Bulgarian Chemical Communications, Volume 56, Issue 3 (pp. 228-232) 2024 DOI: 10.34049/bcc.56.3.IK2-SR

Investigation of mass transfer in infrared drying of Ahlat pears: experimental and modelling approaches

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Accepted: May 24, 2024

Drying is an essential, energy-intensive process in food preservation that involves combined heat and mass transfer mechanisms to remove moisture from food products and extend their shelf life. This study focuses on the efficacy of infrared (IR) drying of Ahlat pear (*Pyrus elaegrifolia* L.) which has rich vitamin content and high nutritional value. It can be consumed both fresh and dried under various infrared powers (38, 50, 62, 74, and 88 W). The effects of different power levels on drying kinetics was investigated and a comprehensive analysis was performed to evaluate the drying characteristics and kinetics. Results clearly showed the effect of IR dryer on drying time. The drying curves depicted a falling-rate period during the drying process, while no constant-rate period was observed. By using Fick's second law, the effective moisture diffusivity was determined, revealing a range from 1.07×10^{-8} to 2.03×10^{-8} m^2/s across the conditions of experiments. Activation energy was calculated by a modified Arrhenius type equation as 1.6382 kW/kg. The variation of moisture content during drying of Ahlat pears was investigated by selecting six mathematical models. Regression analysis results showed that the Alibas model is the most suitable model to describe drying behavior.

Keywords: Infrared drying, Ahlat pear, effective diffusivity, modeling

INTRODUCTION

Ahlat pear, a member of the *Rosaceae* family, is a wild pear species that can grow in dry and harsh conditions across a wide area from Anatolia to Europe. Economically significant since ancient times, this fruit has a pleasant taste and aroma and can be consumed fresh or dried. In addition, various parts of the fruit have anti-inflammatory, antioxidant, analgesic, antimicrobial, antispasmodic, wound-healing and antibacterial properties, allowing it to be used in folk medicine to treat fever, pain, diarrhea, snake bites and other diseases [3, 5].

For the sustenance of human life, it's crucial that foods, including fruits and vegetables, can be preserved without spoiling, making the methods of food preservation extremely important.

Among these methods, drying, which is a traditional and industrial food preservation technique used in the food industry for many years, stands out due to its ease of application and cost advantage.

Decreasing of moisture content through drying plays an important role in extending the shelf life of food products, thus leading to a reduction in transportation, packaging and storage expenses.The food industry has recognized the significance of different drying methods, including spray-drying, freeze-drying, and non-thermal techniques [6-8]. Infrared drying technology is efficient and maintains product quality in various food processing applications. Infrared radiation reduces drying time and enhances color, rehydration, and antioxidant content [8].

Using mathematical models plays a vital role in comprehending and optimizing the drying process of food products. Theoretical, semi-theoretical, and empirical models are the three categories of mathematical models. Each category considers different aspects of the drying phenomenon [9]. Thin-layer drying models have been extensively utilized to depict the drying process of agricultural products. Effective moisture diffusivity and the kinetics of the drying process can be determined by applying these models [10]. A limited amount of information can be found in the literature regarding mathematical modeling of Ahlat pear drying. The primary objectives of this study were to assess the influence of infrared power on drying duration, to model the experimental data using six drying models, and to determine the effective moisture diffusivity and activation energy.

EXPERIMENTAL

Materials and methods

- *Preparation of samples and drying procedures.* High-quality Ahlat pears were obtained from a local market in Istanbul, Turkey. The initial moisture content of the Ahlat pears was determined

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by oven-drying at 105°C for 6 h. Triplicate samples were used to measure the moisture content, and the average value was found to be 68.75% on wet basis. Drying experiments were conducted in an infrared dryer (Snijders, Tilburg, Netherlands). 32±0.9 g of Ahlat pear samples were used in the experiments and samples were dried at 38, 50, 62, 74 and 88 W infrared power. Moisture losses were recorded at 15-min intervals throughout the drying process using a digital balance. Once the moisture content reached 20%, the drying process was halted, and the samples were allowed to cool before being packed into polyethylene bags and stored at room temperature. The data from the experiments were gathered and utilized to create the drying curves.

- *Mathematical modeling and data analysis*. The drying kinetics of the Ahlat pear samples was described by evaluating six models (Table 1). The moisture content and moisture ratio of Ahlat pears were denoted as M and MR, respectively and calculated using equations commonly used in the literature [1, 17, 18].

The data collected from the experiments were analyzed utilizing the Statistica 10 software package (StatSoft Inc., USA). Model parameters were determined *via* a nonlinear regression process employing the Levenberg-Marquardt algorithm. The assessment of the alignment between experimental data and all models was conducted using metrics including the coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE). R^2, χ^2, and RMSE were calculated using the formulas presented in Table 2 where $MR_{exp,i}$ stands for the experimental dimensionless moisture ratio, $MR_{pre,i}$ denotes the predicted dimensionless moisture ratio, N represents the number of observations, and z signifies the number of constants [17].

Table 1. Mathematical models designed for fitting to the drying of Ahlat pear.

Ref.	Model name	Model
[12]	Alibas	$MR = a \exp(-kt^n + bt) + g$
[13]	Aghbashlo et al.	$MR = a \exp(-at/(1 + bt))$
[14]	Henderson&Pabis	$MR = a \exp(-kt)$
[11]	Logarithmic	$MR = a \exp(-kt) + c$
[15]	Page	$MR = a \exp(-kt^n)$
[16]	Logistic	$MR = a/(1 + b \exp(kt))$

Table 2. The R^2, χ^2 and RMSE formulas

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

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

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

Determination of effective moisture diffusivity and computation of activation energy

The effective moisture diffusivity (D_{eff}) values for dried Ahlat pear were determined by applying Fick's second law of diffusion equation. The analytical solution for Fick's second law, considering unsteady-state diffusion in Cartesian coordinates, assumes moisture migration through diffusion with constant effective diffusivity, constant temperature, and negligible shrinkage during the drying process. This solution is then reformulated in logarithmic form (Eq. 1). All equations for determining effective moisture diffusivity and activation energy are given in Table 3. To ascertain the effective moisture diffusivity, the experimental drying data are graphed with ln(MR) plotted *versus* time. This representation reveals a linear correlation, where the slope of the line corresponds to the parameter K, as defined in Eq. 2.

The correlation between effective diffusivity and temperature is frequently represented by the Arrhenius equation (Eq. 3). In this context, D_0 stands for the pre-exponential factor in the Arrhenius equation, measured in m²/s. E_a denotes the activation energy in kW/kg, while m represents the mass of dried samples in kilograms, and p signifies the infrared power in W.

Table 3. Equations for effective moisture diffusivity and activation energy

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t \qquad (1)$$

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

$$D_{eff} = D_0 \exp\left(\frac{-E_a m}{p}\right) \qquad (3)$$

RESULTS AND DISCUSSION

Analysis of drying curves and evaluation of models

The changes in the moisture content over drying time at 38, 50, 62, 74 and 88 W are illustrated in Figure 1(A). Drying time decreased with the increase in the infrared power, as expected. The drying times were recorded as 285, 255, 195, 150 and 135 min at infrared powers of 38, 50, 62, 74 and 88 W, respectively. The moisture content consistently decreased as the drying time progressed. At 50 W infrared power, the drying time was 1.889 times longer than the drying time at 88 W infrared power. This finding is consistent with the results of Doymaz and Ismail [18], where the drying time at 50 W was 1.807 times longer than the drying time at 88 W.

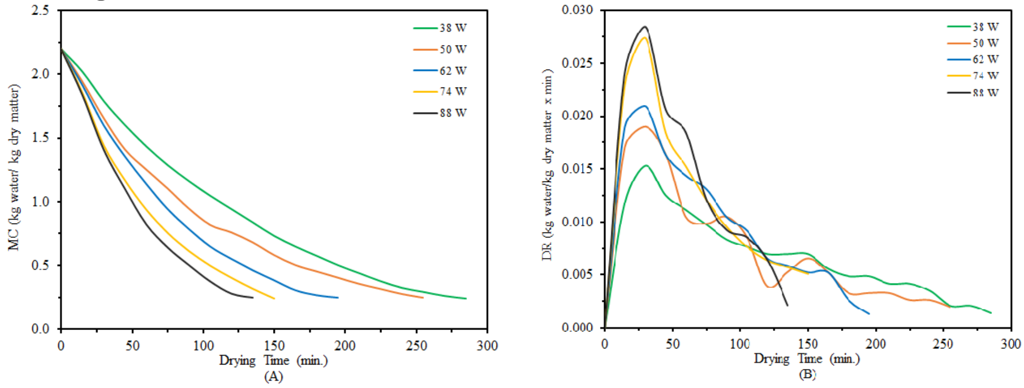

Fig. 1. Moisture content *versus* drying time (A), Drying rate *versus* drying time (B) at 38, 50, 62, 74 and 88 W.

Table 4. Statistical parameters of models for different infrared powers.

IR Power (W)	Model	R^2	χ^2	RMSE
38	Alibas	0.9996	0.000036	0.017902
	Aghbashlo *et al.*	0.9996	0.000033	0.017787
	Henderson and Pabis	0.9984	0.000134	0.040341
	Logarithmic	0.9996	0.000037	0.019987
	Page	0.9994	0.000046	0.024614
	Logistic	0.9995	0.000042	0.022012
50	Alibas	0.9994	0.000053	0.020612
	Aghbashlo *et al.*	0.9993	0.000056	0.021064
	Henderson and Pabis	0.9982	0.000142	0.041833
	Logarithmic	0.9992	0.000069	0.024560
	Page	0.9990	0.000073	0.023640
	Logistic	0.9978	0.000185	0.045852
62	Alibas	0.9998	0.000020	0.011198
	Aghbashlo *et al.*	0.9992	0.000073	0.021254
	Henderson and Pabis	0.9990	0.000095	0.028115
	Logarithmic	0.9992	0.000079	0.024049
	Page	0.9996	0.000034	0.014259
	Logistic	0.9995	0.000047	0.016829
74	Alibas	0.9998	0.000030	0.009844
	Aghbashlo *et al.*	0.9989	0.000110	0.019765
	Henderson and Pabis	0.9989	0.000106	0.019111
	Logarithmic	0.9990	0.000109	0.020418
	Page	0.9991	0.000084	0.019836
	Logistic	0.9991	0.000101	0.021278
88	Alibas	0.9997	0.000056	0.015138
	Aghbashlo *et al.*	0.9979	0.000228	0.027170
	Henderson and Pabis	0.9970	0.000328	0.041763
	Logarithmic	0.9978	0.000276	0.034924
	Page	0.9990	0.000103	0.019982
	Logistic	0.9987	0.000158	0.024377

Figure 1(B) illustrates the drying rate curves of Ahlat pear. The drying rate shows a continual decrease over time. At the beginning, there are higher drying rates, which then decrease as the sample's moisture content is reduced. This decrease is due to the samples shrinking, causing a decrease in porosity and an increase in resistance to water movement, ultimately leading to a further reduction in drying rates. The predominance of the falling-rate period indicates that moisture movement in Ahlat pear slices is mainly controlled by diffusion as the primary physical mechanism [19].

The most suitable model was selected by the highest R^2 and the lowest χ^2 and RMSE values. Statistical computing results are shown in Table 4. The R^2 values for all models are above 0.99. Alibas model provided the highest R^2 values as 0.9996 and the lowest χ^2 values as 0.000036 and RMSE values as 0.017902 which makes it the best model for 38 W. For 50, 62, 74 and 88 W, Alibas model is also the best model and the R^2 values are 0.9994, 0.9998, 0.9998 and 0.9997, χ^2 values are 0.000053, 0.000020, 0.000030 and 0.000056 and RMSE values are 0.020612, 0.011198, 0.009844 and 0.015138 for 50, 62, 74 and 88 W, respectively.

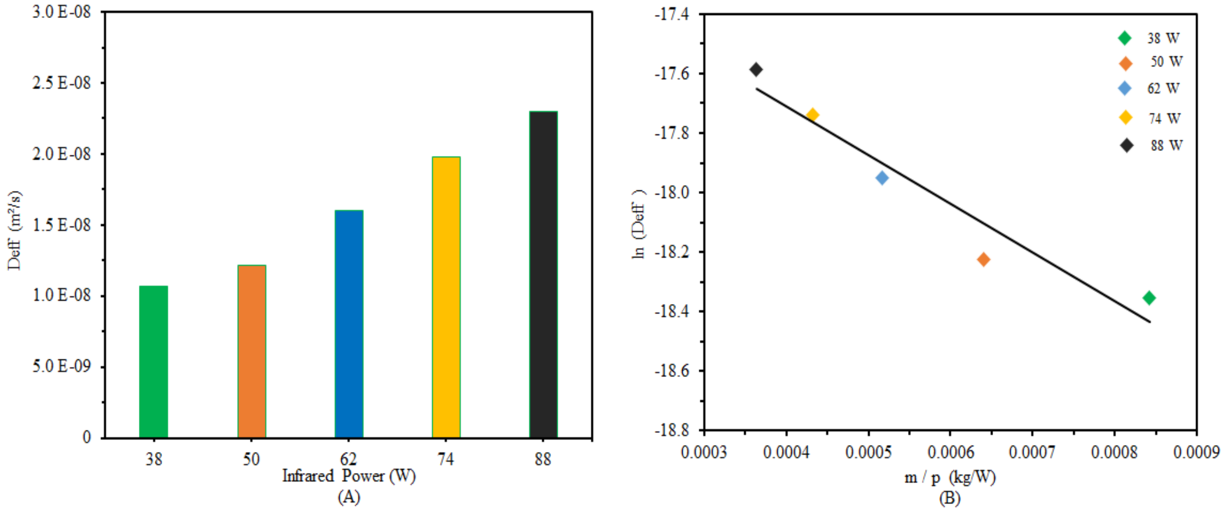

Fig. 2. Variation of effective moisture diffusivity with IR powers (A), Arrhenius-type relationship between effective diffusivity and IR powers (B)

Effective moisture diffusivity and activation energy

The effective moisture diffusivity was determined by plotting ln (MR) *versus* drying time. The values of effective moisture diffusivity (D_{eff}) were calculated according to Eq. (3) and are displayed in Figure 2(A). For the Ahlat pear, the D_{eff} values ranged from 1.07×10^{-8} to 2.03×10^{-8} m²/s within the IR power range of 38-88 W. The highest D_{eff} value was recorded at 88 W, while the lowest was at 38 W. The D_{eff} values obtained for Ahlat pear slices are like those reported by Doymaz and Ismail [18].

Drawing ln(D_{eff}) *versus* m/p results in a linear relationship with a slope equivalent to ($-E_a$), facilitating the straightforward estimation of E_a (Figure 2. (B)). Equation (4) shows the impact of infrared power on D_{eff} for the samples, with the associated coefficients:

$$D_{eff} = 3.9145 \times 10^{-8} \, exp\left(\frac{-1638.2 \times m}{p}\right) \quad (R^2 = 0.9315) \qquad (4)$$

The calculated activation energy value is 1.6382 kW/kg, exhibiting a close resemblance to the activation energy values reported in the literature for the drying process of pears [18].

CONCLUSION

The drying behavior of Ahlat pears was investigated using an infrared dryer at different power levels ranging from 38 to 88 W. According to the results, infrared power has a significant role in the drying process of Ahlat pears and a higher power reduces the drying time. Six drying models were utilized to analyze the drying kinetics of Ahlat pears, and statistical analysis established that the Alibas model was the most suitable model in predicting the experimental data at all power levels. The effective diffusivity values for Ahlat pear samples ranged from 1.07×10^{-8} to 2.03×10^{-8} m²/s, while the activation energy was calculated to be 1.6382 kW/kg. These findings offer valuable insights into the drying characteristics of Ahlat pears under different drying conditions.

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