# EXPERIMENTAL AND MODELING INVESTIGATION OF MASS TRANSFER DURING HOT AIR DRYING OF AHLAT PEAR

***Osama T. A. ALSHAMHAZI1,[[1]](#footnote-1)\*[C:\Users\Abdullah\AppData\Local\Microsoft\Windows\INetCache\Content.Word\ORCID-iD_icon-16x16.gif](https://orcid.org/xxxx-xxxx-xxxx-xxxx), İlknur KÜÇÜK2 [C:\Users\Abdullah\AppData\Local\Microsoft\Windows\INetCache\Content.Word\ORCID-iD_icon-16x16.gif](https://orcid.org/xxxx-xxxx-xxxx-xxxx), İbrahim DOYMAZ3 [C:\Users\Abdullah\AppData\Local\Microsoft\Windows\INetCache\Content.Word\ORCID-iD_icon-16x16.gif](https://orcid.org/xxxx-xxxx-xxxx-xxxx)***

*1,2,3 Chemical Engineering Department, Yıldız Technical University, İstanbul, Turkey*

|  |
| --- |
| **Abstract**  Drying is an energy-intensive process involving both heat and mass transfer, widely employed as a technique for preserving food. Ahlat pear (*Pyrus elaegrifolia* L), naturally grown in Turkey and contains C and B vitamins, caroten, pectin, fruit acid, sugar and tannin. It can be consumed in dried or fresh form. The focus of this study is examining the efficacy of a cabinet dryer under diverse air temperatures (45, 55, and 65°C) with a consistent air velocity of 2 m/s in the drying process of Ahlat pears. The initial moisture content of Ahlat pears’ samples was successfully reduced from 68.75% to 20% (wet basis), and a comprehensive analysis was made for their drying characteristics and kinetics. The impact of drying air temperature on drying time is clearly substantiated by the results. Drying curves illustrate a falling-rate period during the drying process without noticing any constant-rate period. The study further elucidates the effective moisture diffusivity, evaluated via Fick's second law, revealing a range from 3.25×10-9 to 7.04×10-9 m²/s across the investigated conditions. Activation energy was estimated by an Arrhenius type equation as 35.51 kJ/mol. Five different mathematical models (Alibas, Aghbashlo, Logarithmic, Logistic, Page ve Henderson and Pabis) were evaluated for moisture ratios using nonlinear regression analysis. The results of regression analysis indicated that the Alibas model is the best model to describe the drying behaviour with the lowest χ2 and RMSE values and highest R2 values. |
| Keywords: Hot-air drying, Ahlat pear, effective diffusivity, mathematical modelling, Alibas model. |

1. **Introduction**

Ahlat pear is a species of wild pear that has a wide distribution area in the region, starting from Southeastern Europe to Anatolia, the Caucasus and Crimea, and can survive in dry and unfavorable conditions. This thorny tree, belonging to the Rosaceae family, helps to solve many health concerns [1-4]. Ahlat pear is traditionally used for treating diarrhea while its leaves are employed for anti-inflammatory purposes and its bark infusion is prescribed for intestinal ulcers and palpitations. Additionally, it exhibits diverse biological activities such as analgesic, anti-inflammatory, antioxidant, antispasmodic, antimicrobial, antibacterial, and wound-healing properties. After Ahlat pear is collected from the tree, it can be consumed both fresh and dried [3,5].

Drying is a traditional or industrial preservation method that is used in the food industry. The reduction of moisture content through drying is essential for increasing the shelf life of food products, thereby reducing transportation, packaging, and storage costs. Various drying techniques such as spray-drying, freeze-drying, and non-thermal methods have gained importance in the food industry [6-8]. Hot-air drying is a commonly used method in the food industry due to its cost-effectiveness [8].

Mathematical models play a crucial role in understanding and optimizing the drying process of food products. These models can be categorized into theoretical, semi-theoretical, and empirical models, each considering different aspects of the drying phenomenon [9]. Thin-layer drying models have been widely used to describe the drying process of agricultural products. These models are essential for determining effective moisture diffusivity and understanding the kinetics of the drying process [10]. There is very few information in the literature regarding mathematical modeling of Ahlat pear drying. In this present study, the main objectives were to investigate the effect of air temperature on the drying time, fit the experimental data to five drying models, and compute effective moisture diffusivity and activation energy.

1. **Materials and Methods**
   1. **Preparation of samples and drying procedures**

Good quality Ahlat pears were bought from a local market in Istanbul, Turkey. The initial moisture content of Ahlat pear was determined by using an oven at 105°C for 6 hours. Triplicate samples were used for the determination of moisture content and the average values were reported as 68.75%, w.b.

Drying experiments were carried out in a cabinet dryer (APV & PASILAC, UK) at Yıldız Technical University Department of Chemical Engineering. The experiments were conducted with about 50±0.9 g of ahlat pear samples and samples dried at 45, 55, and 65°C air temperatures. The moisture losses were recorded at 15 minute intervals during the drying process, using a digital balance (Mettler-Toledo AG, Switzerland) during drying. After achieving 20% moisture content, drying process was stopped and dried samples were waited to cool down then packed into polyethylene bags and stored at ambient temperature. The experiments data was collected and used to draw the drying curves.

* 1. **Mathematical modelling and data analysis**

Six models were evaluated to describe the drying kinetics of the Ahlat pear samples (Table 1). The moisture content (M) and moisture ratio (MR) of Ahlat pear slices were computed by the following equations:

where M represents the moisture content (kg water/kg dry matter), W is the sample weight (kg), Wd is the dry matter content of the sample (kg), and t is the drying time (min). Me and Mt stand respectively for equilibrium moisture content and moisture content at time t (kg water/kg dry matter). Considering that Me is significantly smaller than both M0 and Mt values, Me can be ignored, allowing the expression of MR as Mt/M0 [11].

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

|  |  |  |
| --- | --- | --- |
| Reference | Model Name | Model |
| [12] | Alibas |  |
| [13] | Aghbashlo et al. |  |
| [14] | Henderson and Pabis |  |
| [11] | Logarithmic |  |
| [15] | Page |  |
| [16] | Logistic |  |

The experimental data underwent analysis utilizing the Statistica 10 software package (StatSoft Inc., USA). Model parameters were determined through a non-linear regression procedure employing the Levenberg-Marquardt algorithm. The assessment of the fitting accuracy of experimental data to all models was conducted using metrics such as the coefficient of determination (R2), reduced chi-square (χ2), and root mean square error (RMSE). The R2, χ2 and RMSE were calculated from the following formulas that are given in Table 2:

**Table 2.** The R2, χ2 and RMSE formulas

|  |  |  |
| --- | --- | --- |
|  |  |  |

where MRexp,i represents the experimental dimensionless moisture ratio, MRpre,i denotes the predicted dimensionless moisture ratio, N stands for the number of observations, and z signifies the number of constants. A superior fit is indicated by a higher R2 value, accompanied by lower χ2 and RMSE values [17].

* 1. **Determination of effective moisture diffusivity and Computation of activation energy**

The values of the effective moisture diffusivity (Deff) for dried Ahlat pear are based on the application of Fick’s second law of diffusion equation. The analytical solution for Fick's second law in the context of unsteady-state diffusion within Cartesian coordinates, assuming moisture migration occurs through diffusion, with negligible shrinkage, constant effective diffusivity, and temperature throughout the drying process is reformulated in logarithmic form as follows:

The effective moisture diffusivity is determined by graphing the experimental drying data as *ln* (*MR*) against time (min). According to Eq. (3), the plotted *ln* (*MR)* versus time yields a linear relationship with a slope represented by (K), where:

The relationship between effective diffusivity and temperature is commonly expressed by the Arrhenius equation:

where D0 represents the pre-exponential factor in the Arrhenius equation (m²/s), Ea expresses the activation energy (kJ/mol), *R* stands for the universal gas constant (kJ/(mol×K)), and *T* represents the temperature (°C).

1. **Results and Discussion** 
   1. **Analysis of drying curves and Evaluation of models**

Figure 1(A) presents variations in the moisture content as a function of drying time at 45, 55 and 65°C. It can be noticed that drying time was reduced along with the increase in the air-drying temperatures as awaited. The drying times were found to be 855, 630 and 405 minutes at air temperatures of 45, 55 and 65°C, respectively. The moisture content decreases constantly with drying time. The drying time at 45°C temperature was 2.111 times bigger than the drying time of 65°C temperature. A similar result was observed in the study done by Doymaz and İsmail [18], when the air temperature was increased by 20°C, the drying time at the first temperature was 2.5 bigger than the drying time of the second temperature.

**A close-up of a graph

Description automatically generated**

**Figure 1.** (A) Moisture content versus drying time, (B) Drying rate versus drying time of Ahlat pear samples at 45,55,65°C.

Figure 1(B) illustrates the drying rate curves of Ahlat pear. The drying rate exhibits a continual decrease throughout the drying period. Initially, higher drying rates are observed, followed by a decline corresponding to the reduction in sample moisture content. This decline is attributed to the shrinking of samples, leading to decreased porosity and an increased resistance to water movement, resulting in a further reduction in drying rates. The complete prevalence of the falling-rate period suggests that moisture movement in Ahlat pear slices is predominantly governed by diffusion as the primary physical mechanism [19].

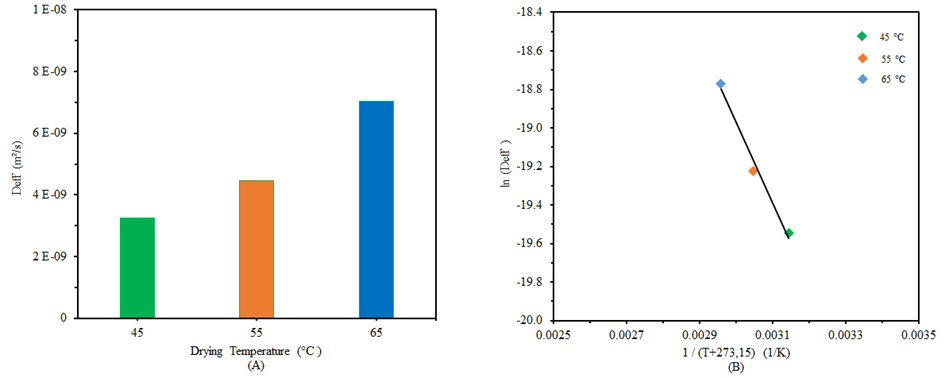
The best model selected is based on the highest R2 and the lowest χ2 and RMSE values. Results of the statistical computing are shown in Table 3. The R2 values for all models were above 0.99. Among the drying models tested, Alibas model obtained the R2 values as 0.9994 and the lowest χ2 values as 0.000037 and RMSE values as 0.037659 describe best model for 45°C. For 55 and 65℃, Alibas model is also the best model and the R2 values are 0.9997 and 0.9994, χ2 values are 0.000017 and 0.000041 and RMSE values are 0.015918 and 0.022185 for 65°C and 75°C, respectively.

**Table 3.** Statistical parameters of models for different temperatures.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| T (°C) | Model | R2 | χ2 | RMSE |
| 45°C | Alibas | 0.9994 | 0.000037 | 0.037659 |
| Aghbashlo et al. | 0.9969 | 0.000177 | 0.088279 |
| Henderson and Pabis | 0.9968 | 0.000183 | 0.066819 |
| Logarithmic | 0.9968 | 0.000185 | 0.068799 |
| Page | 0.9961 | 0.000222 | 0.067127 |
| Logistic | 0.9936 | 0.000360 | 0.114856 |
| 55°C | Alibas | 0.9997 | 0.000017 | 0.015918 |
| Aghbashlo et al. | 0.9991 | 0.000053 | 0.038997 |
| Henderson and Pabis | 0.9981 | 0.000112 | 0.057381 |
| Logarithmic | 0.9956 | 0.000244 | 0.084117 |
| Page | 0.9951 | 0.000279 | 0.088475 |
| Logistic | 0.9909 | 0.000507 | 0.110386 |
| 65°C | Alibas | 0.9994 | 0.000041 | 0.022185 |
| Aghbashlo et al. | 0.9988 | 0.000075 | 0.036828 |
| Henderson and Pabis | 0.9983 | 0.000116 | 0.046981 |
| Logarithmic | 0.9970 | 0.000191 | 0.058423 |
| Page | 0.9966 | 0.000223 | 0.062423 |
| Logistic | 0.9950 | 0.000319 | 0.069941 |

* 1. **Effective moisture diffusivity and activation energy**

The effective moisture diffusivity of the was calculated by plotting ln(MR) against drying time and employing the slope method. The calculated values of effective moisture diffusivity (Deff), determined using Eq. (3), are presented in Figure 2(A). Within the drying temperature range of 45-65°C, the Deff values for Ahlat pear ranged from 3.25×10-9 to 7.04×10-9 m²/s. The highest Deff value was observed at 65°C and the lowest at 45°C. Furthermore, the Deff values obtained for Ahlat pear slices are like those proposed by Toğrul et al. [19].



**Figure 2.** (A) Variation of effective moisture diffusivity with air temperatures, (B) Arrhenius-type relationship between effective diffusivity and reciprocal absolute temperature.

Graphing ln(Deff) against 1 / (T+273.15) results in a linear relationship with a slope equivalent to (-Ea/R), facilitating the straightforward estimation of Ea (Figure 2.(B)). Equation 6 shows the impact of temperature on Deff for the samples, with the associated coefficients:

The determined activation energy value is 35.51 kJ/mol, which closely aligns with activation energy values reported in the literature for pear drying [18,19].

1. **Conclusion**

Drying characteristics of Ahlat pear were examined using a cabinet dryer at varieous temperatures of 45, 55, and 65°C, with a consistent air velocity of 2 m/s. Air temperature emerged as a crucial factor influencing the drying process of Ahlat pear, where higher drying temperatures led to shorter drying times. To elucidate the drying kinetics of Ahlat pear, six drying models were applied and fitted to the experimental data. Statistical analysis revealed that the Alibas model effectively predicted the experimental data across all air temperatures. The effective diffusivity values for Ahlat pear samples ranged from 3.25×10-9 to 7.04×10-9 m²/s. Additionally, the activation energy was determined to be 35.51 kJ/mol. These findings contribute valuable insights into the drying behavior of Ahlat pear under various conditions.

**References**

1. Beigi, M. (2016). Energy efficiency and moisture diffusivity of apple slices during convective drying. *Food Science and Technology*, 36(1), 145-150.
2. Ilhan, M., Akkol, E.K., Taştan, H., Dereli, F.T.G., & Tümen, I. (2019). Efficacy of Pyrus elaeagnifolia subsp. elaeagnifolia in acetic acid–induced colitis model. *Open Chemistry*, 17(1), 13-22.
3. Yerliturk, F.U., Arslan, O., Sinan, S., Gencer, N., & Ozensoy, O. (2008). Characterization of polyphenoloxidase from wild pear (Pyrus elaegrifolia). *Journal of Food Biochemistry*. 32(3), 368-383.
4. Anşin, R., & Özkan, Z. C. (1993). Seed Plants (SPERMATOPHYTA) Woody Taxa, *Karadeniz Technical University, Faculty of Forestry*, Publication No: 19, Trabzon, Turkey.
5. Siddiq, M., & Cash, J.N. (2000). Physico‐chemical properties of polyphenol oxidase from D'anjou and Bartlett pears (*Pyrus communis* L.). *Journal of Food Processing and Preservation*, 24(5), 353-364.
6. Witrowa-Rajchert, D., Wiktor, A., Sledz, M., & Nowacka, M. (2014). Selected emerging technologies to enhance the drying process: a review. *Drying Technology*, 32(11), 1386-1396.
7. Kandasamy, S., & Naveen, R. (2022). A review on the encapsulation of bioactive components using spray‐drying and freeze‐drying techniques. *Journal of Food Process Engineering*, 45(8), e14059.
8. Martínez-Sánchez, C., Solis‐Ramos, A., Rodríguez-Miranda, J., Juárez-Barrientos, J., Ramírez-Rivera, E., Ruiz-López, I., Gomez-Aldapa, C.A., & Herman-Lara, E. (2022). Evaluation of ascorbic acid impregnation by ultrasound‐assisted osmotic dehydration in plantain. *Journal of Food Processing and Preservation*, 46(10), e16839.
9. Wang, Z., Sun, J., Liao, X., Chen, F., Zhao, G., Wu, J., & Hu, X. (2007). Mathematical modeling on hot air drying of thin layer apple pomace. *Food Research International*, 40(1), 39-46.
10. Kara, C., & Doymaz, İ. (2014). Effective moisture diffusivity determination and mathematical modelling of drying curves of apple pomace. *Heat and Mass Transfer*, 51(7), 983-989.
11. Afolabi, T.J., Tunde-Akintunde, T.Y., & Adeyanju, J.A. (2015). Mathematical modeling of drying kinetics of untreated and pretreated cocoyam slices. *Journal of Food Science and Technology*, 52, 2731-2740.
12. Alibas, I. (2012). Microwave drying of grapevine (*Vitis vinifera* L.) leaves and determination of some quality parameters*. Journal of Agricultural Sciences*, 18(1), 43–53.
13. Aghbashlo, M., Kianmehr, M.H., Khani, S., & Ghasemi, M. (2009). Mathematical modeling of thin-layer drying of carrot. *International Agrophys*, 23, 313-317.
14. Henderson, S.M., & Pabis, S. (1961). Grain drying theory I: Temperature effect on drying coefficient. *Journal of Agricultural Engineering Research,* 6, 169–174.
15. Page, G. (1949). Factors influencing the maximum rates of air-drying shelled corn in thin layer. M.S. Thesis. *Department of Mechanical Engineering, Purdue University*, West Lafayette, IN, USA.
16. Chandra, P.K., & Singh, R.P. (1995). Applied numerical methods for food and agricultural engineers. *CRC Press. Boca Raton*, FL. pp. 163-167.
17. Marianni, V.C, Perussello, C.A., Cancelier, A., Lopes, T.J., & Silva, A. (2015). Hot-air drying characteristics of soybeans and influence of temperature and velocity on kinetic parameters. *Journal of Food Process Engineering*, 37, 619-627.
18. Doymaz, İ., & İsmail, O. (2012). Experimental characterization and modelling of drying of pear slices. *Food Science and Biotechnology*, 21, 1377-1381.
19. Toğrul, İ. T., Çelebi, R.S., & Toğrul, H. (2018). Modeling of drying and shrinkage behavior of Ahlat with applied various pretreatment. *Journal of the Faculty of Engineering and Architecture of Gazi University*, 33(4), 1231-1245.

1. \* Corresponding author. *e-mail address: osama7alshamhazi@gmail.com.* [↑](#footnote-ref-1)