MATHMATICAL MODELING AND EFFECT OF BLANCHING PRETREATMENT ON THE DRYING KINETICS OF CHINESE YAM (Dioscorea opposita)

Article Highlights
• Drying kinetics of Chinese yam slices are investigated
• Effects of blanching pretreatment on drying kinetics
• Six thin layer drying models are compared
• The effective diffusivities and activation energy are obtained

Abstract
The effects of blanching pretreatment on the drying kinetics of Chinese yam (Dioscorea opposita) slices were investigated. Drying experiments were carried out at 60, 70, 80 and 90 °C. Six thin layer models were evaluated and the coefficient of determination (R²), chi-square (χ²), and root means square error (RMSE) were used to analyze the model performance for both raw and blanched samples. The Wang and Singh model gave best results with R² of 0.9987 and RMSE of 0.0136 for raw yam slices, and R² of 0.9989 and RMSE of 0.0119 for blanched samples. The effective moisture diffusivity coefficient Deff varied in the range of 0.7295×10⁻⁹ to 2.4087×10⁻⁹ m² s⁻¹ for raw slices, and 1.3748×10⁻⁹ to 3.8524×10⁻⁹ m² s⁻¹ for the blanched ones. The activation energies of yam slices drying were 41.149 and 33.499 kJ mol⁻¹ for raw and blanched yam slices, respectively. The results show that blanching pretreatment can reduce the total drying time and improve the effective moisture diffusivity compared to the raw samples.

Keywords: Chinese yam, hot air drying, kinetics, modeling, blanching.

The Chinese yam (Dioscorea opposita), called “Shan Yao” (which means “mountain medicine”) in Chinese herbalism, has a long history of cultivation in China and Eastern Asia for its edible tuber [1]. The yam tuber is also a traditional ingredient of herbs that prescribed in Chinese herbalism to treat diseases like nephritis, hyperthyroidism and diabetes [1]. It contains a large amount of water, similar to fruits, and can be eaten raw or cooked before consumption. The dried yam slices can be served fried, roasted and boiled, used as an ingredient in herbs and for the production of yam starch [2].

Drying is one of the most important preservation processes commonly used for food products that are easily deteriorated [3]. As a simple postharvest technology, drying can prolong the shelf life of food products, and reduction in volume and weight in favor of transportation. Drying can also preserve food quality by lowering their water activity, thus avoiding contamination and spoilage during transportation and storage. Convective drying by hot air is a common technology for food postharvest processing because of its large scalability and easy to performance [3,4]. However, hot air drying is a high energy consumption process. It is a complex process containing both the heat and mass transfer where water is transferred from the inside of food materials to the outside atmosphere by diffusion, which is very slow. The total energy consumption in hot air drying process depends on many parameters such as pretreatments, drying temperature drying time and air velocity [4,5].
High drying temperature may shorten the drying time, however, it can bring disadvantages such as color deterioration and nutrients degradation [5,6]. Previously, many investigations have explored the effects of different drying parameters, including drying temperature, air velocity, relative humidity and sample thickness on the drying characteristics of agricultural and food products, such as bottle gourd [7], Chinese jujube [8], carrots [9], sweet potatoes [10,11] and pumpkins [12].

Meanwhile, many pretreatments methods are employed in order to mitigate quality attributes degradation [3,6]. They can also reduce the total drying time, which is more energy efficient and generate final products with good quality. Many natural or synthetic chemicals are used for dipping pretreatments prior to drying such as ascorbic acids [13], potassium metabisulphide and alkaline ethyl oleate [14]. Alternatively, raw foods and vegetables can also be pretreated by thermal methods such as hot water blanching prior to drying. Generally, thermal blanching is carried out by exposing samples either at low temperature for a long time (LTLT) or high temperature for a short time (HTST). Blanching is the most commonly used thermal pretreatments before processing of agricultural products as it can destroy enzymes, which cause deterioration reactions, off-flavour and undesirable changes in color, texture and nutrients [15]. In addition, blanching can also enhance drying rate by expelling intercellular air from the tissues, softening the texture or by dissociating the wax on the products skin [16,17].

Mathematical modeling and simulation of the drying kinetics of food products is an important tool for designing novel drying systems, drying equipment and minimize operative energy consumption [3]. Recently, several studies have been conducted on the experimental and mathematical modeling of the drying characteristics of different agricultural and food materials is available. Some studies have been published concerning the drying process of yam [2,18-23]. However, some of them were concerning about the drying process of yam starch [2]. Xiao et al. [21] investigated the effect of superheated steam blanching on the drying kinetics and quality of yam slices under air impingement drying. Lin et al. [22] studied the dehydration of yam slices by using FIR-assisted freeze drying. Sobukola et al. [23] studied the convective hot air drying at temperature 70, 80 and 90 °C of blanched yam slices (Dioscorea rotun-

**Materials and Methods**

**Materials**

Chinese yams (Dioscorea opposita) were purchased from a local supermarket (Hangzhou Wumart Supermarket) in Hangzhou, China. They were selected by homogeneous diameter as well as the absence of physical damage. The yams were washed by tap water and put into a refrigerator at about 4 °C for storage before usage.

**Experimental apparatus**

The drying experiments were performed in a continuous convective dryer as described previously by Meng et al. [24]. It is composed of a heater, blower, square air tunnel and other temperature instruments and is shown in Figure 1. The air was sucked by the blower and heated to the desired temperature automatically by regulating voltage to the heaters inside the air channel. The air velocity is controlled by a revolution speed regulator. A digital electronic balance (Model BS124S, Beijing Sartorius instrument system Co., LTD., China) with an accuracy of 0.01 g and a range of 0-210 g was used to continuously measure the moisture loss of samples. The values shown in the electronic balance were monitored by a camera connected to a computer for recording.

**Experimental procedures**

Yams were cut into cylindrical slices homogeneously with height of 3±0.2 mm and diameter of 15±0.2 mm. The slices were put into the drying chamber after the target condition was steady for about 1 h. Then, the slices were placed on wire
meshes, which were weighed by the electronic balance. The experiments were performed at air temperatures 50, 60, 70 and 80 °C with a constant perpendicular air velocity of 1.2 m s\(^{-1}\). The mass of yam slices were recorded at first and about 17.5±0.5 g of yam samples were utilized in the each run. The weight of slices was recorded continuously at 3 s intervals during the drying process. For drawing the drying curve, the time for certain change of slice weight was obtained by manual statistics. The drying process was stopped until the weight of slices was invariable for more than 2 h. The final weight of dried slices was taken as the equilibrium moisture content \((M_e)\) that used to calculate the moisture ratio \((MR)\). The yam slices were placed on the stainless steel wire mesh in an electric cooker and blanched by the saturated water steam at atmosphere. The blanching temperature was estimated at 98±2 °C and 100% relative humidity. All the yam slices were blanched at the same condition for 3 min prior to drying.

Mathematical modeling of drying curves

The moisture ratio \((MR)\) can be calculated from the moisture content of drying sample at time \(t\) as shown below:

\[
MR = \frac{X_t - X^*}{X_0 - X}
\]

where \(X_0\), \(X_0\) and \(X^*\) are the moisture content at time \(t\), the initial moisture content and the equilibrium moisture content, respectively; and the moisture content \(X\) is expressed as:

\[
X_t = \frac{m_t - m_s}{m_d}
\]

where \(m_t\) and \(m_s\) are the mass of sample at time \(t\) and the final mass of dried samples, respectively.

The experimental convective drying data for Chinese yam were fitted to six thin-layer drying models. For the details of each model, readers can refer to the comprehensive review \[3\]. The empirical equations of each model are shown in Table 1.

The parameters of equations in Table 1 were estimated by using the nonlinear Levenberg-Marquardt algorithm. The primary criterion for the selection of the best equation to describe drying curves was the coefficient of determination \((R^2)\). In addition, the chi

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Equation</th>
<th>Model name</th>
<th>Parameters</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(MR = \exp(-kt))</td>
<td>Newton</td>
<td>(k)</td>
<td>[25]</td>
</tr>
<tr>
<td>2</td>
<td>(MR = \exp(-kt^n))</td>
<td>Page</td>
<td>(k, n)</td>
<td>[26]</td>
</tr>
<tr>
<td>3</td>
<td>(MR = a\exp(-kt))</td>
<td>Henderson and Pabis</td>
<td>(a, k)</td>
<td>[27]</td>
</tr>
<tr>
<td>4</td>
<td>(MR = 1 + at + bt^2)</td>
<td>Wang and Singh</td>
<td>(a, b)</td>
<td>[28]</td>
</tr>
<tr>
<td>5</td>
<td>(MR = a\exp(-kt^n))</td>
<td>Modified page</td>
<td>(a, k, n)</td>
<td>[29]</td>
</tr>
<tr>
<td>6</td>
<td>(MR = a\exp(-kt) + c)</td>
<td>Logarithmic</td>
<td>(a, k, c)</td>
<td>[30]</td>
</tr>
</tbody>
</table>
square ($\chi^2$) and root mean square error (RMSE) were also used to determine the goodness of correlation. $\chi^2$ stands the mean square of the deviations between the predicted and experimental values of the equation. It is known that the higher the values of $R^2$, the lower were the values of $\chi^2$ and RMSE, and hence the better of model performance. These statistical parameters are calculated by equations shown as below:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{i,\text{pre}} - MR_{i,\text{exp}})^2}{N - n}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (MR_{i,\text{pre}} - MR_{i,\text{exp}})^2}{N}}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (MR_{i,\text{exp}} - MR_{i,\text{mean}})^2}{\sum_{i=1}^{N} (MR_{i,\text{pre}} - MR_{i,\text{mean}})^2}$$

where $MR_{i,\text{pre}}$ and $MR_{i,\text{exp}}$ stand for the $i$th predicted moisture ratio and the experimental moisture ratio, respectively; $N$ is the number of observations, and $n$ is the number of parameters in the drying equation.

**Determination of effective moisture diffusivity**

The effective moisture diffusivity coefficient is an important transport property in the drying of food materials. It was calculated by fitting the experimental data to the Fick’s second law of diffusion equation:

$$\frac{\partial X}{\partial t} = \frac{n}{2} \frac{\partial^2 X}{\partial x^2}$$

With the assumption of uniform initial moisture distribution, negligible shrinkage and external resistance, constant diffusion coefficients and temperature, the solution of Eq. (6) for slab geometry is solved as follows [3,20]:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-\frac{(2n-1)^2 D_{\text{eff}} t}{4L^2}\right)$$

where $D_{\text{eff}}$ is the effective moisture diffusivity ($m^2 s^{-1}$), $t$ is the drying time (s), $L$ is the half-thickness of samples (m). When for a long drying time, Eq. (7) can be simplified to the following equation:

$$MR = \frac{8}{\pi} \exp\left(-\frac{n^2 D_{\text{eff}} t}{4L^2}\right)$$

Plot ln($MR$) against the time $t$ gives the value of slope that contain the effective moisture diffusivity, $D_{\text{eff}}$, as:

$$\text{Slope} = \left(\frac{\pi^2}{4L^2}\right) D_{\text{eff}}$$

When given the value of the half-thickness of sample $L$, the $D_{\text{eff}}$ could be determined from Eq. (9).

**Determination of activation energy**

The activation energy for moisture diffusion, $E_a$, during the drying process can be related with the effective diffusion coefficient as following equation [19,20]:

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{R(T + 273.15)}\right)$$

where $D_0$ is the pre-exponential factor of the Arrhenius equation in $m^2 s^{-1}$, $R$ is the universal gas constant, and $T$ is temperature in °C.

**RESULTS AND DISCUSSIONS**

**Influence of drying air temperature**

The change of moisture ratio, $MR$, with drying time at hot air temperatures of 50, 60, 70 and 80 °C for Chinese yam slices at thickness of 3 mm and air velocity of 1.2 m s$^{-1}$ are shown in Figure 1. It is shown that the increase in hot air temperature leads to a decrease in the total drying time. It is well known that the higher temperature makes the relative humidity of air around sample slices become lower. As a result, the heat transfer and evaporation of water from the samples are greatly enhanced which then reduce the drying time. However, the drying rate increased as the temperature increased, but the increase became gradually smaller especially for the blanched yam slices as shown in Figure 2. Similar trends can also be found in several studies for different agricultural and food products [17,19-20].

On the other hand, although the increase of air temperatures can dramatically reduce the total drying time, it has disadvantageous effects on the total energy consumption and the quality of end products like the oxidation of phytochemicals and color deterioration [31]. For yam slices, it was found that the samples dried at 80 °C had the highest drying rate in all the temperatures concerned; however, the extent of surface hardening and shrinkage effect was intensified on the slice surface. This can be explained by the fact that the migration rate of moisture to the surface is lower than the moisture evaporation rate from...
surface to air at that drying temperature. This allows the presence of phenomena such as hardening and shrinkage of yam slices. Moreover, high temperatures will also lead to color changes, which are not desirable.

**Influence of pretreatment on drying time**

Pretreatment is an important parameter that affects the drying characteristics. As can be seen in Figure 1, the yam slices blanched prior to the hot air drying are found to shorten the drying time compared with the raw yam slices. For example, the total time required for the drying of raw yam slices to the MR of 10% at 60°C is about 110 min, while for blanched yam slices 81 min are needed to reach this moisture content. Blanching pretreatment can shorten the drying time with about 30% to reach the same moisture content at that condition. Similar trends are found at other drying temperatures. It is believed that the blanching pretreatment can loosen the cellular network and separate along the middle lamella in organic materials which then result in the softening of tissues [14-17]. Moreover, it was shown that the reducing cohesiveness of the matrix for food materials could improve the absorption capability of water, which led to better rehydration at their end use [32]. Furthermore, blanching pretreatment can avoid enzymes to be active at least during the drying process [15]. These profiles have been regarded as beneficial effects of the blanching prior to hot air drying.

**Fitting of drying curves**

Six thin layer drying equations listed in Table 1 are used to correlate the experimental drying data of Chinese yam slices at 4 different drying temperatures (50, 60, 70 and 80 °C). These equations are frequently used in literatures for the description of drying curves. The Levenberg-Marquardt algorithm is used to obtain the parameters of these six equations. The statistical parameters $R^2$, $\chi^2$, and RMSE obtained for six equations are shown in Table 2. The best equation that can describe the hot air drying characteristics of yam slices should have the highest $R^2$ and lowest values of $\chi^2$ and RMSE.

The results showed in Table 2 shows that the values of $R^2$ are all greater than 0.94, indicating a good fitness. The values of $R^2$, $\chi^2$, and RMSE for different equations for raw yam slices are range from 0.9487 to 0.9995, 0.000046 to 0.004033, and 0.006716 to 0.062729, respectively. Better results are obtained for blanched yam slices, the values of $R^2$, $\chi^2$ and RMSE are range from 0.9754 to 0.9993, 0.006716 to 0.062729, and 0.006716 to 0.062729, respectively. Model 4 (Wang and Singh) gave the best results to fit the experimental data of yam slices for all temperatures, followed by model 5 (Modified page). The average $R^2$ of Wang and Singh equation for different temperatures is 0.9987 and 0.9989, respectively. Hence, the Wang and Singh model could be selected as the most suitable model to represent the thin-layer hot air drying behavior of the yam slices. For the convenience of calculation, the parameters of Wang and Singh equation are shown in Table 3 for raw and blanched yam slices. Actually, the Wang and Singh model use the polynomial equations to represent the logarithmic relation between MR and t. Many studies shows that the Wang and Singh model can be well used to represent the drying curves of different agricultural and food materials, such as green apples [33] and long grain paddy [34].

**Effective moisture diffusivity**

Table 4 shows the calculated effective moisture diffusivity, $D_{eff}$, by Eq. (10) for the raw and blanched...
Table 2. The fitting models and statistical results for models at different temperatures

<table>
<thead>
<tr>
<th>Model No.</th>
<th>T / °C</th>
<th>Raw, RMSE</th>
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<th>$R^2$</th>
<th>Blanched, RMSE</th>
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Table 3. Values of parameters of the Wang and Singh equation for raw and belched samples at different temperatures

<table>
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<tr>
<th>T / °C</th>
<th>Raw, $a$</th>
<th>$b \times 10^5$</th>
<th>Blanched, $a$</th>
<th>$b \times 10^5$</th>
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Table 4. The effective moisture diffusion coefficient ($D_{eff}$) of raw and blanched yam at different temperatures

<table>
<thead>
<tr>
<th>T / °C</th>
<th>Raw $D_{eff} \times 10^5 / m^2 s^{-1}$</th>
<th>Blanched $D_{eff} \times 10^5 / m^2 s^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>50</td>
<td>0.7295</td>
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<tr>
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<td>1.0126</td>
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<td>80</td>
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</table>

The values of $D_{eff}$ varied in the range of $0.7295 \times 10^{-9}$ to $2.4087 \times 10^{-9}$ $m^2 s^{-1}$ for raw yam slices, while $1.3748 \times 10^{-5}$ to $3.8524 \times 10^{-5}$ $m^2 s^{-1}$ for blanched samples. The results show that the values of $D_{eff}$ increased with the increase of drying temperature. For food materials, many studies have showed that the value of $D_{eff}$ are in a general range of $10^{-12}$ to $10^{-8}$ $m^2 s^{-1}$ [35]. Sobukola et al. [23] obtained the values of $D_{eff}$ from $7.62 \times 10^{-6}$ to $9.06 \times 10^{-5}$ $m^2 s^{-1}$ for blanched yam slices (Dioscorea rotundata) under LTTLT pretreatment. The values of $D_{eff}$ obtained in this study for Chinese yam (Dioscorea opposita) slices are similar to those for other food products, like $5.61 \times 10^{-10}$ to $1.03 \times 10^{-9}$ $m^2 s^{-1}$ for peach slices at 60-80 °C [20], $1.68 \times 10^{-9}$ to $4.77 \times 10^{-9}$ $m^2 s^{-1}$ for tomatoes at 40-80 °C [36], $2.74 \times 10^{-9}$ to $4.64 \times 10^{-9}$ $m^2 s^{-1}$ for tomatoes at 40-80 °C [36].
m² s⁻¹ for carrot pomace at 60-75 °C [37]. The differences between these results can be explained by effect of material type, slice thickness, temperature and tissue characteristics. It can be found that the Deff values are larger than some root crops with more firm tissue characteristics, such as sweet potato slices at level of 9.32×10⁻¹¹ to 1.75×10⁻¹⁰ m² s⁻¹ at 50-70 °C [11].

Activation energy

The activation energy of Chinese yam slices drying at temperature range 50-80 °C is obtained by the Arrhenius relationship as shown in the Eq. (10). The results and values are shown in the Eq. (11) and (12) for raw and blanched yam slices with R² of 0.9407 and 0.9400, respectively:

\[
D_{eff,\text{raw}} = 3.223 \times 10^{-3} \exp\left(-\frac{-41149}{R(T+273.15)}\right) \tag{11}
\]

\[
D_{eff,\text{blanched}} = 3.879 \times 10^{-4} \exp\left(-\frac{-33499}{R(T+273.15)}\right) \tag{12}
\]

As shown in Figure 3, the values of activation energy are found to be 41.149 and 33.499 kJ mol⁻¹ for raw and blanched yam slices, respectively. The values of activation energy of yam slice are in the range of 15-40 kJ mol⁻¹ found for various food materials [3]. As can be seen above, the obtained activation energy are similar to those found by other authors for different agricultural and food products: 28.14 kJ mol⁻¹ for tiger nuts [38]; 25.35 to 30.83 kJ mol⁻¹ for blanched eggplant slices [39]; 38.78 kJ mol⁻¹ in cape gooseberry [40]; 37.76 kJ mol⁻¹ in red chilies drying [41].

CONCLUSIONS

The effects of temperature on drying characteristics of raw and blanched Chinese yam slices were investigated. The results show that blanching pretreatment can reduce the total drying time compared to the raw samples. Six thin layer drying models were calculated and compared by their capability in the correlation of drying curves at four temperatures. The Wang and Singh model gave best results with R² of 0.9987 and RMSE of 0.0136 for raw yam slices, and R² of 0.9989 and RMSE of 0.0119 for blanched samples. The effective moisture diffusivity coefficient, Deff, varied in the range of 0.7295×10⁻⁹ to 2.4087×10⁻⁹ m² s⁻¹ for raw slices, and 1.3748×10⁻⁹ to 3.8524×10⁻⁹ m² s⁻¹ for blanched samples. The activation energy of yam slices drying were 41.149 and 33.499 kJ mol⁻¹ for raw and blanched yam slices, respectively.

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NAUČNI RAD

MATEMATIČKO MODELOVANJE I EFEKAT PRETRETMANA BLAŠIĆANJEM NA KINETIKU SUŠENJA KINESKOG JAMA (Dioscorea opposita)

U radu je analiziran uticaj pretretmana blaširićanjem na kinetiku sušenja kriški kineskog jama (Dioscorea opposita). Ekperimenti sušenja su izvedeni na temperaturama od 60, 70, 80 i 90 °C. Analizirano je šest modela sušenja tankog sloja. Koeficijent determinacije (R²), hi-kvadrat test (χ²) i srednja kvadratna greška (RMSE) su korišćeni za analizu performansi modela za sirove i blanširane uzorke. Wang i Singh model daje najbolje rezultate sa R² = 0,9987 i RMSE = 0,0136 za sirove uzorke, kao i R² = 0,9989 i RMSE = 0,0119 za blanširane uzorke. Efektivni koeficijent difuzivnosti vlage je u opsegu od 0,7295 × 10⁻⁹ do 2,4087 × 10⁻⁹ m² s⁻¹ za sirove uzorke, a u opsegu od 1,3748 × 10⁻⁹ do 3,8524 × 10⁻⁹ m² s⁻¹ za blanširane uzorke. Energija aktivacije za sirove i blanširane kriške iznosi 41,149 i 33,499 kJ mol⁻¹, redom. Rezultati pokazuju da pretretman blaširićanjem može da smanji ukupno vreme sušenja i da poboljša efektivnu difuzivnost vlage u odnosu na sirove uzorke.

Ključne reči: kineski jam, sušenje toplim vazduhom, kinetika, modelovanje, blanširanje.