# Modeling of some pistachio drying characteristics in fix, semi fluid and fluid bed dryer

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**Abstract:** Modeling of pistachio (cv. Ohadi) drying kinetic was carried out in a thin layer dryer of fix, semi fluid and fluid bed. Initial moisture content of pistachio samples was about 50.3% (d.b.). Three drying characteristics of effective diffusivity, energy of activation and specific energy consumption were computed and influences of drying parameters were investigated. Air temperature levels of 45, 60, 75 and 90℃ and bed conditions of fix, semi fluid and fluid bed were applied in these experiments. Six mathematical models were used to predict the moisture ratio of pistachio samples in thin layer drying. Results showed that the Two-term model had supremacy in prediction of pistachio drying behavior. Effective moisture diffusivity of pistachio was calculated using Fick's second law. Maximum and minimum values of effective moisture diffusivity calculated between $8.60\times10^{-9}$ m$^2$ s$^{-1}$ and $1.98\times10^{-9}$ m$^2$ s$^{-1}$, respectively. The calculated values of energy of activation for pistachio samples were computed between 30.52 kJ mol$^{-1}$ and 35.26 kJ mol$^{-1}$ for temperature boundary of 45 to 90℃ and bed conditions of fix to fluid bed. Specific consumption of energy in thin layer drying of pistachio varied between $0.531\times10^6$ and $1.447\times10^6$ kJ kg$^{-1}$. Increase in air temperature in each bed condition cause decrease inspecific consumption of energy. These pistachio properties are necessary to design the dryer system and to adjust the dryer in the best point.

**Keywords:** two-term model, thin layer drying, pistachio, diffusivity, energy

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## 1 Introduction

*Pistacia vera* is the only commercially species of pistachio, because of its adequate size of nut and marketability. Warm arid climate was needed for growing of pistachio tree and production of pistachio. Pistachio kernel is a high nutritional product with a favorable taste. Iran is the biggest producer and exporter of pistachio in the world. Pistachio is planted mainly for export in Iran. About 635477 tones pistachio was produced in 2009 (FAOSTAT, 2009).

Pistachios are consumed mainly as salted nuts. Small package of pistachio nuts used as snack food. The other applications of pistachio nut are in the food industries, such as: cakes, biscuits, pies, candies, ice cream and pistachio butter.

The main ingredient of pistachio nuts are protein, carbohydrate, oil and fiber (Shokraii and Esen, 1988). Kernel of pistachio is edible and it enclosed in a thin and bony shell, which is covered by the yellowish hull. The pistachio bony shell will growth and develop one month before harvesting season. The enlarged bony shell pushes on the covering shell to create a natural split. After harvesting of pistachio fruit, covering shell should be removed and drying process should be started within a short period of time. Aflatoxin will be growth after 48 hourson pistachio nuts with splitted bony shell; also this time for unsplitted pistachio nuts is about 10 days (USDA Std., 1990). The best moisture content level for storing of pistachio nuts is 7% - 8% (w.b.) (USDA Std., 1990). Ambient air drying of pistachio is very slow which causes

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pollution of pistachio nuts with mold (Hsu, Mannapperuma and Sing, 1991).

Quality of pistachio nuts depend on proper harvesting and post-harvest processing. Drying is very important in marketability of final product. Hot air forced drying is a conventional method in removing of pistachio moisture content.

Fluid bed drying is a profitable drying method and has been used in drying of different materials. Therefore it was proposed for pistachio nut drying. If air flow passed upward through a bed of pistachio, at a low flow rate, a fix bed is created. At a higher air velocity, the entire pistachio nut started to suspend. At this point the weight of pistachio nuts was counterbalances the frictional force between particles. This point called minimum fluidization. The maximum value of the static pressure drop is obtained at the semi fluid bed condition. With increase in input air flow, bubbling fluid bed is created. In this condition, air bubbles cause to mix the pistachio nuts. After bubbling condition, transportation of pistachio nuts was carried out.Pneumatic conveying of pistachio nut is occurred at the transportation phase. From minimum fluid bed to transportation condition is defined as the fluidization condition (Brooker, Bakker-Arkema and Hall, 1992; Kunii and Levenspiel, 1991).

Mathematical modeling of crop drying using empirical equations can satisfactorily explain the crop behavior in a drying system. The simulation of drying process must allow computation of the process parameters as a function of time at any point in the drying based on the primary crop condition (Kaleta and Górnicki, 2010). Hence, mathematical simulation method is an important tool for estimation of a drying systems performance.

Moisture diffusivity, energy of activation and specific consumption of energy are the most important parameters in designing, optimizing and modeling of the drying process. Air velocity and temperature are effective parameters in convective dryers. Mass transfer phenomenon of a drying process is represented by effective moisture diffusivity (Sharma and Prasad, 2004; Doymaz, 2004). Evaluation of energy requirement for starting and continuing of drying process in a crop drying is carry out using energy of activation. It is very important parameter to estimate the minimum drying condition to obtain a favorite dried material with suitable equilibrium moisture content (Aghbashlo,Kianmehr and Samimi-Akhijahani, 2008).

Energy requirement for evaporating of 1 kg water from fresh crop in a convective dryer is defined as specific consumption of energy. It is an important criterion both in designing dryer system and selecting proper values of drying parameters and adjusting of a dryer apparatus (Koyuncu, Pinar and Lule, 2007).

Effective moisture diffusivity and activation energy of various agricultural and food products were determine by many researchers. These include grapes (Pahlavanzadeh, Basiri and Zarrabi, 2001), potato slices (Akpinar,Midilli and Bicer, 2003), kiwi fruit (Simal et al., 2005), candle nuts (Tarigan et al., 2006), onion slices (Pathare and Sharma, 2006), plums (Goyal et al., 2007), red bell pepper (Vega et al., 2007), beriberi fruit (Aghbashlo, Kianmehr and Samimi-Akhijahani, 2008), and milky mushroom (Arumuganathan et al., 2009), carrot slices (Zielinska and Markowski, 2010). Although effective moisture diffusivity, energy of activation and specific consumption of energy have been determined by many researchers for different crops. It is not published any information about this properties for pistachio in the literature during semi fluid and fluid bed convective drying.

The main goals of this study were to study kinetic modeling of pistachio during drying process in fix, semi fluid and fluid bed conditions, determining, comparing and modeling of the effective moisture diffusivity, energy of activation and specific consumption of energy for pistachio nuts during drying of fix, semi fluid and fluid bed thin layer drying and finding their dependence on drying parameters such as the air temperature and bed condition.

## 2 Materials and methods

### 2.1 Experimental setup

One of the best pistachio cultivars is Ohadi which is selected for drying experiments. Fresh pistachio supplied from a local market and sealed in double layers of polyethylene bags and stored in refrigerator at 4±1℃. Initial moisture content of pistachio samples was 50.30%±0.2% (d.b.). Initial moisture content of pistachio samples was obtained using oven method at 103±2℃ and 24 h (Kashaninejad et al., 2003).

In order to specify bed conditions (air velocities) in experiments, the increasing values of air velocity against pressure drop were recorded, simultaneously. A measuring and recording unit for differential digital manometer and a vane type digital anemometer (Standard ST-8897) was used to obtain the fluidization curve. To achieve the net air pressure drop across the pistachio bed, at first, total static pressure drop due to pistachio column and bed plate was measured, and then was subtracted from air pressure drop due to empty chamber.

The maximum value of static pressure drop against a specific air velocity in fluidization curve is defined as minimum fluidization point or semi fluidized bed (Kunii and Levenspiel, 1991). Fluidization experiments were performed in three replicates for thin layer drying of pistachio samples with about 100 g load. After obtaining the semi fluid bed point (air velocity about 2.6 m $s^{-1}$), two points with air velocities of 1.6 m $s^{-1}$ and 4.1 m $s^{-1}$ were selected as fix and fluid bed conditions respectively (Figure 1).

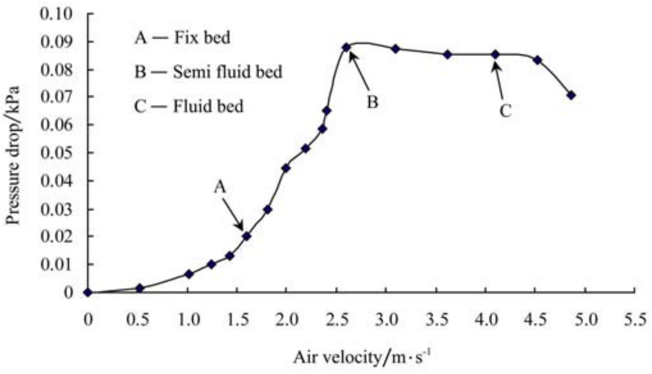
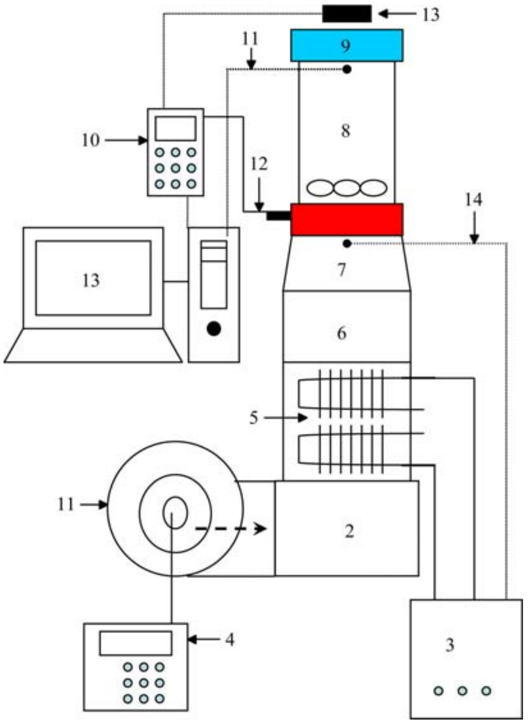


Figure 1 Fluidization curve of pistachio nuts and three points selected as experimental points

Drying process of pistachio samples were continued until final moisture content were received to average of about 9% (d.b.). Only the splitted nuts were used in drying experiments. Ambient air temperature of laboratory in the time of experiments was at the range of 28 to 32℃ and air relative humidity was 21% to 33%.

A laboratory fluid bed dryer was used for drying experiments. This apparatus was fabricated in agricultural machinery engineering of Bu-Ali Sina University (Figure 2). The main parts of the dryer are forward radial fan, drying chamber, electrical heater, inverter, temperature controller. The dryer attachments are input and output temperature sensors, anemometer and computer.

Two parameters of air temperature and bed condition (air velocity) were considered as input variables. Four air temperature levels of 45, 60, 75 and 90℃ and three bed conditions of fixed (1.6 m $s^{-1}$), semi fluidized (2.6 m $s^{-1}$) and fluidized bed (4.1 m $s^{-1}$) were applied in the drying experiments. Each experiment was performed in three replications.



1-Fan and electrical motor, 2-Mixing chamber, 3-Thermostat, 4-Inverter, 5-Electrical heater, 6-Pipe network, 7-Diffuser, 8-Drying chamber input air temperature recorder, 9-Outlet air cap, 10-Digital manometer and anemometer, 11-Output air temperature sensor, 12-Pressure pipe, 13-Air velocity sensor, 14-Input air temperature sensor

Figure 2 Schematic diagram of laboratory scale of fluidized bed dryer

In each drying experiment, about 100 g pistachio samples were loaded in drying chamber. Pistachio nuts were spread in a thin-layer form in the drying chamber and the experiment was started. The ambient air temperature, input and output air temperature, air velocity, air relative humidity and sample weight were continuously monitored and recorded during drying process. A digital balance (AND GF-6000) with 0.01 g accuracy was used to online weighing the drying samples during the drying experiments.

Moisture content of the pistachio samples in each drying run was computed based on the initial and final moisture content of the samples and initial sample mass.

### 2.2 Theoretical principle

Pistachio nuts considered as sphere and second law of Fick about diffusion in spherical body was applied in this study. Three assumptions were utilized as follow: 1) mass transfer occurred in diffusion mode, 2) volume shrinkage of pistachio nuts was negligible, 3) applied temperature and therefore coefficients of diffusion are fixed (Crank, 1975; DiMatteo et al., 2000):

$$\frac{\partial M}{\partial t} = \nabla(D_{eff}.\nabla(M)) \tag{1}$$

where, $M$ is the moisture content (%, d.b.); $t$ is the time of drying (s) and $D_{eff}$ is the effective moisture diffusivity and indicator of all agents cause moisture transfer in material ($m^2\ s^{-1}$).

In thin layer drying of pistachio, one dimensional moisture diffusivity, uniform distribution of moisture content and negligible resistance at external surface of sphere, Equation (1) can be simplified as follows:

$$M = M_e + \frac{6}{\pi^2}(M_0 - M_e)\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D_{eff}n^2\pi^2 t}{r^2}\right) \tag{2}$$

where, $M_0$ is the initial moisture content (%, d.b.); $M_e$ is the equilibrium moisture content (%, d.b.); $n$ is the number of terms taken into consideration (1, 2, 3, . . .) and $r$ is the radius of pistachio nut (m).

Equation (2) can be written in a dimensionless form as follow:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D_{eff}n^2\pi^2 t}{r^2}\right) \tag{3}$$

where, $MR$ is the moisture ratio, decimal; $M$ is the moisture content at any time, kg water (kg dry mater)$^{-1}$; $M_0$ is the initial moisture content, kg water (kg dry mater)$^{-1}$; $n$=1, 2, 3, . . . is the number of terms taken into consideration; $t$ is the drying time, s and $r$ is the radius of pistachio nuts, m.

For a long drying time, only the first term of Equation (3) can be considered, without any negative effect on the accuracy of the prediction (Lopez et al., 2000; Ramesh et al., 2001):

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{D_{eff}\pi^2 t}{r^2}\right) \tag{4}$$

The linear form of the $MR$ is as follow:

$$MR = \left(\frac{6}{\pi^2}\right)\exp\left(\frac{D_{eff}\pi^2 t}{r^2}\right) \tag{5}$$

The slope ($C$) is calculated by plotting t against $\ln(MR)$ as follow:

$$C = \frac{\pi^2 D_{eff}}{r^2} \tag{6}$$

The energy of activation of pistachio nuts was determined using an Arrhenius type equation (Akpinar, Midilli and Bicer, 2003):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{7}$$

For calculating $E_a$ Equation (7) can be written as follows:

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) \tag{8}$$

where, $E_a$ is the energy of activation, kJ mol$^{-1}$; $R$ is the universal gas constant, 8.3143 kJ mol$^{-1}$ K$^{-1}$; $T_a$ is the absolute air temperature, K and $D_0$ is the pre-exponential factor of the equation, m$^2$ s$^{-1}$.

From Equation (8), the plot of $1/T$ against $\ln(D_{eff})$ gives a straight line with the slope of $C_1$.

$$C_1 = \frac{E_a}{R} \tag{9}$$

Linear form of Equation (8) was used to fit to the experimental data and then index of coefficient of determinations ($R^2$) was obtained.

Equation (3) can be simplified as follow:

$$MR = \frac{M - M_e}{M_0 - M_e} = a\exp(-kt) \tag{10}$$

Many mathematical models for thin layer drying proposed by researchers and can be used to predict the drying behavior of crops. Some commonly models used in this study were presented in Table 1. All these models were fitted to experimental drying curves of pistachio and the best model was selected through comparing of their obtained $R^2$ values.

Equilibrium moisture content ($M_e$) of samples in each temperature and relative humidity is relatively small compared to $M$ or $M_0$ (Arumuganathan et al., 2009). Therefore $(M-M_e)/(M_0-M_e)$ can be simplified as $M/M_0$. The basic Equation (3) and all empirical models in Table 1 can be written as follow:

$$MR = \frac{M}{M_0} \tag{11}$$

**Table 1 Thin layer drying models used in modeling of pistachio drying**

| Model name | Equation* | References |
|---|---|---|
| Page | $MR = a\ \exp(-kt^n)$ | Zhang and Litchfield (1991) |
| Two-term | $MR = a\ \exp(k_0 t) + b\ \exp(-k_1 t)$ | Henderson (1974) |
| Wang and Singh | $MR = 1 + at + bt^2$ | Wang and Singh (1978) |
| Midilli et al. | $MR = a\ \exp\ (-kt^n) + bt$ | Midilli, Kucuk and Yapar (2002) |
| Demir et al. | $MR = a\ \exp(-kt)^n b$ | Demir et al. (2007) |
| Aghbashlo et al. | $MR = \exp\ (-at/(1+bt))$ | Aghbashlo et al. (2009) |

Note: * $a$, $b$, $c$, $k$, $k_0$, $k_1$ and $n$ are drying constants.

The specific consumption of energy in drying process of pistachio samples can be calculated using the following thermodynamic Equation (12) (Zhang et al., 2002):

$$SCE = \frac{(C_{Pa} + C_{Pv} h_a)}{m_v V_h} Qt(T_{in} - T_{am}) \tag{12}$$

where, $SCE$ is the specific consumption of energy, kJ kg$^{-1}$; $C_{Pv}$ and $C_{Pa}$ are the specific heat capacity of vapor and air, respectively (1,004.16 and 1,828.8 J kg$^{-1}$ ℃$^{-1}$); $Q$ is the inlet air to drying chamber, m$^3$ s$^{-1}$; $h_a$ is the absolute air humidity, kg vapor (kg dry air)$^{-1}$; $T_{in}$ and $T_{am}$ are the inlet air to drying chamber and ambient air temperatures, respectively, ℃; $m_v$ is the mass of removal water, kg and $V_h$ is the specific air volume, m$^3$ kg$^{-1}$.

Fitting of empirical models to experimental data and analysis of non-linear regression were carried out using MATLAB (version 7) software. Coefficient of correlation ($R^2$) was used as the main criteria for selecting the best model and two indices of reduced chi-square ($\chi^2$) and root mean square error ($RMSE$) also were used as the goodness of fit. The best selected model has the highest value of $R^2$ and the lowest values of $\chi^2$ and $RMSE$ (Erenturk,Gulabogluand Gultekin, 2004; Demir et al., 2004). Equations of indices are as follow:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}[MR_{\exp,i} - MR_{pre,i}]}{\sum_{k=1}^{N}\left[MR_{pre,i} - \frac{\sum_{k=1}^{n} MR_{pre,i}}{N}\right]} \tag{13}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{14}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2\right]^{\frac{1}{2}} \tag{15}$$

where, $MR_{\exp,i}$ is the experimental moisture ratio of $i^{th}$ data; $MR_{pre,i}$ is the predicted moisture ratio of $i^{th}$ data; $N$ is the number of observations and $z$ is the number of drying constants.

## 3 Results and discussion

### 3.1 Mathematical models

Drying curves of pistachio samples for all bed conditions and temperature levels have been presented in Figure 3. Pistachio samples were dried to about 9% (d.b.). Results showed that the effect of air temperature on drying time was more than air velocity. With increasing in air temperature, the drying time was decreased. When the upper temperature levels were applied to the pistachio bed, exerted energy rate to the bed of pistachio sample and thereafter drying rate were increased. Similar results are presented by many researchers such as: egg plant (Akpinar and Bicer, 2005), peach (Kingsly et al., 2007), plum (Goyal et al., 2007), berberis fruit (Aghbashlo, Kianmehr and Samimi-Akhijahani, 2008), mushroom (Arumuganathan et al., 2009) and carrot (Aghbashlo et al., 2009).

Six different mathematical models were tested to find the best model for prediction pistachio drying time. Software of MATLAB 7 (R 14) was used to fit the mathematical models on experimental drying data. Non linear regression analysis was used in this process. Three indices of $R^2$, $\chi^2$ and $RMSE$ were calculated for all models and presented in Table 2. Comparative parameters of $R^2$ and $\chi^2$ for the best model should have the highest and lowest values, respectively. Mathematical models of Page, Two-term and Midilli et al. have the $R^2$ values greater than 0.99 for the most drying conditions. The $R^2$ value for Two-term model, for all drying conditions, was the highest, also $\chi^2$ and *RMSE* of this model were the lowest. Thus, the Two-term model was the best for estimation of thin layer drying behavior of pistachio in applied drying conditions. Adjusted coefficients of Two-term model for all drying conditions are presented in Table 3. To test the adjusted Two-term model in prediction of drying curve, all experimental data against predicted data by the model are shown in Figure 4. The obtained value of $R^2$ in this curve was high and proved that the application of Two-term model was the best selection.

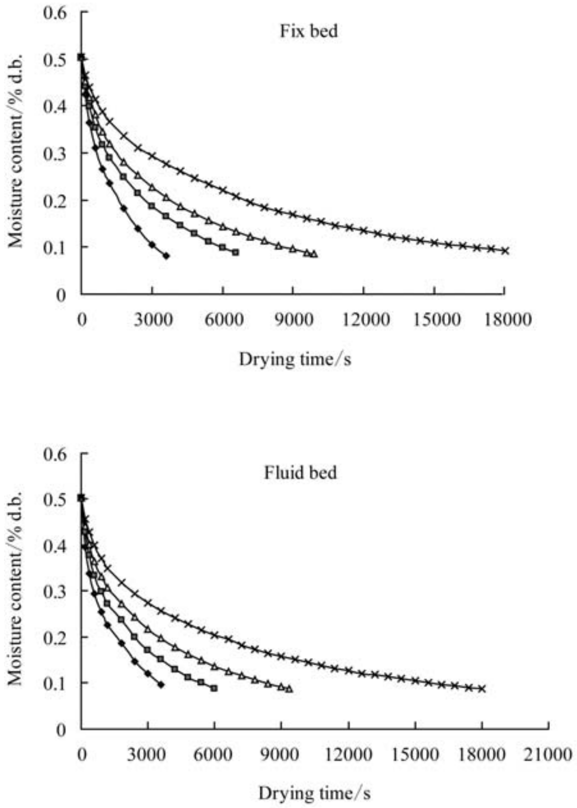


Figure 3 Drying kinetic of pistachio in fixed, semi fluidized and fluidized bed conditions

**Table 2 Indices values of applied statistical model for pistachio thin layer drying**

| Model name | Air temperature /℃ | $R^2$ | | | $\chi^2$ | | | *RMSE* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1.6 m $s^{-1}$ | 2.6 m $s^{-1}$ | 4.1 m $s^{-1}$ | 1.6 m $s^{-1}$ | 2.6 m $s^{-1}$ | 4.1 m $s^{-1}$ | 1.6 m $s^{-1}$ | 2.6 m $s^{-1}$ | 4.1 m $s^{-1}$ |
| Page | 45 | 0.9993 | 0.9996 | 0.9997 | 0.0011 | 0.0007 | 0.0005 | 0.0324 | 0.0253 | 0.0226 |
| | 60 | 0.9995 | 0.9995 | 0.9994 | 0.0005 | 0.0005 | 0.0006 | 0.0219 | 0.0220 | 0.0239 |
| | 75 | 0.9994 | 0.9991 | 0.9984 | 0.0003 | 0.0008 | 0.0012 | 0.0155 | 0.0266 | 0.0321 |
| | 90 | 0.9992 | 0.9982 | 0.9985 | 0.0006 | 0.0011 | 0.0009 | 0.0221 | 0.0297 | 0.0271 |
| Two-term | 45 | 0.9991 | 0.9994 | 0.9990 | 0.0016 | 0.0009 | 0.0016 | 0.0374 | 0.0291 | 0.0371 |
| | 60 | 0.9997 | 0.9999 | 0.9997 | 0.0004 | 0.0001 | 0.0004 | 0.0179 | 0.0094 | 0.0169 |
| | 75 | 0.9999 | 0.9999 | 0.9998 | 0.0000 | 0.0000 | 0.0001 | 0.0040 | 0.0062 | 0.0093 |
| | 90 | 0.9999 | 0.9998 | 0.9995 | 0.0000 | 0.0001 | 0.0003 | 0.0051 | 0.0086 | 0.0134 |
| Wang and Singh | 45 | 0.9592 | 0.9493 | 0.9911 | 0.0705 | 0.0788 | 0.0086 | 0.2579 | 0.2717 | 0.0757 |
| | 60 | 0.9343 | 0.9624 | 0.9486 | 0.0755 | 0.0448 | 0.0555 | 0.2485 | 0.2013 | 0.2235 |
| | 75 | 0.9712 | 0.9582 | 0.9503 | 0.0151 | 0.0372 | 0.0386 | 0.1121 | 0.1795 | 0.9503 |
| | 90 | 0.9633 | 0.9441 | 0.9795 | 0.0260 | 0.0344 | 0.0125 | 0.1471 | 0.1678 | 0.0999 |

| Model name | Air temperature /℃ | $R^2$ | | | $\chi^2$ | | | $RMSE$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1.6 m $s^{-1}$ | 2.6 m $s^{-1}$ | 4.1 m $s^{-1}$ | 1.6 m $s^{-1}$ | 2.6 m $s^{-1}$ | 4.1 m $s^{-1}$ | 1.6 m $s^{-1}$ | 2.6 m $s^{-1}$ | 4.1 m $s^{-1}$ |
| Midilli et al. | 45 | 0.9996 | 0.9998 | 0.9907 | 0.0007 | 0.0002 | 0.0570 | 0.0247 | 0.0141 | 0.2068 |
| | 60 | 0.9996 | 0.9997 | 0.9998 | 0.0004 | 0.0003 | 0.0002 | 0.0183 | 0.0163 | 0.0139 |
| | 75 | 0.9995 | 0.9997 | 0.9992 | 0.0003 | 0.0003 | 0.0006 | 0.0135 | 0.0144 | 0.0207 |
| | 90 | 0.9996 | 0.9995 | 0.9993 | 0.0003 | 0.0003 | 0.0004 | 0.0143 | 0.0139 | 0.0155 |
| Demir et al. | 45 | 0.9946 | 0.9930 | 0.9995 | 0.0093 | 0.0109 | 0.0004 | 0.0909 | 0.0976 | 0.0182 |
| | 60 | 0.9940 | 0.9939 | 0.9916 | 0.0054 | 0.0073 | 0.0090 | 0.0665 | 0.0767 | 0.0850 |
| | 75 | 0.9964 | 0.9963 | 0.9897 | 0.0014 | 0.0025 | 0.0080 | 0.0303 | 0.0425 | 0.0756 |
| | 90 | 0.9926 | 0.9871 | 0.9951 | 0.0052 | 0.0079 | 0.0030 | 0.0601 | 0.0711 | 0.0424 |
| Aghbashlo et al. | 45 | 0.9913 | 0.9899 | 0.9993 | 0.0150 | 0.0156 | 0.0006 | 0.1191 | 0.1210 | 0.0200 |
| | 60 | 0.9901 | 0.9935 | 0.9902 | 0.0114 | 0.0077 | 0.0106 | 0.1018 | 0.0836 | 0.0976 |
| | 75 | 0.9956 | 0.9918 | 0.9899 | 0.0023 | 0.0073 | 0.0079 | 0.0361 | 0.0793 | 0.0823 |
| | 90 | 0.9937 | 0.9888 | 0.9955 | 0.0044 | 0.0069 | 0.0028 | 0.0614 | 0.0752 | 0.0470 |

**Table 3 Adjusted coefficients of Two-term model for prediction of pistachio thin layer drying kinetic**

| Bed condition | Coefficients | Drying temperature | | | |
|---|---|---|---|---|---|
| | | 45℃ | 60℃ | 75℃ | 90℃ |
| Fixed bed (1.6 m $s^{-1}$) | $a$ | 0.8073 | 0.7458 | 0.8169 | 0.8162 |
| | $k_0$ | -0.2417 | -0.3907 | -0.6581 | -0.9798 |
| | $b$ | 0.1850 | 0.2479 | 0.1831 | 0.1848 |
| | $k_1$ | 3.2789 | 5.1096 | 7.7073 | 11.4947 |
| Semi fluidized bed (2.6 m $s^{-1}$) | $a$ | 0.7828 | 0.7970 | 0.8120 | 0.7990 |
| | $k_0$ | -0.2554 | -0.4482 | -0.7523 | -1.0978 |
| | $b$ | 0.2055 | 0.2004 | 0.1875 | 0.2011 |
| | $k_1$ | 3.4698 | 5.1130 | 10.0211 | 16.1524 |
| Fluidized bed (4.1 m $s^{-1}$) | $a$ | 0.2336 | 0.7890 | 0.8131 | 0.8779 |
| | $k_0$ | -3.1311 | -0.4653 | -0.7337 | -1.3333 |
| | $b$ | 0.7518 | 0.2062 | 0.1879 | 0.1242 |
| | $k_1$ | 0.2369 | 6.4900 | 10.7918 | 13.8360 |

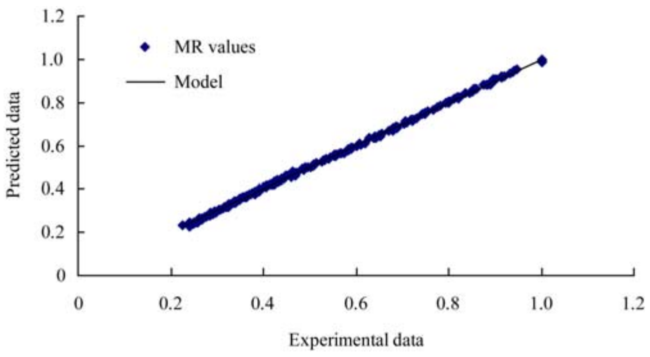


Figure 4 Experimental values of moisture ratio against predicted values using Two-term model in fix, semi fluid and fluid bed conditions

### 3.2 Effective moisture diffusivity

Factor of ln($MR$) for all drying conditions was calculated and was drown against drying time (s). These curves are similar to linear line (Figure 5). Results showed that drying of pistachio was occurred in falling rate period. Therefore mass transfer was controlled using drying force. The slope of linear line was increased as well as the temperature values were increased. Air velocity was affected the slope of $D_{eff}$ adversely. In the other word increasing in air velocity caused decreasing in $D_{eff}$. Values of $D_{eff}$ was calculated using Equation (4). Calculated values of $D_{eff}$ for all drying conditions are presented in Table 4. Maximum values of $D_{eff}$ has been obtained during fluidized bed drying with air velocity of 4.1 m $s^{-1}$ and air temperature 90℃. This result proved that the influence of effective parameters on mass transfer phenomenon in fluidized bed was more than the other bed conditions. Most effective contact between air and pistachio nuts for mass transfer was accrued in fluidized bed condition. Maximum value of $D_{eff}$ ($7.67\times10^{-9}$ m$^2$ s$^{-1}$) in convective drying of pistachio nuts was obtained for fluidized bed condition and air temperature 90℃. Minimum value of $D_{eff}$ ($1.64\times10^{-9}$ m$^2$ s$^{-1}$) was obtained for fixed bed condition and air temperature 45℃.

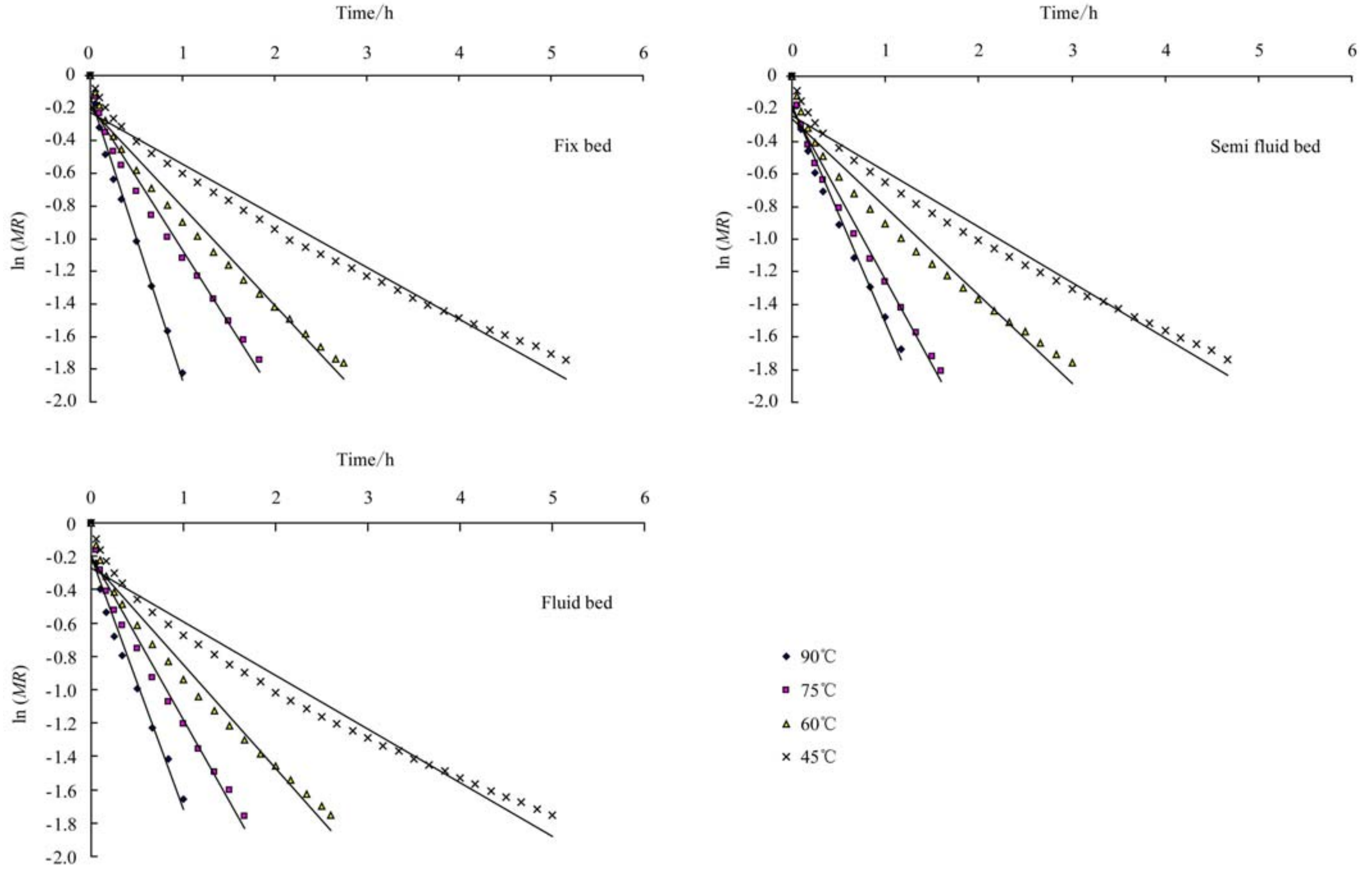


Figure 5 Values of ln(MR) against drying time for pistachio nuts in fixed, semi fluidized and fluidized bed conditions

Effect of air temperature on $D_{eff}$ values of pistachio was more than bed condition (Table 4). Results showed that $D_{eff}$ was increased with increase of air temperature. Similar result was obtained for mushroom in fluidized bed condition (Arumuganathan et al., 2009). Relation between air temperature and effective moisture diffusivity during fixed bed drying of some agricultural and food products was reported, such as: plums (Goyal et al., 2007), peaches (Kingsly et al., 2007), berberis fruit (Aghbashlo, Kianmehr and Samimi-Akhijahani, 2008), and carrot slices (Aghbashlo et al., 2009).

**Table 4 Effective moisture diffusivity and related correlation coefficient for pistachio thin layer drying in fix, semi fluid and fluid bed conditions**

| Temperature /℃ | Fix bed (1.6 m s$^{-1}$) | | Semi fluid bed (2.6 m s$^{-1}$) | | Fluid bed (4.1 m s$^{-1}$) | |
|---|---|---|---|---|---|---|
| | $D_{eff}$ (m$^2$ s$^{-1}$) | | $D_{eff}$ (m$^2$ s$^{-1}$) | | $D_{eff}$ (m$^2$ s$^{-1}$) | |
| 45 | $1.98\times10^{-9}$ | 0.9870 | $2.15\times10^{-9}$ | 0.9850 | $2.02\times10^{-9}$ | 0.9797 |
| 60 | $3.79\times10^{-9}$ | 0.9891 | $3.93\times10^{-9}$ | 0.9798 | $3.91\times10^{-9}$ | 0.9865 |
| 75 | $5.63\times10^{-9}$ | 0.9911 | $6.25\times10^{-9}$ | 0.9908 | $6.15\times10^{-9}$ | 0.9889 |
| 90 | $8.25\times10^{-9}$ | 0.9959 | $8.43\times10^{-9}$ | 0.9906 | $8.60\times10^{-9}$ | 0.9868 |

Variations of $D_{eff}$ against air temperature for all drying conditions were depicted in Figure 6. Three exponential models were applied to fit the calculated values of $D_{eff}$ against air temperatures for different bed conditions (Tables 5). Four linear models were fitted on

$D_{eff}$ values against air velocities. These models and related $R^2$ values are presented in Table 6.

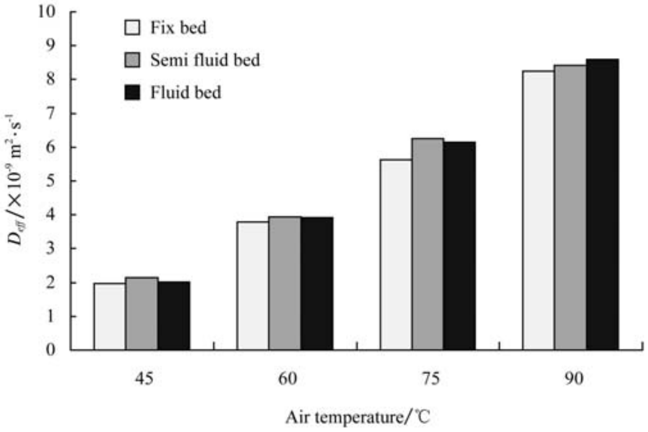


Figure 6 Effect of air temperature and bed condition on $D_{eff}$ of pistachio nut in thin-layer drying

**Table 5 Applied exponentioal models to $D_{eff}$ value of pistachio nut for different air temperatures**

| Bed condition | Model | $R^2$ |
|---|---|---|
| Fixed bed (1.6 m s$^{-1}$) | $D_{eff}=9\times10^{-13}T^{2.034}$ | 0.9978 |
| Semi fluidized bed (2.6 m s$^{-1}$) | $D_{eff}=1\times10^{-12}T^{1.994}$ | 0.9975 |
| Fluidized bed (4.1 m s$^{-1}$) | $D_{eff}=7\times10^{-13}T^{2.097}$ | 0.9976 |

**Table 6 Applied linear models to $D_{eff}$ value of pistachio for different air velicities ($v$)**

| Air temperature/℃ | Model | $R^2$ |
|---|---|---|
| 45 | $D_{eff}=-3\times10^{-11}v^2+3\times10^{-10}v+8\times10^{-9}$ | 1 |
| 60 | $D_{eff}=-3\times10^{-10}v^2+2\times10^{-9}v+3\times10^{-9}$ | 1 |
| 75 | $D_{eff}=-6\times10^{-11}v^2+4\times10^{-10}v+3\times10^{-9}$ | 1 |
| 90 | $D_{eff}=-1\times10^{-10}v^2+6\times10^{-10}v+1\times10^{-9}$ | 1 |

### 3.3 Energy of activation

Values of ln($D_{eff}$) were calculated for all drying conditions and was plotted against 1/$T$ (Figure 7). Equation(8) was used for calculation energy of activation ($E_a$). The obtained $E_a$ for all drying conditions and their $R^2$ values for equations are presented in Table 7. Researcher studies showed that the $E_a$ value of all food and agricultural products is between 12.7 and110 kJ mol$^{-1}$ (Aghbashlo, Kianmehr and Samimi-Akhijahani, 2008).

**Table 7 Energy of activation of pistachio nuts and related $R^2$ values for all applied bed conditions**

| Bed condition | Fixed bed (1.6 m s$^{-1}$) | Semi fluidized bed (2.6 m s$^{-1}$) | Fluidized bed (4.1 m s$^{-1}$) |
|---|---|---|---|
| $R^2$ Equation | 0.9900 | 0.9881 | 0.9872 |
| $E_a$ (kJ mol$^{-1}$) | 35.26 | 30.52 | 32.73 |

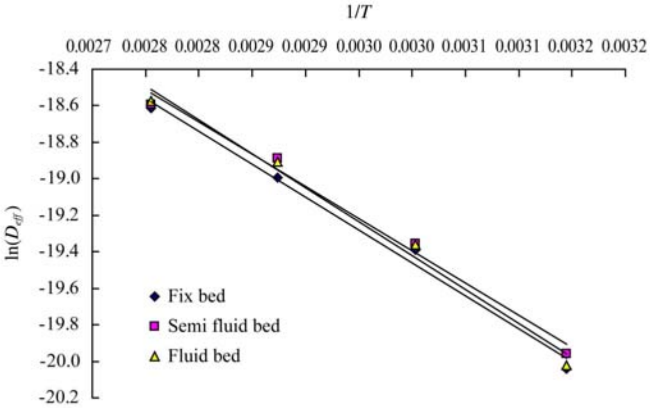


Figure 7 Values of ln($D_{eff}$) against 1/$T$ at different bed conditions for thin-layer drying of pistachio nuts

Minimum and maximum values of $E_a$ for pistachio nuts in domain of fix and fluid bed conditions were obtained between 30.52 and 35.26 kJ mol$^{-1}$. Minimum and maximum values of $E_a$ for fig fruit were between 30.8 and 48.47 kJ mol$^{-1}$ (Babalis and Belessiotis, 2004), for grape were between 46.95 and 46.30 kJ mol$^{-1}$ (Amiri Chayjan et al., 2011) and for berberis fruit were between 110.84 and 124.36 kJ mol$^{-1}$ (Aghbashlo, Kianmehr and Samimi-Akhijahani, 2008). Two forms of water in pistachio nuts are surface and chemical moisture. Most of the water in pistachio nut is as the chemical moisture, thus this type of water transferred in falling rate period, so relatively much energy was needed to exit from pistachio nut. Undesirable change of pistachio due to drying condition such as air temperature is notable in this falling rate period (Brooker, Bakker-Arkema and Hall, 1992). If proper adjustments such as air velocity and temperature were applied in pistachio drying, damages such as: decrease in nutritive value, color degradation and mechanical damage in handling stage should be decreased. Activation energy of pistachio nuts is relatively high, compared with some other crops. Many factors are effect in this phenomenon as follow:

Relatively low initial moisture content of pistachio (50.03%d.b.) cause the form of water in pistachio was being as chemical type, tissue of pistachio and fatty structure causes a relatively low mass transfer.

Values of $E_a$ for pistachio nuts at different drying conditions were plotted in Figure 8. An exponential equation was used to fit the calculated data of $E_a$ as well as $R^2$ value was 0.9950. Maximum value of $E_a$

(35.26 kJ $mol^{-1}$) was calculated in fluid bed condition at air velocity of 4.1 m $s^{-1}$ (Figure 7). Minimum value of $E_a$ (30.52 kJ $mol^{-1}$) was calculated in fixed bed condition at air velocity of 1.6 m $s^{-1}$. Difference between minimum and maximum values of $E_a$ was not significant. The fitted exponential equation to obtained data of $E_a$ and air velocity is as follow:

$$E_a = 2.48v^2 - 15.18v + 53.18 \qquad R^2 = 1 \tag{16}$$

Similar trend has been reported by Demirel and Turhan (2003) and Aghbashlo, Kianmehr and Samimi-Akhijahani (2008) about relatively high activation energy requirement for banana slices and berberis fruit.

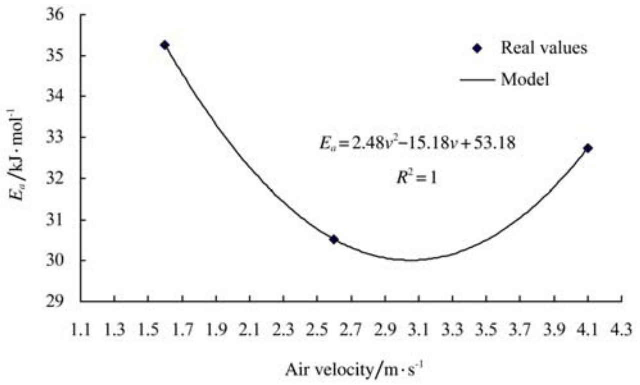


Figure 8 Energy of activation for pistachio nut and effect of bed condition (air velocity)

### 3.4 Specific consumption of energy

The specific consumption of energy (*SCE*) for elimination of 1 kg water from pistachio nuts using fixed, semi fluidized and fluidized bed drying was calculated using Equation (12). Calculated values of *SCE* for pistachio drying were depicted in Figure 9. It was proved that an increase in air temperature for all bed conditions, cause a decrease in *SCE*. Increase in air velocity caused intensively increase in *SCE*. The minimum value of *SCE* ($0.531\times10^6$ kJ $kg^{-1}$) was obtained in fixed bed drying and air temperature of 90℃. The maximum value of *SCE* ($1.477\times10^6$ kJ $kg^{-1}$) was obtained in fluidized bed condition and air temperature of 40℃. Result proved that an inverse relationship is established between *SCE* and drying time. In the other words, in each bed condition, decrease in air temperature, cause an increased in drying time and energy consumption. Pistachio drying in fluidized bed condition leads to decrease in effective contact between air and pistachio nuts relative to the input heat rate and therefore *SCE* was increased. Similar trends have been observed for paddy (Khoshtaghaza, Sadeghi and Amiri Chayjan, 2007) and berberis fruit (Aghbashlo, Kianmehr and Samimi-Akhijahani, 2008).

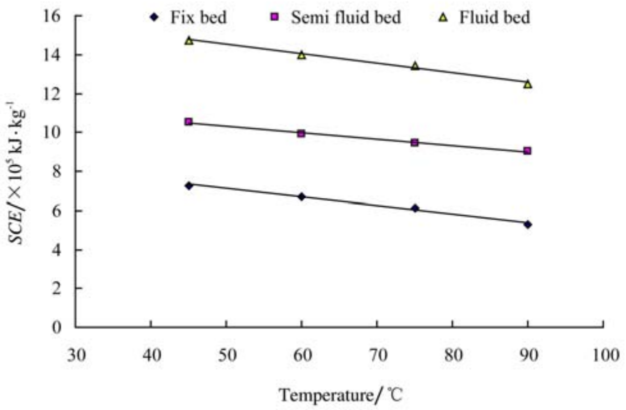


Figure 9 Specific consumption of energy for thin layer drying of pistachio nuts at fix, semi fluid and fluid bed conditions

Three linear models were used to fit the *SCE* data in fixed and semi fluidized and fluidized bed conditions as follow:

$$SCE = (2E+6) - 4870.5T \qquad R^2 = 0.9919 \quad \text{(Fix bed)} \tag{17}$$

$$SCE = (1E+6) - 3378.6T \qquad R^2 = 0.9910 \quad \text{(Semi fluid bed)} \tag{18}$$

$$SCE = (0.93E+6) - 4300.2T \qquad R^2 = 0.9886 \quad \text{(Fluid bed)} \tag{19}$$

## 4 Conclusions

1) Results showed that the Two-term model was the best for prediction of pistachio drying kinetics.

2) Maximum value of $D_{eff}$ during pistachio drying was obtained in fluid bed condition (air velocity of 4.1 m $s^{-1}$) and the air temperature of 90℃. Minimum value of $D_{eff}$ was obtained in fixed bed condition (air velocity of 1.6 m $s^{-1}$) and the air temperature of 45℃. The $D_{eff}$ values of pistachio were also increased as input air temperature was increased.

3) Minimum and maximum values of $E_a$ for dried pistachio were 30.52 and 35.26 kJ $mol^{-1}$, respectively. Maximum value of $E_a$ was calculated in fluidized bed

condition. In fixed bed condition, the activation energy had the minimum value.

4) Maximum value of *SCE* for pistachio drying obtained in fluidized bed condition with drying air temperature of 45℃. Minimum value of *SCE* also was obtained in fixed bed condition with drying air temperature of 90℃. Increase in air temperature in each bed condition cause decrease in *SCE* value.

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