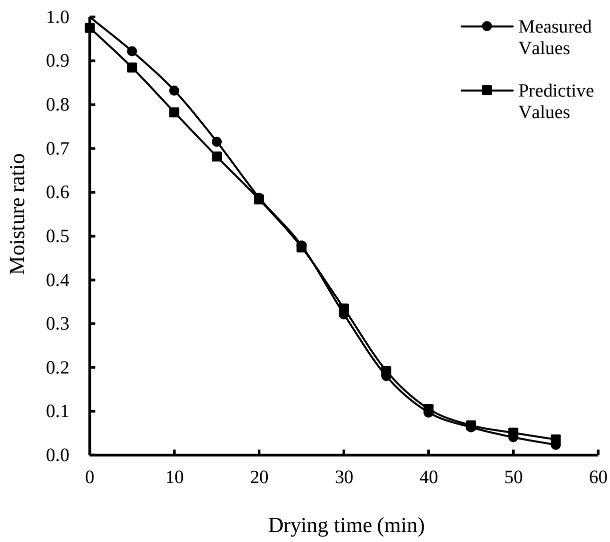

Figure 6. Comparison of the predicted and measured values of the neural network model.

Table 2. Neural network model for experimental data of predicted and measured values.

Drying time	Gross weight	Material heavy	Moisture content	Dry base moisture content	Measured value MR	Predictive value MR
0	134.7	64.9	8.06317E-01	4.16309	1.00002	0.9756
5	130.6	60.8	7.93257 E-01	3.83691	0.92167	0.8845
10	125.9	56.1	7.75936 E-01	3.46301	0.83185	0.7823
15	119.8	50.0	7.48600 E-01	2.97772	0.71528	0.6813
20	113.1	43.3	7.09700 E-01	2.44471	0.58725	0.5836
25	107.4	37.6	6.65691 E-01	1.99125	0.47832	0.4745
30	99.2	29.4	5.72449 E-01	1.33890	0.32162	0.3347
35	91.8	22.0	4.28636 E-01	0.75020	0.18021	0.1922
40	87.47	17.67	2.88625 E-01	0.40573	0.09746	0.1054
45	85.7	15.9	2.09434 E-01	0.26492	0.06364	0.0681
50	84.5	14.7	1.44898 E-01	0.16945	0.04070	0.0509
55	83.6	13.8	0.89130 E-01	0.09785	0.02351	0.0358

In the production process, only a small number of experiments and prediction models are required to predict the internal moisture content of the material at a certain time in any range of parameters, calculate the drying rate and diffusion coefficient, and obtain the law of moisture transfer in the whole process. Meanwhile, predicting the change in moisture content during the drying process is also significant for improving the drying rate and quality. The BP neural network has better applicability and accuracy than a single fixed empirical or semi-empirical model, which is of great significance to the actual processing and production of materials.

Law of quality in the drying process

In the orthogonal test shown in Table 3, the five factors were A, B, C, D, and E, where A represented the power, B represented the loading, D represented the pressure, and C and E represented the control group. The evaluation index score corresponding to the serial number of each test is presented in Figure 7. After calculation, the range (R) of A, B, C, D, and E were 7.73, 8.95, 3.18, 5.40, and 4.95, respectively. Moreover, a larger value of R shows a greater effect on the factor.

Table 3. Orthogonal experimental design and results.

Test number	***A***	***B***	**Empty column**	***D***	**Empty column**	**Y_1 Average drying rate g/min**	**Y_2 rehydration rate / %**	**Y_3 whiteness**	**Y Comprehensive score**
1	1	1	1	1	1	0.706	144.16	84.85	77.73
2	1	2	2	2	2	0.750	161.19	83.82	82.20
3	1	3	3	3	3	0.842	131.77	84.57	77.92
4	1	4	4	4	4	0.912	125.94	85.69	78.55
5	2	1	2	3	4	0.792	110.38	84.95	72.12
6	2	2	1	4	3	0.928	118.65	85.98	77.38
7	2	3	4	1	2	1.053	146.51	85.06	86.13
8	2	4	3	2	1	1.015	153.29	83.57	86.28
9	3	1	3	4	2	0.929	142.13	84.04	82.00
10	3	2	4	3	1	1.024	157.30	83.39	87.33
11	3	3	1	2	4	1.156	149.81	84.06	88.85
12	3	4	2	1	3	1.265	177.85	85.88	98.22
13	4	1	4	2	3	1.00	154.55	81.69	85.58
14	4	2	3	1	4	1.296	143.79	83.01	90.27
15	4	3	2	4	1	1.303	166.52	84.68	96.12
16	4	4	1	3	2	1.336	140.91	86.38	91.69
K_1	316.41	317.43	335.65	352.36	347.47				
K_2	321.91	337.19	348.67	342.91	342.03				
K_3	356.41	349.02	336.48	329.07	339.10				
K_4	363.67	354.74	337.60	334.06	329.79				
k_1	79.10	79.36	83.91	88.09	86.87				
k_2	80.48	84.30	87.17	85.73	85.51				
k_3	89.10	87.26	84.12	82.27	84.78				
k_4	90.92	88.69	84.40	83.51	82.45				
R	11.82	9.33	3.05	5.82	4.42				
Factor primary and secondary				$A > B > D$					
Better collocation				$A_4B_4D_1$					

	Sum Sq.	***df***	**Mean Sq.**	***F*-Value**	***Pr***
A	427.49	3	142.5	12.19	**
B	203.21	3	67.74	5.79	*
D	78.24	3	26.08	2.23	
residual	67.75	6	11.29		
total	776.69	15			

Annotation = A: microwave power; B: loading; D: pressure; The contribution rate from high to low were B, A, and D; Excellent: $A_3B_4D_1$.

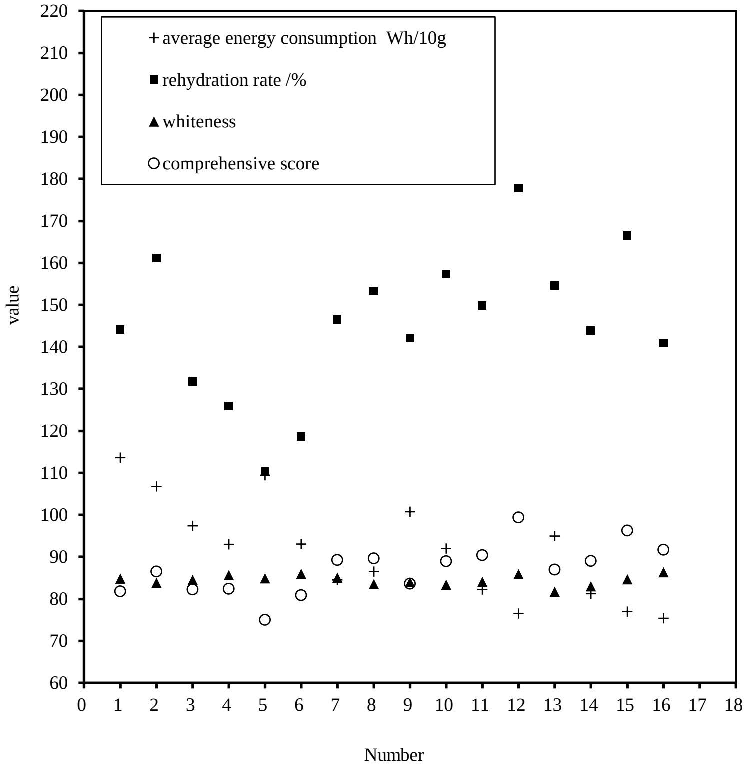

Figure 7. Orthogonal test results and evaluation indices. Annotation = A: microwave power; B: loading; D: pressure; The contribution rate from high to low were B, A, and D; Excellent: $A_3B_4D_1$.

It can be seen from Figure 7 and the range (R) calculation that the power and the loading had a significant effect on the comprehensive score. The effect of drying chamber pressure on the comprehensive score was not significant ($p > 0.05$). Besides, the ranking of the primary and secondary factors from high to low was loading, power, and pressure. The comprehensive score increased with the rise of power and loading, and then the overall quality was improved. For the quality index, power, loading, and pressure, all had extremely significant effects on unit energy consumption, and the unit energy consumption could be decreased with the increase in power, loading, and pressure. However, the power, loading, and pressure had no significant effects on the whiteness and rehydration rate. The optimum process parameters of MVD of yam were $A_3B_4D_1$, *i.e.*, the microwave was 350 W, the material loading was 80 g, and the vacuum cavity pressure was 5 kPa. Under this setting, the actual drying time was 51 min, the unit energy consumption was 7.65 W·h/g, the rehydration rate was 177.9%, the whiteness was 85.9, and the comprehensive score was 99.4.

Hot air drying is widely used in practical production because of its good manoeuvrability and quality. To verify that MVD has a better drying quality, a hot air control experiment was conducted at 60°C. The results indicated that the drying time was 6 h, the rehydration rate was 164%, and the whiteness was 85.56%. When compared with HAD, the optimised drying process of MVD could greatly improve the drying rate, shorten the drying time, and guarantee the quality of dried yam slices.

It was found that in the process of industrial production, increasing microwave power and loading, and maintaining a high vacuum degree can reduce energy consumption and ensure quality, thus improving the economic feasibility of the microwave vacuum drying process.

Conclusion

The drying time and drying rate curves obtained under different drying conditions were quite different. The law of drying kinetics is that the loss of moisture in the MVD of yam slices mainly occurs in the stage of a constant and decreasing speed. When the moisture content of the dry base was decreased to about 1.3 g/g (D.B.), it began to enter the deceleration stage. The drying time could be decreased, and the moisture diffusion rate could be increased by increasing the power, and decreasing the loading and pressure. Moreover, the effective moisture diffusivity coefficient varied from 3.15 to 5.46 × 10^{-9} m^2/s, and the mass transfer coefficient varied from 2.54 to 4.65 × 10^{-6} m/s. Besides, D_{eff} and the mass transfer coefficient were directly proportional to the power, and inversely proportional to the loading capacity and pressure. The established equation of these parameters could well describe this law of change. Finally, a model was established, which could describe the moisture diffusion in the drying process of Chinese yam very well. Further studies are necessary to explain the specific mechanism of water diffusion in the drying process.

The ranking of the contribution rate from high to low was loading, power, and pressure. The comprehensive score increased with the increase in power and loading. In the process of industrial production, increasing microwave power and loading, and maintaining a high vacuum degree could reduce energy consumption and ensure quality, thus improving the economic feasibility of microwave vacuum in the drying process.

Acknowledgement

The present work was financially supported by the Major Science and Technology Special Fund of the Science and Technology Department of Yunnan Province (grant no.: 2018ZF004), and the Yunnan Major Science and Technology Special Program (grant no.: 202102AA310048).

References

Bai, J. W., Xiao, H. W., Ma, H. L. and Zhou, C. S. 2018. Artificial neural network modeling of drying kinetics and color changes of ginkgo biloba seeds during microwave drying process. Journal of Food Quality 2018: 3278595.

Beigi, M. 2017. Mass transfer parameters of celeriac during vacuum drying. Heat Mass Transfer 53: 1327-1334.

Borquez, R., Melo, D. and Saavedra, C. 2015. Microwave-vacuum drying of strawberries with automatic temperature control. Food and Bioprocess Technology 8: 266-276.

Celen, S. 2019. Effect of microwave drying on the drying characteristics, color, microstructure, and thermal properties of Trabzon persimmon. Foods 8: 84.

Chinese Pharmacopoeia Commission. 2015. Pharmacopoeia of the People's Republic of China (volume 1). China: China Medical Science Press.

Darvishi, H. 2017. Quality, performance analysis, mass transfer parameters and modeling of drying kinetics of soybean. Brazilian Journal of Chemical Engineering 34: 143-158.

De Vera, F. C., Comaling, L. A. B., Lao, I. R. A. M., Caparanga, A. R. and Sauli, Z. 2017. Kinetics, mass transport characteristics, and structural changes during air-drying of purple yam (*Dioscorea alata* L.) at different process conditions. The European Physical Journal Conferences 162(1): 01085.

Duan, L. L., Duan, X. and Ren, G. Y. 2019. Water diffusion characteristics and microwave vacuum freeze-drying modeling of Chinese yam (*Dioscorea opposita*) tubers. Shipin Kexue 40: 23-30.

Erle, U. and Schubert, H. 2001. Combined osmotic and microwave-vacuum dehydration of apples and strawberries. Journal of Food Engineering 49: 193-199.

Huang, L. L., Qiao, F. and Fang, C. F. 2015. Studies on the microstructure and quality of iron yam slices during combined freeze drying and microwave vacuum drying. Journal of Food Processing and Preservation 39: 2152-2160.

Ju, H. Y., Law, C. L., Fang, X. M., Xiao, H. W., Liu, Y. H. and Gao, Z. J. 2016. Drying kinetics and evolution of the sample's core temperature and moisture distribution of yam slices (*Dioscorea alata* L.) during convective hot-air drying. Drying Technology 34: 1297-1306.

Kaveh, M., Chayjan, R. A. and Khezri, B. 2018. Modeling drying properties of pistachio nuts, squash and cantaloupe seeds under fixed and fluidized bed using data-driven models and artificial neural networks. International Journal of Food Engineering 14(1): 20170248.

Kaya, A., Aydin, O. and Dincer, I. 2010. Comparison of experimental data with results of some drying models for regularly shaped products. Heat and Mass Transfer 46: 555-562.

Kim, S. S., Koh, K. H., Son, S. M. and Oh, M. S. 2005. Preparation and quality of dried yam chip snack coated with ascorbic acid cocrystallized sucrose. Food Science and Biotechnology 14: 661-666.

Kipcak, A. S. and Ismail, O. 2020. Microwave drying of fish, chicken and beef samples. Journal of Food Science and Technology 58: 281-291.

Markowski, M., Bondaruk, J. and Blaszczak, W. 2009. Rehydration behavior of vacuum-microwave-dried potato cubes. Drying Technology 27: 296-305.

Maurya, V. K., Gothandam, K. M., Ranjan V., Shakya, A. and Pareek, S. 2018. Effect of drying methods (microwave vacuum, freeze, hot air and sun drying) on physical, chemical and nutritional attributes of five pepper (*Capsicum annuum* var. *annuum*) cultivars. Journal of the Science of Food and Agriculture 98: 3492-3500.

Monteiro, R. L., Link, J. V., Tribuzi, G., Carciofi, B. A. M. and Laurindo, J. B. 2018. Microwave vacuum drying and multi-flash drying of pumpkin slices. Journal of Food Engineering 232: 1-10.

Ojediran, J. O., Okonkwo, C. E., Adeyi, A. J., Adeyi, O., Olaniran, A. F., George, N. E. and Olayanju, A. T. 2020. Drying characteristics of yam slices (*Dioscorea rotundata*) in a convective hot air dryer: Application of ANFIS in the prediction of drying kinetics. Heliyon 3: e03555.

Orikasa, T., Koide, S., Sugawara, H., Yoshida, M., Kato, K., Matsushima, U., … and Tagawa, A. 2018. Applicability of vacuum-microwave drying for tomato fruit based on evaluations of energy cost, color, functional components, and sensory qualities. Journal of Food Processing and Preservation 42: e13625.

Patel, J. H. and Sutar, P. P. 2016. Acceleration of mass transfer rates in osmotic dehydration of elephant foot yam (*Amorphophallus paeoniifolius*) applying pulsed-microwave-vacuum. Innovative Food Science and Emerging Technologies 36: 201-211.

Politowicz, J., Lech, K., Lipan, L., Figiel, A. and Carbonell-Barrachina, A. A. 2018. Volatile composition and sensory profile of shiitake mushrooms as affected by drying method. Journal of the Science of Food and Agriculture 98: 1511-1521.

Si, X., Chen, Q. Q., Bi, J. F., Yi, J. Y., Zhou, L. Y. and Wu, X. Y. 2016. Infrared radiation and microwave vacuum combined drying kinetics and quality of raspberry. Journal of Food Process Engineering 39: 377-390.

Suriya, M., Baranwal, G., Bashir, M., Reddy, C. K. and Haripriya, S. 2016. Influence of blanching and drying methods on molecular structure and functional properties of elephant foot yam (*Amorphophallus paeoniifolius*) flour. LWT - Food Science and Technology 68: 235-243.

Turan, O. Y. and Firatligil, F. E. 2019. Modelling and characteristics of thin layer convective air-drying of thyme (*Thymus vulgaris*) leaves. Czech Journal of Food Sciences 37: 128-134.

Vishwanathan, K. H., Hebbar, H. U. and Raghavarao, K. S. M. S. 2010. Hot air assisted infrared drying of vegetables and its quality. Food Science and Technology Research 16: 381-388.

Wang, H. Y., Liu, D., Yu, H. M., Wang, D. H. and Li, J. 2019. Optimization of microwave coupled hot air drying for Chinese yam using response surface methodology. Processes 7: 745.

Wojdylo, A., Figiel, A., Lech, K., Nowicka, P. and Oszmianski, J. 2014. Effect of convective and vacuum–microwave drying on the bioactive compounds, color, and antioxidant capacity of sour cherries. Food and Bioprocess Technology 7: 829-841.

Zielinska, M., Zapotoczny, P., Alves-Filho, O., Eikevik, T. M. and Blaszczak, W. 2013. A multi-stage combined heat pump and microwave vacuum drying of green peas. Journal of Food Engineering 115: 347-256.