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Effect of slice thickness and hot-air temperature on the kinetics of hot-air drying of Crabapple slices

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Abstract

This study was investigated the effects of hot-air temperature and slice thickness on drying characteristics of Crabapple slices. Drying experiments were carried out in the ranges of 60-90 °C. The thickness conditions of Crabapple slices for thin layer drying were 3mm and 5mm. The increase in the temperature of the hot-air and the decrease in the thickness of the slicing causes the drying time to be significantly shortened. Fick's diffusion model was applied to describe the water transfer of the Crabapple slices, and the effective diffusion coefficients varied from $0.6142 \times 10^{-8} m^2/s$ to $1.9867 \times 10^{-8} m^2/s$ in a given range of drying temperature. The effective diffusivity increases with increasing temperature. The activation energy values of Crabapple were 17.46 and 23.82 kJ/mol for the thickness of 3 and 5 mm, respectively. The Page model was revealed to be a better fit to describe the drying curve of Crabapple compared to other models.

Keywords: crabapple slices; hot-air drying; drying kinetics; effective diffusion coefficients; activation energy.

Practical Application: Hot-air drying mathematical model of Crabapple slices can be used as a guideline toward optimal design of drying methods and conditions. Drying-kinetics models are essential for equipment design, process optimization and product quality improvement.

1 Introduction

Crabapple belong to the genus Malus (Rosaceae family). Crabapple are widely distributed in colder regions such as North America, Europe, and East Asia. In China, it is mainly distributed in Heilongjiang Province, Liaoning Province, Jilin Province and Inner Mongolia area (Dadwal et al., 2018). Crabapple are rich sources of nutritional value, such as minerals, vitamins, and fiber, which provide essential nutrients for human health (Li et al., 2014). In addition, the medicinal value of Crabapple has been extensively studied because they contain various phenolic compounds and antioxidant flavonoids (Sharma & Nath, 2016; Li et al., 2014). Li et al. (2016) suggested that Crabapple may reduce cholesterol by enhancing the CYP7A1 function in the liver. Qin et al. (2015) concluded that the dihydrogen detection compounds in begonia leaves have anti-cancer effects.

Compared with apples, the diameter of Crabapple is relatively small, about 3 cm, intensely sour and hard, which is not suitable for ingesting as food directly (Li et al., 2016). Therefore, Crabapple are generally used for jams and jellies and beverages. Drying is a common method used to extend shelf life and ease the storage of Crabapple. Sun-drying is not only limited by weather conditions but also requires a long time. Besides, the sun-drying method is inconvenient in controlling the contamination from microorganisms and dust during exposure (Shree, 2022). The advantage of freeze-drying is that it yields high-quality products, but it requires an expensive process and has a limited range of applications. Hot-air drying is a popular alternative technology because it is simple, quick, and economical (Jha & Sit, 2020).

Drying kinetics describe a complex system between moisture removal and drying process variables, which is influenced by drying conditions, types of dryers and properties of the material to be dried (Deng et al., 2019). Therefore, predicting drying characteristics and optimizing dry parameters facilitate the improvement of the quality of dried Crabapple (Biswas et al., 2022). Finding a suitable kinetic model to evaluate the practicality of drying is necessary to improve the quality of Crabapple and optimize drying parameters. In previous studies, researchers have explored the drying behavior of a variety of fruit slices and developed mathematical models to describe the drying behavior. Kırbaş et al. (2019) studied the effects of freeze drying and microwave drying on the drying characteristics of pomelo fruit treated with different models. Pinar et al. (2021) found the effects of different drying methods on the drying kinetics of different pepper varieties. Hossain et al. (2021) use multiple models, such as Newton, to reveal the thin dewatering characteristics of Tailor. This was also observed by Ataides et al. (2022) for Araticum fruits used multiple models to predict drying properties.

Therefore, the aim of this paper was to investigate the effect of drying temperature and slice thickness on the drying characteristics of Crabapple slices. Furthermore, the impact of different dry variables (thickness and temperature) on the effective diffusion coefficient and activation energy of the

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Crabapple during the drying process were also calculated. This study could help select the best drying model for Crabapple, a better understanding of the drying characteristics of Crabapple and the effect of drying on the quality of Crabapple slices.

2 Materials and methods

2.1 Materials

Crabapple are purchased from local orchards in China. The experiment used fresh, bright colors, uniform size, free from pests and diseases, and sample selection and mechanical damage. The Crabapple are washed with distilled water and peeled manually. In this experiment, the Crabapple were cut into 3mm and 5mm thick with the core removed and measured with a vernier caliper. The average diameter of the Crabapple is 3.39 ± 0.2 cm. The initial moisture content of Crabapple was determined according to standard methods. The sample sections were weighed on an electronic balance. Finally, put it into an electric heating constant temperature blast drying oven (DHG-9053A).

2.2 Experimental procedure

Drying experiments using laboratory-scale electric electrothermal constant temperature blast drying oven (DHG-9053A, Shanghai Jinghong Experimental Facilities Corporation Ltd, Shanghai, China). The dryer mainly consists of a heat control unit, which can fix temperatures ranging from 10 to 250 °C, a heating chamber, a temperature probe, a fan, and a temperature fluctuation of ±1 °C. The experimental drying procedures in the heating air blast were carried out at 60 °C, 70 °C, 80 °C, and 90 °C, respectively. The constant wind speed of the dryer is 1.0 m/s. Before the drying experiment, the dryer was set to the desired temperature for approximately one hour to ensure that each group of experiments was carried out at the predetermined temperature.

Then, Crabapple samples were spread in a thin layer on the wire mesh, ensuring each slice was a single layer without any overlapping parts. Crabapple samples were placed in a thin layer on the stainless net in the middle of the heating chamber. The weight of the sample was kept at 150 ± 0.1 g and recorded at 10 min intervals.

The sample was weighed with an electron analytical balance (±0.01 g accuracy, JA5003, Shanghai Balance Instrument Plant, Shanghai, China). Sample quality was measured every 10 minutes. When the mass of the sample remains constant after three times, it is considered to have reached equilibrium. Each sample was measured at each drying temperature three times to obtain the average value. Samples are randomly taken for analysis based on pre-set drying times.

2.3 Mathematical model

In those models, MR represents the ratio of the free water content of a sample to the initial water content. The moisture ratio(MR) of Crabapple slices under various drying conditions was calculated using the following Equation 1 (Aydar, 2021):

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

where M and M_0 are the moisture content of the product at any drying time and at the initial time, respectively. Me is the equilibrium moisture content. The value of Me is relatively small compared to M or M_0 and can be ignored. Thus, the equations can be simplified to MR =M/M_0.

Then, the drying rate (DR) of Crabapple was calculated as Equation 2 (Tamarit-Pino et al., 2020)

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

where Mt and Mt+Δt are moisture content at time t (kg water/kg dry matter) and moisture content at time t+Δt, respectively, t is time (min), and dt is the time difference (min).

2.4 Correlation coefficient and error analysis

In order to select an appropriate mathematical model to describe the drying process of sliced Crabapple, this study uses the theoretical model-diffusion model and five ordinary classical thin-layer drying model equations to represent the drying curve of sliced Crabapple. Table 1 shows the model equations for empirical thin-layer drying.

This experiment uses OriginPro8.5(OriginPro 8.5; OriginLab Corp., Northampton, MA, USA) mathematical and statistical software to analyze linear and non-linear regression equations and then gives various statistical parameters such as the measurement coefficient (R^2) and the reduced chi-square (χ^2).

R^2 is the primary criteria of the statistical analysis parameters of the drying curve of the material, and the χ^2 is the reduced chi-square. χ^2 is according to the following Equation 3 (Engin, 2020):

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{3}$$

where MR_{exp}, i is the experimentally observed moisture ratio, MR_{pre}, i is the predicted moisture ratio, N is the number of observations, and z is the number of constants in the model.

Table 1. Thin-layer drying models used for mathematical of drying of Crabapple slices.

No.	Model name	Model	References
1	Newton	MR= exp(-kt)	Engin (2020)
2	Henderson and Pabis	MR= aexp(-kt)	Macedo et al. (2020)
3	Page	MR= exp(-kt^n)	İsmail et al. (2015)
4	Logarithmic	MR= aexp(-kt)+c	Demiray & Tulek (2014)
5	Two-term	MR= aexp(-kt)+bexp(-k_0t)	Silva et al. (2022)

Where a, b, c, k and k_0 are characteristic constants of different models; and t is drying time (min).

The model was best when χ^2 was at a minimum value and R^2 at a maximum value.

2.5 *Calculation of effective diffusivities*

The drying characteristics of raw food products in the falling rate period are generally calculated by the Fick diffusion Equation 4. In 1975, Crank developed this equation into Equation 5 (Crank, 1975).

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}\left(\nabla M\right)\right] \tag{4}$$

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2\pi^2 D_e t}{4L_0^2}\right) \tag{5}$$

where Deff is the effective moisture diffusion, m2/ s; L0 - is the half thickness of the Crabapple slices; n is required to be a positive integer.

In the actual calculation, for a longer drying process, Equation 6 can be directly simplified to the following equation (Vijayan et al., 2020).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{dj} t}{4L_0^2}\right) \tag{6}$$

Take the calculated MR to the correct number, then use the drying time T as the horizontal coordinate and Ln (MR) as the vertical coordinate system to make a straight-line equation (Equation 7).

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{\in ff} t}{4L_0^2} \tag{7}$$

Equation 8 is as follows:

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4L_0^2} \tag{8}$$

2.6 *The calculation of activation energy*

The simplified Arrhenius equation represents the water diffusion coefficient and temperature relationship. Activation energy can be confirmed from the slope of the linearized plot of Equation 9 (Demiray & Tulek, 2014):

$$D_{\in ff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{9}$$

where D_0 represents the experimental factor in the Arrhenius equation (m^2/s); Ea stands for activation energy (KJ/mol); R is the gas constant (8.314 KJ/mol K); T stands for absolute temperature (K).

According to the experimental drying data, a line with X-axis as drying time and the y-axis as ln(MR) is drawn. The value of the effective water diffusivity can be obtained from the slope of the line (Equation11). The calculation formula is as follows (Omolola et al., 2019) (Equation 10):

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R} \bullet \frac{1}{T} \tag{10}$$

$$\text{Slope} = -\frac{E_a}{R} \tag{11}$$

3 Results and discussion

3.1 *Drying characteristic*

The Crabapple slices were dried in an electric electrothermal constant temperature blast drying oven and dried with thicknesses of 3 and 5mm at selected temperature levels (60,70,80, and 90°C). Figure 1 shows the variations in the moisture ratio of the Crabapple at different thicknesses and temperatures, depicting the relationship between the water ratio (MR) and the drying time. As seen from the Figure 1, the moisture content continued to decrease with the extension of drying time. Demiray & Tulek (2014) investigated the same results that the MR of the garlic samples considerably decreased with increasing drying time.

Interestingly, the decrease in slice thickness and an increase in operative temperature resulted in a reduction of the drying time. The equilibrium moisture time of the Crabapple with the slice thickness of 3 mm was 160, 130, 110 and 100 min at 60, 70, 80 and 90 °C, respectively. Moreover, the Crabapple slices of 5mm consume significantly longer time which was 260, 200,

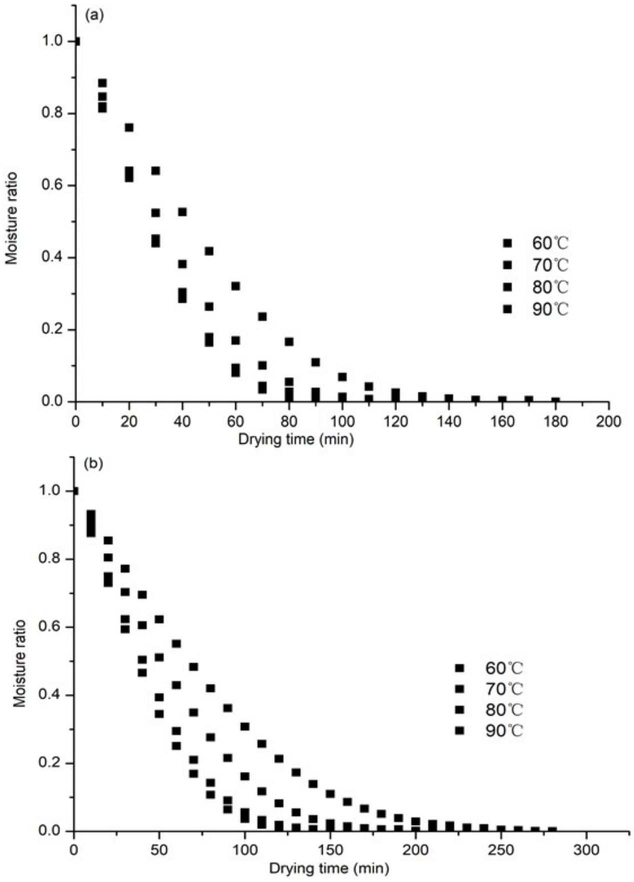

Figure 1. Drying curves of Crabapple slices undergoing hot-air at different temperatures for sample thickness of (a) 3 mm and (b) 5 mm.

150, 140 min at the corresponding temperature, respectively. Regardless of other conditions, the thickness of the red fruit increases, and the drying time is prolonged. One explanation of this phenomenon could be indicated by the reduced water travel distance and increased sample surface area. Doymaz & İsmail (2011) found that the drying time of pumpkin slices is longest at 60 °C and shortest at 75 °C. The effect of temperature and slice thickness on drying time was following earlier study on Madeira banana and Esmolfe apple (Pinheiro et al., 2022).

3.2 Drying rate curve

Figure 2 shows the drying rate curves of the Crabapple slices of 3mm and 5mm at different drying temperatures (60, 70, 80 and 90 °C). The moisture content gradually decreased with the increase in drying time. As expected, the drying temperature of the slices increased, and the drying time was significantly shortened. This is due to the significant difference in steam pressure between the fruit slices and the surrounding environment at a higher temperature. As a result, the rate of water migration gradually decreased from the inside to the outside of the sample (Wang et al., 2022a). The study by Jiang et al. (2021) found that the average migration rate of moisture inside wheat grains was smaller than the average evaporation rate outside wheat grains. He et al. (2021) also concluded that promoting sea cucumber moisture transfer movement during the drying process could shorten the drying time. These results agree with (Bhattacharya et al., 2015; Miraei Ashtiani et al., 2018).

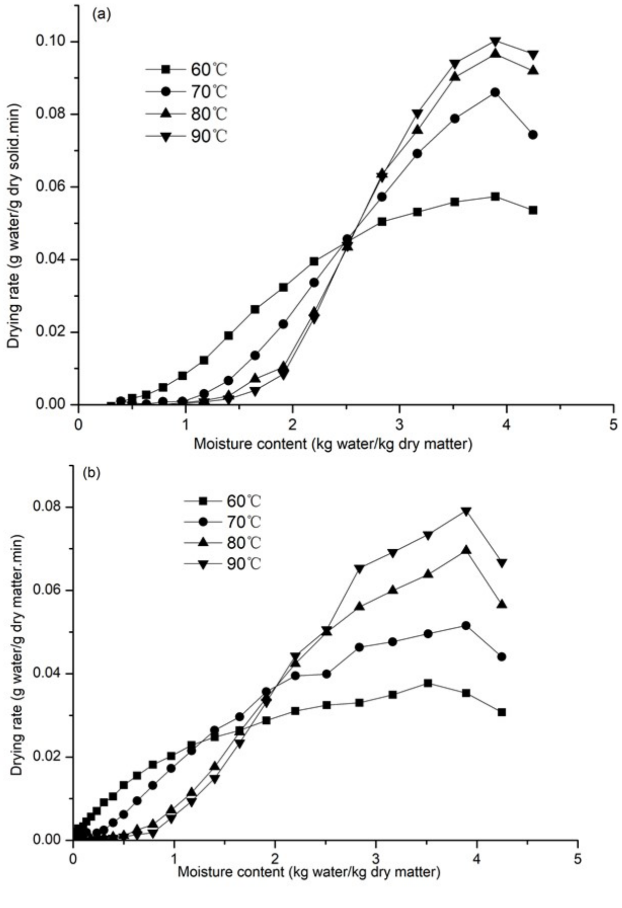

Figure 2. Drying rate versus moisture content of Crabapple slice undergoing hot-air at different temperatures for sample thickness of (a) 3 mm and (b) 5 mm.

The thickness of the Crabapple slices also affects the drying time (Figure 2). With the same moisture content, the thinner the thickness of the piece, the greater the drying rate, and the shorter the drying time of the red sliced slices. The slice thickness is 3mm and 5mm, and the moisture content is more than 2.5 kg water/kg DW and 2 kg water/kg DW, respectively. However, when the moisture content of Crabapple slices was less than 2.5 kg water/kg DW and 2 kg water/kg DW, respectively, the drying rate decreased with the increase in drying temperature. The above phenomenon shows that at the same slice thickness when the drying process is about to end, the lower the water content inside the slice, the smaller the drying rate. It is more difficult to exclude the moisture in the slice. Jongyingcharoen et al. (2019) found that the smaller the thickness of coconut dregs, resulting in a shorter drying time during the drying process (70 minutes). Ndisya et al. (2020) found that the thickness of the sample slice increased the drying time in the hot-air drying experiment of purple spotted coconut slices. Similar results on the effect of the thickness have been reported for carrot slices (Doymaz, 2017), papaya (Sairam et al.,2017) and gastrodia elata (Li et al., 2021). The drying rate decreased continuously with the decrease of moisture content and increased with the increase of temperature. From the figure, the sliced Crabapple did not show a continuous drying period. The whole drying process represents a period of decreasing rate. Some previous studies have also found that the drying rate increases with temperature, such as 'gueroba' fruit pulp (Jorge et al., 2021), pear slices (Doymaz & Ismail, 2012), tomato slices (Sadin et al., 2014) and (Cuccurullo et al., 2019).

3.3 Drying model

Table 2 represents the statistical results and the values of coefficient and reduced chi-square obtained by different thin layer drying models. As can be seen from Table 2, the R^2 and X^2 values in all drying models ranged from 0.9703 to 0.9988,0.00012 to 0.00335, respectively. The values of R^2 obtained from the Page equation are higher than those from other models. The values of R^2 in all the models were greater than 0.96, which indicates that the fitting is good (Doymaz, 2011). From Table 2, the values of R^2 and X^2 in the Page equation model are maximum and minimum, respectively. Therefore, the Page model can be assumed to illustrate the thin layer drying behavior of Crabapple sliced. Figure 3 shows the comparison of the predicted moisture ratios obtained by Page model and the experimental moisture ratio values at various drying air temperatures 60, 70, 80 and 90 °C.

3.4 Effective diffusion coefficient calculation

The effective moisture diffusivity (D_{eff}) is usually considered an index of drying hydrodynamic mass transfer. D_{eff} is affected by temperature and slice thickness (Mahapatra and Tripathy, 2018). The value of the effective diffusion coefficient is calculated based on the Equation 6 of the sliced redness, and the calculation value is shown in Table 3. The effective diffusivity of water of the Crabapple was $0.6142 \times 10^{-9} \sim 1.9867 \times 10^{-8}$($m^2/s$) during the drying process at 60 °C~90 °C. From Table 3, the value of the water effective diffusion coefficient increases with the increase in drying temperature. Generally, the effective diffusion coefficient of food is 10^{-12}~10^{-8} (Jha & Sit, 2020). Macedo et al. (2020) reported that the effective diffusivities of sliced bananas were 3.538×10^{-9} m^2 s^{-1}. Besides, at a constant drying temperature, D_{eff} values increase with slice thickness. Torubeli et al. (2021) studies of the drying kinetics of okra at various thicknesses have shown that values at all temperatures of 5mm are higher than values at 10mm and 15mm. This is because diffusion channels are smaller in larger samples and moisture is more readily migrated, resulting in greater D_{eff} (Deng et al., 2018).

Table 2. Statistical results obtained from various thin-layer drying models.

Model name	Slice thickness(mm)	temperature (°C)	R^2	X^2
Page	3 mm	60	0.9983	0.00018
		70	0.9979	0.00021
		80	0.9987	0.00014
		90	0.9984	0.00019
	5 mm	60	0.9987	0.00013
		70	0.9984	0.00017
		80	0.9987	0.00013
		90	0.9988	0.00012
Two-term	3 mm	60	0.9799	0.00205
		70	0.9762	0.00253
		80	0.9866	0.00144
		90	0.9743	0.00284
	5 mm	60	0.9799	0.00205
		70	0.9762	0.00253
		80	0.9866	0.00144
		90	0.9743	0.00284
Newton	3 mm	60	0.9703	0.00327
		70	0.9791	0.00215
		80	0.9745	0.00294
		90	0.9719	0.00335
	5 mm	60	0.9734	0.00271
		70	0.9713	0.00306
		80	0.9718	0.00303
		90	0.9717	0.00312
Longic	3 mm	60	0.9884	0.00128
		70	0.9882	0.00122
		80	0.9859	0.00162
		90	0.9854	0.00174
	5 mm	60	0.9929	0.00072
		70	0.9903	0.00103
		80	0.9935	0.00137
		90	0.9875	0.00138
Henderson	3 mm	60	0.9985	0.00016
		70	0.9979	0.00021
		80	0.9981	0.00014
		90	0.9984	0.00018
	5 mm	60	0.9980	0.00013
		70	0.9986	0.00014
		80	0.9981	0.00015
		90	0.9982	0.00013

Table 3. Values of effective diffusivity attained at various air temperatures on hot-air drying of Crabapple slices with different thickness.

Hot-air temperature (°C)	Effective diffusivity (m^2/s) $\times 10^{-9}$	
	Slice thickness: 3 mm	Slice thickness: 5 mm
60	0.99	0.61
70	1.41	0.76
80	1.90	0.83
90	1.98	1.08

3.5 Calculation of activation energy

Dry activation can indicate the minimum energy required by the unit Moore's moisture during the drying process. The greater the activation of the material, the more difficult it is to dry (Wang et al., 2018c). The two sides of the Equation 9 take the natural number to get the following equations:

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R} \bullet \frac{1}{T} \qquad (12)$$

The Equation 12 shows that Ln Deff is linear with a slope reciprocal to absolute temperature, and the activation energy (Ea) can be calculated from Figure 4. The activation energy of

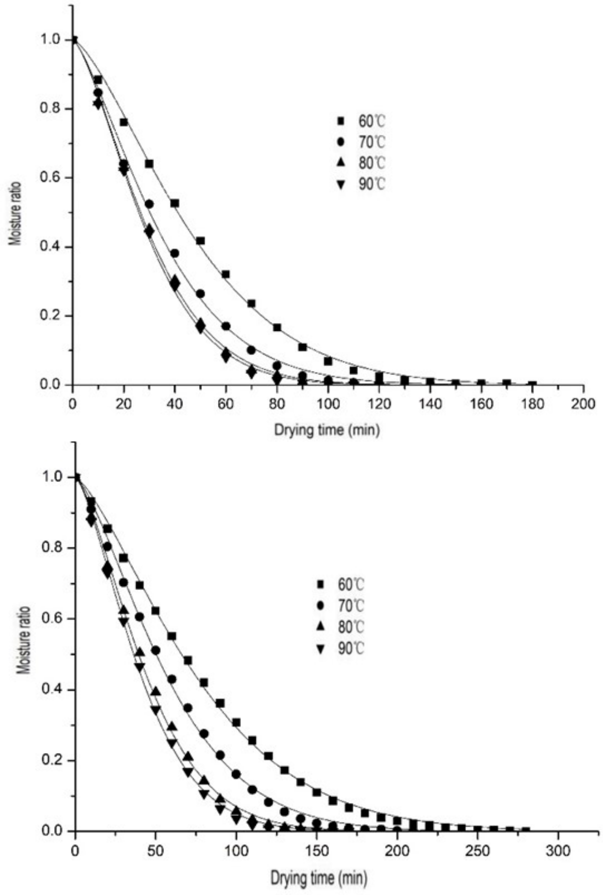

Figure 3. Comparison of drying curves of Crabapple slices undergoing hot-air drying for sample thickness of (a) 3 mm and (b) 5 mm. Solid line (d) represents curve fitting using Page model.

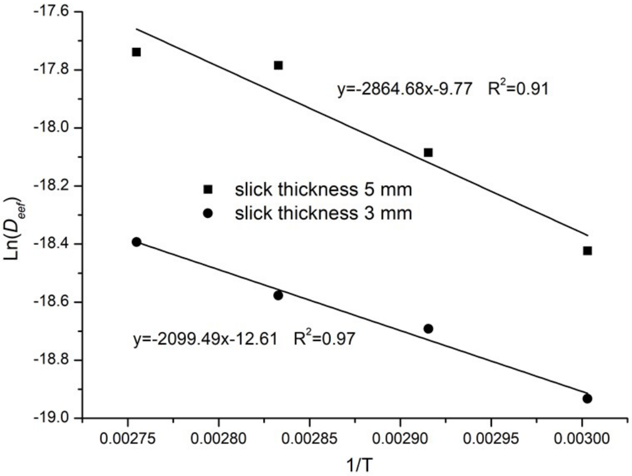

Figure 4. The Arrhenius- type relationship between effective diffusivity and drying temperature.

all samples ranged from 10–110 kJ/mol (Rafiee et al., 2010). The activation energy of 3mm and 5mm sliced Crabapple were 17.46 and 23.82 KJ/mol, respectively. The activation energy of the Crabapple resembles the gala apples (19.20~27.10 kJ/mol) (Kriaa & Nassar, 2022), taro (18.04 ~ 28.78 KJ/mol) (Abbaspour-Gilandeh et al., 2019) and elephant cassava (22.91 KJ/mol) (Kosasih et al., 2020). It is higher than the activation energies of 14.97 kJ/mol for okra slice (Afolabi & Agarry, 2014) and Asian white radish (16.49~20.26KJ/mol) (Lee & Kim, 2009). But these values are lower than that of the walnut kernel (26.35~36.44 kJ/mol) (Kaveh et al., 2018), Flos Lonicerae (28.90~36.05 kJ/mol) (Liu et al., 2015) and values of (25.66~30.29) KJ /mol by Wang et al. (2022b) for Chinese jujube slices.

4 Conclusion

The study showed that drying temperature and slice thickness have a certain effect on the Crabapple slices. The high drying temperature and thin slicing thickness can shorten the drying time. The drying stage of the Crabapple showed a descending rate drying duration without a constant rate interval under our drying conditions. The effective diffusion coefficient increased with the increase of drying temperature and slice thickness. The effective diffusion coefficient was determined to be between 0.6142×10^{-8} m2/s and 1.9867×10^{-8} m^2/s. The activation energy also increased with the thickness of the slice. The value of 3mm sliced red activation energy was found at 17.46 KJ/mol, and that of 5mm was 24.82KJ/mol. The Page equation model can well describe the drying process of Crabapple because it expresses the maximum of R^2 and the minimum of X^2. Therefore, the Page model was the most suitable for describing the drying characteristics of the sliced Crabapple.

Conflicts of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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