Effects of Hot-Air Coupled Microwave on Characteristics and Kinetics Drying of Lotus Root Slices

Yongcai Ma, Dan Liu, Wei Zhang, Jun Li, and Hanyang Wang*

ABSTRACT: Hot-air coupled microwave was employed to dry lotus root slices. The effects of lotus root slice thickness (5, 8, 11, 14, and 17 mm), hot-air velocity (1.5, 2.0, 2.5, 3.0, and 3.5 m/s), hot-air temperature (50, 55, 60, 65, and 70 °C), and microwave power density (2, 4, 6, 8, and 10 W/g) on drying characteristics and kinetics were studied. Results indicated that the drying process involved both the accelerating and decelerating periods but no constant rate period. The drying rate reached the maximum of 1.52 kg/kg when microwave power density was 8 W/g and reached the minimum of 0.02 kg/kg at the last stage of drying. In addition, the drying kinetics of lotus root slices were also investigated using eleven previously reported models. Among the models, the Verma et al. model was the most suitable for description of the drying behaviors of lotus root slices based on $R^2$, root-mean-square error, and chi-square. The moisture transfer from lotus root slices can be effectively described by Fick’s diffusion model. Regardless of drying conditions, the effective diffusivity coefficients ranged from $8.23 \times 10^{-7}$ to $7.08 \times 10^{-6}$ m$^2$/s, and their variations were mostly in agreement with those of moisture ratios. The activation energy of moisture diffusion related to lotus root slices was determined to be 13.754 kJ/mol.

1. INTRODUCTION

Lotus (Nelumbo nucifera Gaertn.) root, a well-known perennial aquatic vegetable belonging to the Nelumbonaceae family, is widely cultivated in China, Korea, Japan, and India. In China, the consumption and cultivation of lotus root can be traced back to 3000 years ago. Nowadays, the planting area of lotus root in China is approximately 330,000 hectares. Fresh-cut lotus root and its products are popular with consumers for its crisp texture, attractive aroma, white color, and favorable taste. Lotus root contains abundant sugar, starch, protein, dietary fiber, vitamin C, vitamin B$_1$, vitamin B$_2$, and minerals such as copper, manganese, and phosphorus. Therefore, it is widely favored by the Asians and often used as salads, vegetable in soups, stir-fried foods, and braised dishes. In addition, lotus root also has a significant medicinal value. For example, it is rich in health-promoting components, including nuciferine, flavonols, lipids, phospholipids, alkaloids, flavonoids, and aporphine. Many studies have evaluated the pharmacological function of phenolic compounds of lotus root, including antioxidative, immunomodulatory, and memory-improving activities. However, lotus root, like other fruits and vegetables, is easily damaged during harvest, transportation, and processing owing to its high moisture content and crispy nature, which leads to short shelf life and rapid decline in quality and even causes enormous annual losses to the farmers. Thus, some chemical treatments have been studied to improve the shelf life of fresh-cut lotus root, such as high hydrostatic pressure treatment, anti-browning treatment, chitosan-based coating treatment, and modified atmosphere packaging treatment. Although these treatments improve the shelf life and sensory properties of lotus root, these techniques have not yet been industrialized due to the efficiency and cost. Traditionally, a nonchemical drying method is used to reduce the moisture content of fruits and vegetables below a threshold to extend shelf life, prevent microbial growth, and reduce the costs of transportation, handling, and storage. Hot-air drying has been one of the most commonly used methods to preserve fruits and vegetables after harvest because of the simple processing, low-cost equipment, and being less
affected by the external environment. During hot-air drying, heat transfer takes place from the surface to the internal structure. Nevertheless, this process is limited by slow heat transfer, high energy consumption, and a long drying period, which may not only decline the texture, color, taste, flavor, and nutritional value of dried products but also the density, water absorbance ability, and the shift of solutes outward.13,14 To avoid the issues, hot-air drying is usually coupled with other drying methods (e.g., microwave drying) to shorten the drying process.

Recently, microwave drying was widely employed to dry various products, including fruits and vegetables. During microwave drying, the interaction between microwave and water molecules can generate internal heat in the materials, thus accelerating drying, enhancing energy efficiency, and reducing the loss of microelements in dried products.15 However, uneven heating of microwave drying may lead to the textural damage if the operation is improper, especially in the later drying stage.13 In addition, overheating and irreversible drying-out, which is produced by excessive temperatures along the corners and edges of drying products, can cause gelatinization and off-flavor, resulting in quality degradation of the product.12 For these reasons, microwave drying is usually combined with other drying methods such as vacuum and hot-air drying.19 In recent years, microwave-vacuum drying has been considered as an innovative drying technique for food drying. In this technique, the limitations of the two drying methods being used alone are avoided.18 Specifically, microwave energy absorbed directly and internally by the material is converted into heat generated in the material, while volumetric heating caused by microwave energy drives water out from the material as vapor or liquid continuously.12,18,19 Consequently, the mutual function of microwave and hot air leads to that drying characteristics and kinetics are significantly different from those of either single drying method.

Drying kinetics can reflect the combination of microscopic and macroscopic heat and mass transfer in the drying process. Drying kinetics are directly influenced by dryers, drying conditions, and properties of materials.20 Thin-layer drying mathematical models can be classified as theoretical models, semi-theoretical models, and empirical models, among which semi-theoretical models serve as a combination of theory and application.21 In the past few years, some researchers have used microwave, hot air, and/or microwave under vacuum conditions for the drying of fruits and vegetables such as longan, soybean, collard leaves, and potato. The drying curves and corresponding mathematical models were also obtained with drying materials, drying conditions, and dryer structure as affecting factors.15,19,22−25 However, information about the effects of MWhA drying on characteristics and kinetics is very limited. To date, no studies of the drying rate, drying moisture ratio, and mathematical model of lotus root slices subjected to

Figure 1. Relationship between the moisture ratio and drying time as affected by (A) slice thicknesses, (B) hot-air velocities, (C) hot-air temperatures, and (D) microwave power densities.
MWHA drying have been reported. Previously, MWHA was used to dry hawthorn slices where the effects of the power density of microwave and the temperature and velocity of hot air on drying characteristics were investigated, and the optimized fitting model was obtained. However, the thickness of the drying material, which was very important to the thin-layer drying characteristics and kinetics, was not considered.

The aim of this study was to investigate the effects of MWHA drying on characteristics and kinetics of drying. The sliced lotus root was selected due to its unique tissue structure, high moisture content, and low sugar content. Material thickness, power density of microwave, and temperature and velocity of hot air were tuned to investigate the drying characteristics, including the moisture ratio, effective diffusivity, drying rate, and activation energy. The optimized mathematical models fitting experimental data were identified for prediction of the drying characteristics of lotus root slices by MWHA drying.

2. RESULTS AND DISCUSSION

2.1. Moisture Ratio. The trends of the moisture ratio as a function of the drying period under different conditions are depicted in Figure 1. In all cases, the moisture ratio decreased continuously with the increase in the drying period.

Figure 1A shows that under constant drying conditions (air velocity = 2.5 m/s, air temperature = 60 °C, and power density of microwave = 6 W/g), the drying period for a moisture content of 8% (dry basis) increased from 10.5 to 14 min as the sample thickness increased from 5 to 17 mm, indicating significant effects of sample thickness on the drying period (p < 0.05). This can be attributed to the fact that increasing slice thickness leads to increased transfer distance of moisture in samples. In summary, sample thickness is a key factor affecting the drying process. This is consistent with drying of mushroom and cowpea.

Figure 1B shows that the moisture ratio or drying time decreased as the air velocity increased from 1.5 to 3.5 m/s at constant sample thickness (11 mm), air temperature (60 °C), and power density of microwave (6 W/g). Indeed, the air velocity has a dual effect on the drying period. The drying period increased by 5.5% as the air velocity increased from 1.5 to 2.0 m/s and then decreased by 7.4, 13.5, and 22.2% as the air velocity increased from 2.0 to 2.5, 2.5 to 3.0, and 3.0 to 3.5 m/s, respectively. The minimum drying period was 10.5 min at an air velocity of 3.5 m/s. The reason for the fluctuation is that microwave drying played a dominant role in the drying process when air velocity was at a low level, and with the increase in air velocity, the role of hot air was gradually greater than that of microwave that can accelerate the evaporation of surface water, reducing the drying time. In summary, air velocity has negligible effects on the drying period (p > 0.05). The results indicated that the air velocity within a reasonable range could promote moisture diffusion from the sample surface to air, resulting in a reduced drying period. The dual effects of air velocity on MWHA drying were reported previously.

Figure 1C shows that the drying period decreased as the air temperature increased at constant sample thickness (11 mm), air velocity (2.5 m/s), and power density of microwave (6 W/g). The drying medium may increase the thermal current gradient and thermal influx between the sample and hot air, leading to accelerated heat transfer. Meanwhile, the increasing air temperature reduces the humidity of the medium and exacerbates the deficit of vapor pressure, hence
accelerating the transfer of external mass. Additionally, water molecules inside the drying materials could acquire higher motivation energy at higher air temperature, resulting in improved moisture diffusion inside the sample. Therefore, the increase in air temperature has a positive effect on mass transfer inside the sample. Similar phenomena were reported for sweet potato,29 yacon,30 and persimmon.31 However, if air temperature is too high and exceeds a reasonable value, the evaporation rate of surface water may be far greater than the diffusion rate of internal water, which will lead to the formation of a hard shell on the surface of the drying material, and hinder the migration of moisture from inside to the surface and increase the drying time.

Figure 1D shows the effects of power density of microwave on moisture content as a function of the drying period at constant sample thickness (11 mm), air velocity (2.5 m/s), and air temperature (60 °C). The drying period decreased from 30.5 to 6.7 min as the power density of microwave increased from 2 to 10 W/g. This is due to the fact that the microwave energy absorbed by water molecules intensifies collision and friction between water molecules, resulting in severe friction between water molecules, resulting in severe friction and accelerated migration and diffusion of moisture inside the sample. During this process, microwave drying played a leading role on moisture evaporation and transfer.15 The decrease in drying time with increasing power density of microwave has also been reported for other agricultural products.23,32,33

### 2.2. Drying Rate

Figure 2 reveals the correlation of the drying rate and moisture content (dry basis) under different drying conditions. As observed, all drying rate curves consisted of two drying periods: the accelerating period and the decelerating period. The drying curves obtained in this study are consistent with those of carrots using two-stage intermittent MWHA drying.13 At the early stage, because of the higher moisture content, water molecules moved fast due to an enhanced heat transfer rate caused by increased drying temperature under the combination of microwave and hot air. Subsequently, migration and diffusion of moisture inside the sample were accelerated. Meanwhile, moisture on the sample surface was rapidly heated and evaporated. In summary, the accelerated drying at the early stage can be attributed to moisture migration inside and synergistic effects. As drying...
The drying was decelerated because the decrease in moisture content reduced the capability of microwave absorption by the sample, resulting in reduced moisture diffusivity. As the abovementioned analysis, drying was concentrated in the decelerating period, indicating that the drying rate was dominated by the mass transfer in the sample.

### 2.3. Mathematical Modeling of Drying Curves

The moisture contents (dry basis), attained at varied drying conditions (sample thickness, power density of microwave, and velocity and temperature of air) were fitted to the selected mathematical models (Table 1) after being converted to the moisture ratio. The statistical values of $R^2$ (0.97007 to 0.99996), $\chi^2$ (5.102 × $10^{-6}$ to 3.42 × $10^{-3}$), and RMSE (0.00226 to 0.05846) under different drying conditions were derived by nonlinear regression, and the results are presented in Table 1.

Among these models, the one proposed by Verma et al. fitted experimental data with the highest $R^2$ (0.99792 to 0.99996), the lowest $\chi^2$ (5.102 × $10^{-6}$ to 2.67438 × $10^{-4}$), and the lowest RMSE (0.00226 to 0.01635). Therefore, this model was regarded as the optimized model for description of the drying behaviors of lotus root using MWHA drying in this study. However, the drying materials and drying parameters may affect model fitting. Some studies regarding the MWHA drying of pumpkin and potato were reported. The results indicated that the Page model was the optimized one for fitting. In the present study, Weibull distribution was the optimized model to describe the drying behavior of hawthorn fruits. Herein, nonlinear regression was employed to calculate coefficients and constants of the Verma et al. model under different conditions, as listed in Table 2.

To clarify the effect of drying variables on the Verma et al. model, the regression method was employed to investigate the relationship between coefficients and constants ($a$, $k$, and $g$) and the drying parameters. The polynomial regression equations are as follows:

With air velocity = 2.5 m/s, air temperature = 60 °C, and power density = 6 W/g,

\[
\begin{align*}
    a & = 8.0 \times 10^{-4} L^3 - 0.021 L^2 + 0.221L + 0.465 \quad (R^2 = 0.989) \\
    k & = -4.0 \times 10^{-5} L^3 + 0.002L^2 - 0.0359L + 0.508 \quad (R^2 = 0.977) \\
    g & = -0.123L^3 + 4.698L^2 - 57.578L + 226.680 \quad (R^2 = 0.981)
\end{align*}
\]

With sample thickness = 11 mm, air temperature = 60 °C, and power density = 6 W/g,

\[
\begin{align*}
    a & = 0.386V^3 - 3.006V^2 + 7.333V - 4.232 \quad (R^2 = 0.952) \\
    k & = 0.021V^3 - 0.148V^2 + 0.346V + 0.057 \quad (R^2 = 0.995) \\
    g & = -6.380V^3 + 58.781V^2 - 195.190V^2 + 277.420V - 141.280 \quad (R^2 = 0.995)
\end{align*}
\]

With sample thickness = 11 mm, air velocity = 2.5 m/s, and power density = 6 W/g,

![Figure 3. Comparison of experimental and predicted MR from the Verma et al. model: (A) at different slice thicknesses, (B) at different hot-air velocities, (C) at different hot-air temperatures, and (D) at different microwave power densities.](image)

![Figure 3.](image)
mic, and Weibull distribution, have been demonstrated to be the optimized models for description of drying characteristics of yacon slices,30 carrot slices,36 betel leaves,37 and Chinese jujube,38 respectively.

2.4. Determination of Effective Moisture Diffusivities. During the decelerating stage, the mass transfer was governed by internal resistance, while the moisture transfer was dominated by internal diffusion. Hence, the effective moisture diffusivity (EMD) can be obtained according to Fick’s second law. According to the drying period and ln(MR) obtained experimentally, the EMDs under different experimental conditions were calculated using eqs 19 and 20, and the results are shown in Table 3.

The EMDs varied from 8.23 × 10⁻⁷ to 7.08 × 10⁻⁶ m²/s. The EMDs were proportional to sample thickness, air temperature, and power density. The air velocity had a dual effect on the EMD. Specifically, the EMD initially decreased and then increased as air velocity increased. The EMDs obtained in this study were much higher than those of mango drying by microwave-assisted convective air (1.16 × 10⁻⁹ to 7.97 × 10⁻⁷ m²/s)24 and hawthorn drying by microwave coupled with hot air (1.16 × 10⁻⁷ to 3.77 × 10⁻⁶ m²/s).26 Additionally, other factors, including drying materials, the range of drying parameters, physical or chemical pretreatment, the composition and geometry (i.e., thickness or radius), and moisture content, may also affect the effective diffusivity.26,30

2.5. Determination of Activation Energy. As shown in eq 22, ln(MR) is linear to the reciprocal of drying temperature (1/(T + 273.15)). Therefore, the activation energy was calculated to be 13.754 kJ/mol using the slope derived. The activation energy was higher than that of sweet potato (11.38 kJ/mol)39 but lower than that of hazelnuts (15.62 kJ/mol)40 and apricot halves (31.40 kJ/mol).41 The differences can be attributed to the fact that MWHA accelerated water removal from the drying materials, resulting in a reduced drying period and activation energy. The activation energy in this study was in the range of 12.7–110 kJ/mol for agricultural and food products.42

Table 3. Statistical Results from Different Mathematical Models at Different Drying Conditions

| drying conditions | slope | R²  | D.mm (10⁻⁶ m²/s) |
|-------------------|-------|-----|------------------|
| slice thickness (mm) | hot-air velocity (m/s) | hot-air temperature (°C) | microwave power density (W/g) |       |       |
| 5                 | 2.5   | 60  | 6                | -0.36433 | 0.99618 | 0.8284 |
| 8                 | 2.5   | 60  | 6                | -0.34813 | 0.99187 | 1.9331 |
| 11                | 2.5   | 60  | 6                | -0.31792 | 0.99622 | 3.3254 |
| 14                | 2.5   | 60  | 6                | -0.31723 | 0.99299 | 5.2719 |
| 17                | 2.5   | 60  | 6                | -0.29072 | 0.99418 | 7.0755 |
| 11                | 1.5   | 60  | 6                | -0.31153 | 0.99602 | 3.2646 |
| 11                | 2.0   | 60  | 6                | -0.29999 | 0.99572 | 3.1018 |
| 11                | 2.5   | 60  | 6                | -0.31694 | 0.99580 | 3.3066 |
| 11                | 3.0   | 60  | 6                | -0.33798 | 0.99242 | 3.5442 |
| 11                | 3.5   | 60  | 6                | -0.35703 | 0.98587 | 3.7218 |
| 11                | 2.5   | 50  | 6                | -0.28394 | 0.98930 | 2.9002 |
| 11                | 2.5   | 55  | 6                | -0.30259 | 0.99383 | 3.1131 |
| 11                | 2.5   | 60  | 6                | -0.31698 | 0.99661 | 3.4241 |
| 11                | 2.5   | 65  | 6                | -0.35980 | 0.97975 | 3.6388 |
| 11                | 2.5   | 70  | 6                | -0.37827 | 0.97992 | 3.8775 |
| 11                | 2.5   | 60  | 4                | -0.12287 | 0.99087 | 1.3292 |
| 11                | 2.5   | 60  | 6                | -0.27757 | 0.99420 | 2.9494 |
| 11                | 2.5   | 60  | 8                | -0.32135 | 0.99505 | 3.3693 |
| 11                | 2.5   | 60  | 10               | -0.59753 | 0.99167 | 6.2622 |

\[ a = -2.0 \times 10^{-4}T^2 + 0.045T^3 - 3.952T^2 + 153.980T - 2238.300 \quad (R^2 = 1.000) \]  

\[ k = -7.0 \times 10^{-3}T^3 + 0.012T^2 - 0.662T + 12.810 \quad (R^2 = 0.912) \]  

\[ g = 0.033T^3 - 5.695T^2 + 323.860T - 6107.100 \quad (R^2 = 0.980) \]  

With sample thickness = 11 mm, air velocity = 2.5 m/s, and air temperature = 60 °C,

\[ a = -2.0 \times 10^{-4}M^3 - 0.005M^2 + 0.127M + 0.814 \quad (R^2 = 0.983) \]  

\[ k = -2.0 \times 10^{-4}M^3 + 0.002M^2 + 0.052M + 0.015 \quad (R^2 = 0.970) \]  

\[ g = -0.896M^4 + 21.610M^3 - 178.400M^2 + 576.750M - 544.760 \quad (R^2 = 1.000) \]
3. CONCLUSIONS

In this study, the drying kinetics of lotus root under different drying conditions (sample thickness = 5–17 mm, air velocity = 1.5–3.5 m/s, air temperature = 50–70 °C, and power density = 2–10 W/g) were investigated. The drying process can be divided into accelerating and decelerating stages, with no constant rate stage. Mathematical models were employed to fit the drying curves obtained. The model proposed by Verma et al. was demonstrated to be the optimized one for drying of lotus root as it exhibited the highest R² and the lowest χ² and RMSE. The EMD coefficients (8.23 × 10⁻⁷ to 7.08 × 10⁻⁸ m²/s) were proportional to sample thickness, air temperature, and power density. The air velocity had a dual effect on the EMD. Specifically, the EMD initially decreased and then increased as air velocity increased. The activation energy was calculated to be 13.754 kJ/mol. The results showed that MWHA drying can significantly reduce the drying period.

4. MATERIALS AND METHODS

4.1. Materials. Fresh lotus roots in consistent shapes and sizes were purchased from a local supermarket. The initial moisture contents of these samples were kept at 81% (wet basis). Specifically, fresh lotus roots were cut into slices with a thickness of 11 mm and left in an air-forced oven at 70 °C for 12 h. All samples were free from decay, diseases, or mechanical damages. The samples were washed, drained, and then packed before being stored at 4 ± 0.5 °C.

4.2. Drying Apparatus. The MWHA dryer (YHMW900-100) was provided by the Heilongjiang Bayi Agricultural University (Figure 4).

![Figure 4. Schematic diagram of the microwave coupled hot-air dryer (1) electric control part, (2) control buttons, (3) indicator, (4) control panel, (5) regulator, (6) temperature control device, (7) microwave control digital display, (8) air flow velocity indicator, (9) magnetron, (10) temperature sensor, (11) microwave cavity, (12) hot-air distributor inlet, (13) rotating glass plate, (14) heater, (15) stainless-steel inlet duct, (16) air flow velocity sensor, (17) centrifugal blower, (18) stainless-steel air outlet duct, and (19) axial fan.](image)

It is composed of a microwave system and a hot-air system. The microwave system includes a magnetron with a frequency of 2450 MHz, a microwave resonator cavity, and a control system. The input and output microwave powers are 1300 and 900 W, respectively. The output microwave power can be tuned in 900–180 W with a step of 180 W, and the drying period can be tuned in 0–180 min. The 330 × 215 × 350 mm³ resonator cavity is made of 304 stainless steels. The hot-air system consists of an airflow distributor, a heater, a control system, and a 550 W centrifugal fan. The 150 × 150 × 30 mm³ airflow distributor is made of 304 stainless steels, and the outlet has 106 holes with a diameter of 8 mm. Additionally, holes with a diameter of 3 mm are evenly distributed on the cavity side wall to remove wet air during drying. The 800 W heater is composed of three far-infrared heating tubes made of carbon fiber and an 89 mm-in-diameter tube made of stainless steels. The temperature and velocity of hot air can be tuned in 30–100 °C and 0–5 m/s, respectively. An interconnection is installed between the cavity and the distributor to achieve uniform feeding of hot air inside the cavity.

4.3. Drying Procedure. Fresh lotus roots were cut into slices with thicknesses of 5, 8, 11, 14, and 17 mm. All slices had a diameter of 60 mm. The hot-air system was kept operating for 10 to 20 min before each test so that the air temperature in the cavity was stabilized at the target level. Then, the samples on a plastic tray were placed in the cavity. Drying of samples with different thicknesses was carried out at varying temperatures (50, 55, 60, 65, and 70 °C) and velocities (1.5, 2, 2.5, 3, and 3.5 m/s) of air and varying power densities of microwave (2, 4, 6, 8, and 10 W/g). During drying, the mass changes of lotus root slices were weighed every 60 s by a balance with an accuracy of 0.01 g. The drying process was completed when the final moisture content of the sample was 8.7% (dry basis). All experiments were conducted in triplicate.

4.4. Moisture Ratio and Drying Rate. During drying, the moisture ratio, which reflects the final moisture contents (dry basis) of samples, was determined by:

\[
MR = \frac{M_t - M_e}{M_0 - M_e},
\]

(13)

where MR refers to the dimensionless moisture ratio, \(M_t\) refers to the moisture content at moment \(t\), \(M_e\) refers to the moisture content at equilibrium, and \(M_0\) refers to the moisture content at moment \(t_0\).

The drying rate is an important parameter for drying kinetics study, and it was calculated by:

\[
DR = \frac{M_t - M_{t+\Delta t}}{\Delta t},
\]

(14)

where DR refers to the drying rate (kg water/kg dry mass min⁻¹), and \(M_t\) and \(M_{t+\Delta t}\) are the moisture contents at moments \(t\) and \(t + \Delta t\), respectively.

To further understand drying kinetics, eleven mathematical models were employed to fit the drying curves (Table 4). Generally, these models are obtained based on simplified Fick’s second law and the direct correlation of the average moisture content (dry basis) and the drying period.

The coefficient of determination (R²), chi square (\(\chi^2\)), and root-mean-square error (RMSE) were employed to identify the optimized fitting. Among them, R² serves as the primary criteria to evaluate the quality of fittings by these models, while \(\chi^2\) and RMSE reflect the fitting suitability. \(\chi^2\) and RMSE are negatively related to the fitting suitability. R², \(\chi^2\), and RMSE were calculated by:

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

(15)
Table 4. Mathematical Models Used to Fit Drying Curves

| model name     | model equation | reference |
|----------------|----------------|-----------|
| Page           | MR = exp(−kt*) | 45        |
| modified Page  | MR = exp(−kt)  | 46        |
| Newton         | MR = exp(−kt)  | 30        |
| Verma et al.   | MR = a exp(−kt) + (1 − a) exp(−gt) | 34        |
| two-term       | MR = a exp(−kt) + (1 − a) exp(−kt*) | 47        |
| Milli et al.   | MR = a exp(−kt*) + bt | 48        |
| Wang and Singh | MR = 1 + at + bt² | 49        |
| logarithmic    | MR = a exp(−kt) + ε | 50        |
| Henderson and  | MR = a exp(−kt) | 51        |
| Pabis           | two term       | 42        |
|                 | MR = a − b exp(−kt) | 52        |

\[
\chi^2 = \sum_{i=1}^{N} \frac{(MR_{\text{exp},i} - MR_{\text{pre},i})^2}{N - j} \tag{16}
\]

\[
\text{RMSE} = \sqrt{\sum_{i=1}^{N} \frac{(MR_{\text{pre},i} - MR_{\text{exp},i})^2}{N}} \tag{17}
\]

where MR_{\text{exp},i} refers to the \(i\)th moisture ratio obtained experimentally, MR_{\text{pre},i} refers to the \(i\)th moisture ratio predicted based on models, \(N\) refers to the quantity of observations, and \(j\) refers to the quantity of constants.

4.5. Effective Diffusivity of Moisture. The effective diffusivity of moisture, which is an essential parameter for calculation and simulation of moisture migrations in food and other materials, can be determined based on simplified Fick’s second law. Assuming that moisture was migrated by diffusion and shrinkage was negligible, the effective diffusivity of moisture can be calculated by \(^{26,43}\)

\[
MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n + 1)^2} \exp\left(-\frac{(2n + 1)^2\pi^2D_{\text{diff}}t}{4L^2}\right) \tag{18}
\]

where \(D_{\text{diff}}\) refers to the effective diffusivity of moisture (\(\text{m}^2/\text{s}\)), \(L\) refers to the half-thickness of the sample (m), \(t\) refers to the drying period (s), and \(n\) is a positive integer.

Since \(M_t\) is much smaller than \(M_0\) and \(M_0 - M_e\) is negligible in the calculation of MR. Hence, eq 18 could be further simplified as \(^{64}\)

\[
\ln(MR) = \ln\left(\frac{8}{\pi^2} \frac{\pi^2D_{\text{diff}}t}{4L^2}\right) \tag{19}
\]

\(D_{\text{diff}}\) could be calculated by plotting curves in the form of \(\ln(MR)\) vs the drying period

\[
\text{slope} = \frac{\ln(MR) - \ln\left(\frac{8}{\pi^2}\right)}{t} = -\frac{\pi^2D_{\text{diff}}}{4L^2} \tag{20}
\]

4.6. Activation Energy. The activation energy, which refers to the amount of energy required to remove one mole of moisture from the drying material, can be calculated by \(^{69}\)

\[
D_{\text{diff}} = D_0 \exp\left(-\frac{E_a}{R(T + 273.15)}\right) \tag{21}
\]

where \(D_0\) refers to the pre-exponential factor (\(\text{m}^2/\text{s}\)), \(E_a\) refers to the activation energy (kJ/mol), \(R = 8.314 \times 10^{-3}\) \(\text{kJ mol}^{-1}\) \(\text{K}^{-1}\) refers to the universal gas constant, and \(T\) refers to the drying temperature (°C).

Equation 21 can be rearranged by taking logarithms of both sides

\[
\ln(D_{\text{exp}}) = \ln(D_0) - \frac{E_a}{R(T + 273.15)} \tag{22}
\]

4.7. Statistical Analysis. Data analysis was conducted by Origin (Version 8.5). The least significant differences at a 95% confidence level (\(p < 0.05\)) were obtained by Duncan’s multiple-range test. All tests were conducted in triplicate.

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Notes
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