Mathematical modeling of debittered apricot (Prunus armeniaca L.) kernels during thin-layer drying

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ABSTRACT
In this paper, the effect of drying temperature was investigated on the drying kinetics of the debittered and skin-removed apricot kernels, and the thin-layer drying model was also constructed by fitting the eight mathematical models such as Henderson and Pabis, Logarithmic, Midilli et al. and Approximation of diffusion model. Among them, the Midilli et al. and Approximation of diffusion models were selected to describe the drying characteristics of apricot kernels due to their relatively higher coefficient of determination ($R^2$), and lower chi-square ($\chi^2$) and root mean square error (RMSE). Beyond that, the moisture loss and the effective moisture diffusivity ($D_{eff}$) of the kernels during drying were also described and estimated by Fick’s second law and the data obtained, getting a range of $1.39 \times 10^{-8}$ to $3.5 \times 10^{-8}$ m$^2$/s, respectively. The temperature dependence of the diffusivity coefficients was described with the activation energy (Ea) value of 16.5 kJ/mol. All these results are beneficial for better understanding and controlling the drying of apricot kernels.

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1. Introduction
The apricot (Prunus armeniaca L.) is included in the genus prunus of the subfamily Prunoideae in the family Rosaceae. It is mainly distributed throughout Central Asia, West Asia, the Mediterranean region and Western China. According to Food and Agricultural Organization (FAO), the total global production of apricots is about 4.1 million tons. Turkey, Iran, Uzbekistan, Algeria and Italy are the major producers of apricot (FAO, 2015).

Apricot kernels are a rich source of nutrients such as crude oil (43–53%, w/w, dry weight basis), protein (25–26%, w/w, dry weight basis), and soluble sugar (6.5–14%, w/w, dry weight basis) (Femenia, Roselló, Mulet, & Cañellas, 1995) and are associated with the improvement of human health in the following examples. They can decrease low-density lipoprotein (LDL) cholesterol levels, increase the high density lipoprotein (HDL) cholesterol levels in human beings (Hyson, Schneeman, & Davis, 2002) and reduce the risk of colon cancer (Davis & Iwahashi, 2001). Polyphenols are also health-promoting compounds in apricot kernels which have been shown to be a protective agent against cancer and cardiovascular disease (Liu, 2004; Knekt et al., 2002). The antioxidant properties and the function of regulating intestinal flora of human beings have also been studied by some researchers (Durmag & Alpaslan, 2007; Korekar, Stobdan, Arora, Yadav, & Singh, 2011). Regarding consumption, apricot kernels are typically used as snack foods in the same way as roasted almonds, salted almonds and spiced almonds, and they are used as ingredients in a variety of processed foods, especially in confectionery and bakery products (Sang, et al., 2002).

According to the amygdalin content, apricot kernels can be classified as bitter apricot kernels and sweet apricot kernels (usually called almonds), and the amygdalin content in the former is higher than that of the latter (Yildirim & Askin, 2010). The bitter apricot kernels cannot be eaten directly due to the hydrolysed products of amygdalin-hydrocyanic acid, a toxic substance. Thus, the elimination of amygdalin is a necessary procedure during the processing of bitter apricot kernels. Nowadays, the method usually employed to remove the amygdalin is immersing the bitter kernels into water at a given temperature for a long time. The immersion, however,
leads to the relatively high moisture content and rancidity of fatty acids in the amygdalin-eliminated apricot kernels. Therefore, some treatments are required to effectively preserve them, and drying is one of the most effective (Vagenas & Marinos-Kouris, 1991). The products made from the dried apricot kernels have a leading position in the apricot nuts market because their long shelf life and the ways in which they can be eaten.

Drying of foodstuffs is a common industrial preservation method applicable to a wide range of agricultural and industrial products. After drying, the content of moisture and hence water activity of fruits and vegetables are reduced in order to decrease the chemical, biochemical and microbiological deterioration. Natural open-air sun drying is the most common method employed for long-term preservation of agricultural products as it is a cheap method of preservation thanks to the free and renewable energy source. However, this technique is extremely weather dependent and risky as it is open to environmental contamination, insect infestation, and microbial attack (Aghbashloo, Kianmehr, & Samini-Akhvijanahi, 2008; Doymaz & Ismail, 2011). Also, quite a long drying time is required for a given load. In order to improve the quality of products, many industrial drying methods have been studied such as solar, hot-air, vacuum, oven and microwave drying to replace sun drying (Midilli & Kucuk, 2003; Doymaz, 2007; Arslan & Özcan, 2010). Thin-layer drying is also an important drying method in food processing where the drying materials are fully exposed to the dry environment (Wang et al., 2007).

Although several authors have reported research thin-layer drying behavior of different food materials (Kashaninejad, Mortazavi, Safekordi, & Tabil, 2007; Sacilik, Keskin, & Elicin, 2006; Toğrul & Pehlivan, 2003; Shi, Zheng, & Zhao, 2013), to the best of our knowledge, there is little literature available about the thin-layer drying of the apricot kernel and its kinetic model. Generally, knowledge of drying kinetics of the bitterness-eliminated apricot kernels is essential to designing, simulating, optimizing and managing the industrial drying process. In addition, the increasing demand for high quality dried products also requires an investigation of the drying characteristics of apricot nuts to retain the quality attribution in the dried products (Irigoien & Giner, 2014). Considering this, the main objective of this paper is focused on the following objectives:

1. To determine the influence of drying temperature on the drying behavior of amygdalin elimination apricot kernels at laboratory scale.
2. To evaluate a suitable drying mathematical model for interpreting the drying process of apricot nuts.
3. To estimate the effective drying mathematical model for interpreting the drying process of apricot nuts.

Information derived from this work will available to design an appropriate dryer and make recommendations for optimal drying conditions for the drying of bitterness-eliminated apricot kernels.

2. Materials and methods

2.1 Sample preparation and drying process

Drying experiments were performed in an electrothermal air blast dryer (Type 101, Beijing KeWei Instrument Co. Ltd, China) at laboratory scale. The experiments were conducted at four drying temperatures of 60, 80, 100, 120 °C, each drying set-up was performed in triplicate, and the average values of recorded moisture content were used for further analysis. Before each drying experiment, the dryer was run at the selected temperature for about 20–30 min to achieve a steady state. Raw unpeeled bitter apricot kernels were purchased from the Northwest medicine market in Xi’an City, China. The uniform size and full grain nuts were manually selected without noticeable defects and cracks. The selected samples were immersed in water heated to 100 °C for 3–5 min to peel off the skins, and then the peeled samples were steamed in water heated to 60 °C for about 6–8 h to remove the amygdalin. Then about 500 g of debittered apricot kernels were uniformly distributed on a tray (48.5×30 cm) in the dryer at the given drying conditions. The digital balance with accuracy ±0.001 g (JA2003, HangPing Instrument Co. Ltd., China) was used to measure the mass of samples. Periodic weighing was performed every 5 min throughout the drying process. Drying was terminated until the moisture content decreased to 2.3±0.7% (d.b) from the initial value of 44.6±0.5% (d.b.). Drying experiments were repeated three times. Figure 1 shows the flowsheet of the experiments.

2.2 Mathematical modeling of drying curves and formulation

The moisture ratio (MR) and the drying rate (DR) of debittered apricot kernels were calculated using the following equations during the drying experiments:

\[
MR = \frac{M - M_e}{M_0 - M_e} \\
\frac{DR}{dt} = \frac{M_{k,dt} - M_k}{dt}
\]

where \(M, M_0, M_e, M_k\), and \(M_{k,dt}\) are the moisture content at a given time, initial moisture content, equilibrium moisture content, moisture content at the time of \(t\) and moisture content at the time of \(t+dt\) (kg water/kg dry matter), respectively, and \(t\) is the drying time (min).

Accurately modeling the drying behavior of debittered apricot kernels is very important for studying drying kinetics. For the sake of this, the experimental drying kinetics data for each of the four tested temperatures were correlated to eight commonly used drying models, which are widely used for most organic and biological materials (Kashaninejad et al., 2007; Goyal, Kingsly, Manikantan, & Ilyas, 2007; Doymaz, 2007; Ong & Law, 2009; Pereira-Flores et al., 2012; Shi et al., 2013; Zhu & Shen, 2014; Koukouch et al., 2015). The selected models used to explain the drying data of apricot nuts are described below.

2.2.1 The Henderson and Pabis model

The Henderson and Pabis model is the first term of a general series solution of Fick’s second law. Bi-parametric exponential model is another definition of this model. The Henderson and Pabis model has produced good correlations in predicting the drying of corn (Henderson & Pabis, 1961) and pumpkins (Hashim, Daniel, & Rahaman, 2014). This model can be written as:
2.2.2 The Modified Henderson and Pabis model

The Modified Henderson and Pabis model is proved to be a common drying mathematical model. This model has been successfully used to correlate drying kinetics at different operation conditions for apricots (Toğrul & Pehlivan, 2004) and cork planks (Costaa & Pereirab, 2013). The model can be expressed as follows:

\[ MR = \frac{M - M_e}{M_0 - M_e} = a \exp\left(\frac{-kt}{y}\right) + b \exp\left(\frac{-k_0t}{y}\right) + c \exp\left(\frac{-k_1t}{y}\right) \]  

(4)

where \( a, b, c, k, k_0 \) and \( k_1 \) are the constants of the model and \( t \) is the time.

2.2.3 The Page model

The Page model is an empirical modification of the Lewis model that corrects some shortcomings. This model has been used to describe the drying of many agricultural products, such as corn (Page, 1949), pistachio nuts (Kashaninejad et al., 2007) and green soybean (Yang & Zhu, 2015). This model is given as:

\[ MR = \frac{M - M_e}{M_0 - M_e} = \exp\left(\frac{-kt}{y}\right) \]  

(5)

where \( k \) and \( y \) are the constants of the model and \( t \) is the time.

2.2.4 The Modified Page model

The Page model was modified to explain the drying characteristics of biological materials called Modified Page model. This model could sufficiently describe the drying kinetics of soybeans (Overhults, White, Hamilton, & Ross, 1973) and onions (Arslan & Özcan, 2010). The model is expressed as:

\[ MR = \frac{M - M_e}{M_0 - M_e} = \exp\left[\frac{-(kt)^y}{c}\right] \]  

(6)

where \( k, y \) are the constants of the model and \( t \) is the time.

2.2.5 Logarithmic model

The Logarithmic model was modified by adding an empirical constant (c) to the Henderson and Pabis model. It was successfully used to describe the drying characteristics of apricots (Toğrul & Pehlivan, 2002) and pumpkin slices (Doymaz, 2007). This model is expressed as:

\[ MR = \frac{M - M_e}{M_0 - M_e} = a \exp\left(-kt\right) + c \]  

(7)

where \( a, k \) and \( c \) are the constants of the model and \( t \) is the drying time.

2.2.6 The Tow term model

This model is a part of infinite series of negative exponentials derived from a general solution of the diffusion equation. This solution applies regardless of particle geometry and boundary conditions, but assumes that the diffusivity is constant. The drying behavior of sultanas (Yaldiz, Ertekin, & Uzun, 2001) and gelidium sesquipedale (Mohamed et al,
2.2.7 The Midilli et al. model
The Midilli et al. model is a new empirical model for the single-layer drying process, which was verified with the selected experimental data (Midilli, Kucuk, & Yapar, 2002). Recently, drying behaviors of many agricultural and industrial products have been satisfactorily described by this model, such as strained yoghurt (Hayaloglu, Karabulut, Alpaslan, & Kelbaliyev, 2007), yacon (Shi et al., 2013), mushrooms (Dinani, Hamdami, Shahedi, & Havet, 2014) and raw olive pomace (Koukouch et al., 2015). This model is described in the following form:

\[
MR = \frac{M - M_o}{M_0 - M_e} = a \exp(-kt) + b \exp(k_t) \]  \hspace{1cm} (8)

where \(a\), \(b\), \(k\), \(y\) and \(t\) are the constants of the model and \(t\) is time.

2.2.8 Approximation of diffusion model
This model is a modification of the Two-term exponential model, which is well-known as the approximation of diffusion or the diffusion approach model. For some materials as such organic tomatoes (Sacilik et al., 2006) and castor oil seeds (Perea-Flores et al., 2012), this model tends to have a best fit to explain their drying kinetics. The equation of this model is presented as:

\[
MR = \frac{M - M_o}{M_0 - M_e} = a \exp(-kt) + (1 - a) \exp(-kbt) \]  \hspace{1cm} (9)

where \(a\), \(k\), \(b\) and \(t\) are the constants of model and \(t\) is time.

2.3 Data analysis
The drying rate constants and coefficients of all of the models were estimated using the non-linear least squares regression analysis. The coefficient of determination (R²) is the primary factor in judging a simulation equation of the drying curve best fitting sample. The other factors are the chi-square value (\(\chi^2\)) and the root mean square value (RMSE). A high degree of fitting equations should have the highest coefficient of determination (R²), lower chi-square value (\(\chi^2\)) and root mean square error (RMSE). These statistical parameters were calculated according to the following equations:

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N} (MR_{exp,i} - MR_{exp})^2} \]  \hspace{1cm} (11)

\[
\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{N - z} \]  \hspace{1cm} (12)

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}{N}} \]  \hspace{1cm} (13)

where the \(MR_{exp,i}\) refers to the measured moisture content, \(MR_{pre,i}\) is the prediction of moisture content, \(N\) is the number of observations in one drying, \(z\) is the number of the constants in a model.

2.4 Estimation of effective moisture diffusivity
Effective moisture diffusion coefficient (\(D_{eff}\)) reflects dehydration ability of materials under certain drying conditions, and is a significant transport property in modeling the drying process of biological materials, as a function of temperature and moisture content in materials (Doymaz, 2012). The simplified mathematical Fick’s second law for diffusion was used to estimate the effective diffusion coefficient of the debittered apricot kernels during drying. Analytical solution of Fick’s second law is given in the Eq.(14), considering a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution:

\[
MR = \frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-\left(\frac{2n-1}{2}\right)^2 \frac{D_{eff}}{4L^2}\right) \]  \hspace{1cm} (14)

where \(D_{eff}\) is the effective diffusivity coefficient (m²/s), \(L\) is the half thickness of the samples (m), \(n\) is the positive integer, and \(t\) is the drying time (s). For a long drying period, the above-mentioned equation can be simplified to the first term of series and Eq. of (14) can be expressed in a logarithmic form as Eq. of (15) by taking the natural logarithm of both sides.

\[
\ln MR = \ln \frac{8}{\pi^2} - \frac{n^2D_{eff}t}{4L^2} \]  \hspace{1cm} (15)

The method of slopes is used to estimate the effective diffusion coefficient. The slope was obtained from the linear regression of \(\ln(MR)\) against the drying time using Eq. of (16):

\[
slope = \frac{n^2D_{eff}}{4L^2} \]  \hspace{1cm} (16)

Then the effective moisture diffusion coefficient (\(D_{eff}\)) was calculated according to the slope which was obtained by the linear fitting.

2.5 Computation of activation energy
Arrhenius’ equation has been widely used to describe the effect of drying temperature on the effective moisture diffusion coefficient to obtain a better agreement of the predicted curve with the experimental data (Kashaninejad et al., 2007; Perea-Flores et al., 2012). The comparison expression can be written in the following form:

\[
D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T + 273.15)}\right) \]  \hspace{1cm} (17)

where \(D_0\) is the diffusivity constant equivalent to the diffusivity at infinitely high temperature, \(E_a\) the activation energy (kJ/mol), \(R\) the universal gas constant, and \(T\) the drying temperature.
3. Results and discussion

3.1 Drying kinetics analysis

The evolutions of experimental MR as a function of drying time of debittered apricot kernels at different drying temperatures (60–120 °C) are presented in Figure 2. As expected, the moisture ratio decreased considerably with the increase of drying time. The drying time required to reduce the moisture content from the initial moisture (44.6±0.5% d.b) to the final moisture content (2.3±0.7% d.b) was 220, 200, 150, 110 min at oven drying temperature of 60, 80, 100, 120 °C, respectively. It can be seen that the effect of drying temperature on the required drying time was considerably pronounced, which is in agreement with the results from several food materials, such as plums (Goyal et al., 2007), pumpkin slices (Doymaz, 2007), pistachio nuts (Kashaninejad et al., 2007) and castor oil seeds (Perea-Flores et al., 2012). Generally, the decrease of required drying time resulted from the higher driving forces for heat transfer (due to larger temperature difference) and for mass transfer (due to larger difference in relative humidity).

3.2 Drying rate curve analysis

Figure 3 shows the evolutions of drying rates (DR) which presented the amount of water removed from samples at a given temperature interval at 60, 80, 100, 120 °C. It can be seen that during the initial drying stage, there was a significant difference in the drying rates for the different drying temperatures. Nevertheless, the drying rates tended to be similar during the later drying stage, i.e. the drying rates decrease continuously with drying time increasing. Other researchers also reported similar results related to behavior of drying rate curves in some drying studies of foodstuffs, like peppercorns (Promvonge, Boonloi, Pimsarn, & Thanpong, 2011), castor oil seeds (Perea-Flores et al., 2012) and raw olive pomace (Koukouch et al., 2015). It can be deduced that the primary loss of moisture was the free water which attaches to the surface of the debittered apricot kernels and the hydrate water that can easily be eliminated in the early period of drying, whereas it is difficult to remove the bound water during the later period. The higher drying rate during the initial stage than that of the later drying period may be attributed to the less external resistance and greater inner water migration at the early stage, and the very low moisture diffusivity at the later stage. Generally, major drying process occurred during the falling-rate period, which suggested that the drying rate was controlled by the internal diffusion phenomenon according to mass transfer controlling process, and molecular diffusion migration could be the predominant mechanism for the drying of debittered apricot kernels. This result is similar to studies of pistachio nuts (Kashaninejad et al., 2007), olive-wast cake (Vega-Gálvez et al., 2010), sweet sorghum stalk (Shen et al., 2011) and passion fruit peel (Bezerra, Silva, Corrêa, & Rodrigues, 2015). It can also be concluded that probably during the drying period, the volume and the cells gap of apricot kernels decreased with drying time and temperature increased which resulted in the increase of evaporation resistance, and the decrease in DR.

3.3 Drying kinetics models of debittered apricots kernels

The models employed in this present study to describe the drying processes of debittered apricot kernels were the Henderson and Pabis, the Modified Henderson and Pabis, the Page, the Modified Page, the Logarithmic, the Two-term, the Midilli et al. and the Approximation of diffusion, respectively. The coefficient of determination ($R^2$, $\chi^2$) and root mean square error (RMSE) were used to evaluate the models. The results of the statistical analysis for the eight models were presented in Table 1.

For all the models, the ranges of $R^2$, $\chi^2$ and RMSE values were between 0.9978–0.9997, 0.000026–0.00031, 0.001393–0.013927, respectively. The obtained $R^2$ values were all greater than the acceptable $R^2$ value of 0.97 (Perea-Flores et al., 2012). Overall, it could be revealed that the Midilli et al. and Approximation of diffusion model presented the greater $R^2$ values, whereas their $\chi^2$ and RMSE values were relatively lower than those for the other tested models (Table 1). The $R^2$, $\chi^2$ and RMSE values of Midilli et al. and Approximation of diffusion model varied between 0.9994–0.9997, 0.000028–0.000079, 0.004701–0.007247 and 0.9994–0.9997, 0.000028–0.000061, 0.004863–0.007018, respectively. Generally, the higher $R^2$ and the lower $\chi^2$ and RMSE are necessary for optimizing drying mathematical models. Therefore, according to the results from Table 1, where the Midilli et al. and Approximation of diffusion model show better prediction, these two models were chosen as the optimal models providing satisfactory descriptions of drying characteristics of debittered apricot kernels.

The experimental and predicted moisture ratios (MR) by the Midilli et al. and the Approximation of diffusion model at 60, 80,
100 and 120 °C for debittered apricot kernels were shown in Figures 4 and 5, respectively. It can be observed from the figures that the predicted MRs were, in general, in line with the experimental ones. These clearly indicated that these two models could be used to describe the moisture ratio variation during the drying process. The Midilli et al. model has also been reported by other researchers as the most suitable model to explain the drying behavior of pumpkin slices (Doymaz, 2007) and yocan slices (Shi et al., 2013); while the moisture ratio evolution of tomato (Sacilik et al., 2006) and castor oil seeds (Perea-Flores et al., 2012) could be well-described by the Approximation of diffusion model.

The above analysis demonstrates that the drying behavior of debittered apricot kernels at different temperatures can be described perfectly by the chosen mathematical models. Therefore, an understanding of drying kinetics and their mathematical models are important for projecting, simulating and optimizing the drying process of debittered apricot kernels.

3.4 Effective moisture diffusivity (D_{eff})

Fick’s second law can be used to describe the drying process of debittered apricot kernels due to the fact that the drying occurred mainly in the falling-rate period and liquid diffusion controlled the process as above-mentioned. The application is widely accepted by many researchers (Kashaninejad et al., 2007; Perea-Flores et al., 2012; Doymaz & İsmail, 2011; Shi et al., 2013; Bezerra et al., 2015). The determined values of effective moisture diffusion coefficient (D_{eff}) for all the drying temperatures calculated by the Eq.(16) are presented in Figure 6, and the values of effective moisture diffusion coefficient are shown in Table 2. It can be observed that the D_{eff} of debittered apricot kernels varied from 1.39×10^{-8} to 3.5×10^{-8} m²/s in the range of temperatures from 60 to 120 °C, which suggests an increase of D_{eff} with the drying temperature raised, i.e. the higher the drying temperature, the greater the rate of moisture diffusion. This phenomenon can be attributed to the

| Model name                  | T(°C) | R²     | χ²    | RMSE   |
|-----------------------------|-------|--------|-------|--------|
| Henderson and Pabis         | 60    | 0.9991 | 0.000075 | 0.008263 |
|                             | 80    | 0.9995 | 0.000052 | 0.007223 |
|                             | 100   | 0.9978 | 0.000221 | 0.001393 |
|                             | 120   | 0.9984 | 0.001777 | 0.012147 |
| Page                        | 60    | 0.9996 | 0.000331 | 0.005331 |
|                             | 80    | 0.9994 | 0.000499 | 0.006613 |
|                             | 100   | 0.9986 | 0.001939 | 0.012177 |
|                             | 120   | 0.9990 | 0.000107 | 0.009440 |
| Logarithmic                 | 60    | 0.9995 | 0.000043 | 0.006145 |
|                             | 80    | 0.9997 | 0.000040 | 0.004523 |
|                             | 100   | 0.9996 | 0.000236 | 0.013861 |
| Modified Henderson and Pabis| 60    | 0.9991 | 0.000092 | 0.008267 |
|                             | 80    | 0.9997 | 0.000031 | 0.004669 |
|                             | 100   | 0.9997 | 0.000310 | 0.013927 |
|                             | 120   | 0.9984 | 0.000295 | 0.012147 |
| Modified Page               | 60    | 0.9996 | 0.000031 | 0.005337 |
|                             | 80    | 0.9994 | 0.000049 | 0.006113 |
|                             | 100   | 0.9986 | 0.000140 | 0.011043 |
|                             | 120   | 0.9990 | 0.000107 | 0.009440 |
| Two-term                    | 60    | 0.9991 | 0.000083 | 0.008267 |
|                             | 80    | 0.9997 | 0.000026 | 0.004428 |
|                             | 100   | 0.9978 | 0.000259 | 0.013927 |
|                             | 120   | 0.9984 | 0.000221 | 0.012147 |
| Midilli                      | 60    | 0.9997 | 0.000032 | 0.005168 |
|                             | 80    | 0.9997 | 0.000028 | 0.004701 |
|                             | 100   | 0.9994 | 0.000070 | 0.007247 |
|                             | 120   | 0.9994 | 0.000079 | 0.007242 |
| Approximation of Diffusion  | 60    | 0.9997 | 0.000029 | 0.005057 |
|                             | 80    | 0.9997 | 0.000028 | 0.004863 |
|                             | 100   | 0.9994 | 0.000061 | 0.007018 |
|                             | 120   | 0.9996 | 0.000044 | 0.005771 |

![Figure 4](image1.png)  
**Figure 4.** Experimental and predicted moisture ratio (MR) by the Midilli et al. model at different drying temperatures for debittered apricot kernels.

![Figure 5](image2.png)  
**Figure 5.** Experimental and predicted moisture ratio (MR) by the Approximation of diffusion model at different drying temperatures for debittered apricot kernels.

![Figure 6](image3.png)  
**Figure 6.** Experimental logarithmic moisture ratio (MR) in function drying time at different drying temperatures for debittered apricot kernels.

![Figure 7](image4.png)  
**Figure 7.** Experimental and predicted moisture ratio (MR) by the Midilli et al. model at different drying temperatures for debittered apricot kernels.
Table 2. Effective of diffusivity value of debittered apricot kernels in different drying temperatures.

| Drying temperature (°C) | Diffusivity coefficient (D_eff) (m²/s) |
|-------------------------|----------------------------------------|
| 60                      | 1.39 × 10⁻⁸                           |
| 80                      | 1.89 × 10⁻⁸                           |
| 100                     | 2.47 × 10⁻⁸                           |
| 120                     | 3.50 × 10⁻⁸                           |

increase of the vapor’s pressure inside the samples, which would lead to the rapid movement of water at elevated drying temperatures (Shi et al., 2013).

The values of the effective moisture diffusion coefficients obtained from the experiments was similar to the results by some researchers, from 7.20×10⁻⁷ to 1.91×10⁻⁶ m²/s for the thin-layer drying of sweet sorghum stalks at 30–70 °C (Shen et al., 2011), 4.08×10⁻⁶ to 2.35×10⁻⁷ m²/s for convective drying of pumpkin (Cucurbita maxima) at 30–70 °C. However, these values of D_eff are higher than the general range of 10⁻⁸ to 10⁻¹⁷ m²/s as reported for agriculture and industrial products by other researchers, for instance 5.42×10⁻¹¹ to 9.29×10⁻¹⁰ for pistachio nuts (Kashaninejad et al., 2007), 8.21×10⁻¹⁰ to 2.61×10⁻⁹ for castor oil seeds (Perea-Flores et al., 2012), 2.61×10⁻¹⁰ to 9.24×10⁻¹¹ for kaffir lime leaves (Tasirin, Puspasari, Lun, Chai, & Lee, 2014). The difference of the D_eff for different biological materials might be due to the different drying temperatures employed, physical or chemical pretreatment, moisture content and sample variety, composition and geometry of drying materials.

3.5 Computation of activation energy (Ea)

Many researchers (Kashaninejad et al., 2007; Shi et al., 2013; Perea-Flores et al., 2012; Bezerra et al., 2015; Irigoyen & Giner, 2014) also pointed out that the drying temperature has a significant effect on the effective moisture diffusivity during the drying of foodstuff. Consequently, the rate of molecular diffusion increases as the drying temperature rises, causing the higher values of D_eff. The influence of drying temperature on the effective moisture diffusion coefficient has been described by the Arrhenius-type relationship as given by the Eq.(17). The activation energy (Ea) is a measure of the effect on the diffusion coefficient, and can be obtained from experimental data of the effective diffusivity. Figure 7 presents a plot of the logarithm of D_eff vs reciprocal of the absolute temperature (T+273.15).

The plot shows a linear correlation (y = -1982.7x-12.159) between the (ln D_eff) and (1/(T+273.15)) or an Arrhenius-type relationship, with a R² of 0.9928. The diffusivity constant (D_o) and activation energy (Ea) calculated from the linear regression were 5.24×10⁻⁶ m²/s and 16.5 kJ/mol, respectively. The effect of temperature on the D_eff of debittered apricot kernels is shown in Eq.(18). The value of activation energy is usually in the range of 15–40 kJ/mol for various foods as reported by Rizvi (1986). In comparison, the Ea of 16.5 kJ/mol for debittered apricot kernels is higher than that of 13.88 kJ/mol for soybean (Niamnuy, Nachaisin, Poomsaa-ad, & Devahastin, 2012), but lower than that of 41.41 kJ/mol for castor oil seeds (Perea-Flores et al., 2012), 24.1 kJ/mol for sweet sorghum stalk (Shen et al., 2011), 29.571–34.726 kJ/mol for passion fruit peel (Bezerra et al., 2015), 31.4 kJ/mol for presoaked soybean (Irigoyen & Giner, 2014).

\[ D_{\text{eff}} = 5.24 \times 10^{-6} \exp \left( \frac{-1982.7}{T + 273.15} \right) \quad (18) \]

The varieties of the Ea for these materials may be due to the difference between the structure and the initial moisture content, which can be illustrated by the fact that the activation energy of salak with surface membrane higher than those without surface membrane (Ong & Law, 2009). In general, high values of Ea are related to the nature of materials where water is bounded more strongly to the structure and consequently more difficult to be removed (Bezerra et al., 2015). In the present study, the activation energy of debittered apricot kernels was slightly lower, probably because the higher amounts of water were obtained during the bitterness-elimination processing, and caused the bounded water to be relatively weaker than the structure of apricot kernels.

4. Conclusions

Drying experiments were conducted in a laboratory oven to investigate the thin-layer drying kinetics of apricot kernels with a drying temperature range of 60–120 °C, a load of 3.4 kg/m² and a constant air velocity. The drying time required to get the final moisture content was significantly reduced with the increase of drying temperature. Drying of debittered apricot kernels mainly occurred in the falling-rate period under the studied conditions, which implies that the moisture transfer was governed mainly by the internal diffusion. The Midilli et al. and Approximation of diffusion models having the higher coefficient of determination (R²), and lower chi-square (χ²) and root mean square error (RMSE) were considered the most suitable models to describe the drying behavior of debittered apricot kernels. The effective moisture diffusion coefficient increased from 1.39×10⁻⁸ to 3.5×10⁻⁸ m²/s with the increase of drying temperature. The temperature dependence of the effective moisture diffusivity values was well-described by the Arrhenius-type relationship, and the activation energy of moisture diffusion was 16.5 kJ/mol. The information obtained from this research is of significant use in design and simulation of drying equipment, and provides a basic drying knowledge for food sources which are rich in oil and protein such as peanuts.
and pine nuts. However, some results derived from this research could also be influenced by some laboratory factors such as edge and hydrodynamic effects that occurred in a smaller dryer, and ignored several realities of drying process in industry. More researches should be conducted at pilot plant level and industrial scale in the future.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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