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# NATURAL DRYING CHARACTERISTICS OF SESAME SEEDS

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**ABSTRACT -** Since sesame seeds (SS) are more sensitive to high drying temperature, seeds are dried naturally indoor with either natural or forced convection air. In this study, SS with the initial moisture content of around 50.8% (d.b.) were dried until the final moisture content of about 3.0-3.7% (d.b.). The drying characteristics of SS were investigated under indoor conditions with both forced convection (FC) and natural convection (NC) of air. Modelling the correlation between moisture content with drying time and drying method was carried out by using mathematical and artificial neural networks (ANN). During the FC and NC experiments, the time to reach the final moisture content was found to be 400 and 900 min, respectively. The FC drying times were around 55% shorter than the NC drying times. The effective water diffusion coefficients of SS, under FC and NC conditions, were $3.1\times10^{-11}$ and $1.1\times10^{-11}$ $m^2/s$, respectively. The corresponding values for the overall resistance to diffusion were $70.8\times10^5$ and $19.6\times10^6$ $m^2$ s/kg, respectively. The ANN model was capable of predicting the moisture content with a $R^2$ of 0.999, RMSE of less than 0.0116 and MRE of about 1.73%. It was found that both the Khazaei and Peleg's models were suitable for predicting the moisture content of sesame seeds. However, the Khazaei model gave better fit to the drying data. It was concluded that ANN represented the drying characteristics better than the mathematical models.

**Key words**: sesame seeds, natural drying, neural network, mathematical modelling

**REZUMAT – Caracteristicile uscării naturale a semințelor de susan**. Deoarece semințele de susan (SS) sunt mai sensibile la temperaturile mari de uscare, ele sunt supuse procesului de uscare, în spații închise, fie natural, fie cu aer cald de convecție forțată. In această lucrare, semințele de susan, cu un conținut mediu inițial de apă de 50,8% (bază uscată), au fost uscate până au ajuns la un conținut de apă de aprox. 3,0-3,7% (bază uscată). S-au investigat caracteristicile de uscare a semințelor de susan, în interior, şi cu aer cald de convecție forțată (FC) şi cu convecție naturală (NC). Modelarea corelației dintre conținutul de apă**,** timpul şi metoda de uscare a fost realizată prin folosirea rețelelor neurale artificiale şi matematice

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(ANN). In timpul experimentelor cu FC şi NC, timpul necesar pentru a atinge conţinutul final de apă a fost de 400 şi, respectiv, 900 min. Timpul de uscare cu FC a fost cu aprox. 55% mai redus faţă de timpul de uscare cu NC. Coeficienţii de difuzie efectivă în apă a seminţelor de susan, în condiţii de FC şi NC, au fost $3,1\times10^{-11}$ şi, respectiv, $1,1\times10^{-11}$ $m^2/s$. Valorile corespunzătoare pentru rezistenţa totală la difuzie au fost de $70,8\times10^5$ şi, respectiv, $19,6\times10^6$ $m^2$ s/kg. Modelul ANN a fost capabil să estimeze conţinutul de apă cu $R^2$ - de 0,999, RMSE - mai puţin de 0,0116 şi MRE – de aprox. 1,73%. Ambele modele, Khazaei şi Peleg, s-au dovedit adecvate pentru a estima conţinutul de apă din seminţele de susan. Totuşi, modelul Khazaei a oferit estimări mai precise pentru datele de uscare. S-a ajuns la concluzia că ANN a reprezentat caracteristicile de uscare mai bine decât modelele matematice.

**Cuvinte cheie:** seminţe de susan, uscare naturală, reţea neurală, modelare matematică

## INTRODUCTION

Sesame (*Sesamum indicum* L.) seeds are rich in protein, oil, crude fibre, and carbohydrate (Obiajunwa et al., 2005). Dehulling is an essential step in processing sesame seeds (SS) and a variety of solutions has been sought for that. The dehulling process often requires the seeds to be hydrated first, in order to facilitate the operation. The bare seeds are then washed and dried, to produce a premium confectionary product. Dehulled seeds are used in baking, cake, hamburger buns, cookies and snack foods. Since SS are more sensitive to high drying temperature, seeds are dried naturally indoor with either natural or forced convection air. Natural drying is a well-known, popular and inexpensive method to reduce the moisture contents of agricultural products, which prevents deterioration within a period of time, regarded as the safe storage period.

One of the most important aspects of the drying technology, especially for industrial processes, is modelling of the drying processes. The purpose of modelling is to allow the engineers to choose the most appropriate method of drying for a given product, as well as to choose suitable operating conditions. Full-scale experimentation for different products and system configurations is sometimes costly and not possible. Therefore, prediction of drying kinetics of specific crops under various conditions is very useful in design and optimization of dryers.

Thin-layer drying models can be categorized as theoretical, semi-theoretical and empirical models. The most widely studied theoretical model in thin layer drying of various foods is given by the solution of Fick's second law. General series solution of Fick's second law in spherical coordinates with the assumptions of moisture migration being by diffusion, negligible shrinkage, constant diffusion and temperature are given as follows (Crank, 1970; Kashaninejad et al., 2007):

$$\frac{M_t - M_e}{M_o - M_e} = Mr = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp[-\frac{n^2\pi^2 D_e t}{R_e^2}] \quad (1)$$

**Nomenclature**

| | | | |
|---|---|---|---|
| $D_e$ | Effective water diffusivity, ($m^2/s$) | $R_e$ | Equivalent radius of seeds being dried, (mm) |
| $D_o$ | Constant equivalent to the diffusivity at infinitely high temperature, ($m^2/s$) | $R_{ds}$ | Resistance to diffusion, ($m^2$ s/kg) |
| $E_a$ | Activation energy, (kJ/mol) | S | Surface area, ($mm^2$) |
| $G_{md}$ | Geometric mean diameter, (mm) | t | Drying time (min) |
| K1 | Page rate constant, (min/% d.b) | T | Drying temperature, ($^oC$) |
| $K_{rel}$ | Rate of absorption in the relaxation phase, (%d.b/min) | $T_h$ | Thickness, (mm) |
| K2 | Page capacity constant, ( 1/% d.b) | $T_{rel}$ | Relaxation time, (min) |
| L | Length, (mm) | V | Volume of a single seed, ($mm^3$) |
| $M_{rel}$ | Total absorbed water at the first phase of absorption, (% d.b) | $W_o$ | Initial weight of the product, (g) |
| $M_t$ | Moisture content at any time of drying, (% d.b.) | W | Width, (mm) |
| Mr | Moisture ratio | $W_t$ | Weight of the product to be dried at any time, (g) |
| $M_e$ | Final moisture content, (% d.b.) | $\phi$ | Sphericity |
| $M_o$ | Initial moisture content, (% d.b.) | **Abbreviations** | |
| n | Dimensionless constant | ANN | Artificial neural networks |
| $R^2$ | Coefficients of determination | SS | Sesame seeds |

Drying of many food products, such as wheat (Gaston, et al., 2004) and pistachio nuts (Kashaninejad et al., 2007), has been successfully predicted by using the Fick's second law. Some semi-theoretical drying models that have been widely used in the literature are presented under the form of models, namely: the page, Peleg, Henderson and Pabis and the Logarithmic models. These models have been widely used to model drying of different agricultural products (Gunhan et al., 2005; Kashaninejad et al., 2007; Togrul and Pehlivan, 2004; Turhan et al., 2002). The Peleg model (Peleg, 1988) is a simple empirical model that has been used successfully to describe the drying behaviour of agricultural products (Sopade and Kaimur, 1999; Turhan et al., 2002). The linearized form of the Peleg's equation to regress the moisture content versus drying time is as follow (Sopade and Kaimur, 1999; Turhan et al., 2002):

$$M - M_o = -\frac{t}{K_1 + K_2 t} \quad (2)$$

Previous studies showed that the drying kinetics of agricultural products consisted in two phases, an early/primary phase with rapid water transfer rate and a second phase with slower rate (Gunhan et al., 2005; Togrul and Pehlivan, 2004).

The second phase may continue until the product equilibrates. The slopes of the two linear segments corresponding to the first and second phases of drying show the rate of drying in these two phases. The major problem of the Fick, Peleg, Logarithmic and other empirical and semi-theoretical models is the absence of a criterion to evaluate the drying rate, in the second phase of absorption. The constant parameters in these models are considered as indicators of the drying rate in the first phase of the process (Turhan et al., 2002; Kashaninejad et al., 2007). Khazaei and Mohammadi (2008) proposed a mechanistic model (Khazaei model), to describe the two-stage processes for both drying and water absorption behaviours of food products (*Eq. [3]*). In this two-stage model, the first and the second stages are assumed to be diffusion- and relaxation-controlled, respectively (*Figure 1*). According to the Khazaei model, the water uptake curve is given by:

$$M_t = M_o - M_{rel}(1 - e^{-t/T_{rel}}) - K_{rel}\,t \tag{3}$$

In the Khazaei model, time of relaxation, $T_{rel}$, is the time required to reach the moisture content of the product to about 63% of the total removed moisture, $M_{rel}$ (*Fig. 1*). In other words, $T_{rel}$ shows the rate of drying seeds in the first phase of process. The highest amount of this term shows the lower rate of drying in the first phase of the process. Therefore, $K_{rel}$ shows the rate of drying in the relaxation phase and is calculated by determining the slope of the tangent line on the end part of the drying curve (*Figure 1*).

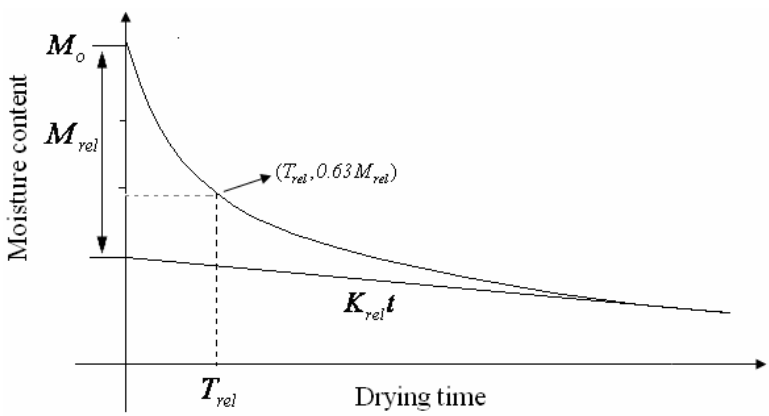


**Fig.1 - Graphical method to determine the constant parameters in the Khazaei model (Eq. [3])**

Although all the above models have been successful in explaining the drying kinetics of agricultural products, they are just related to the drying time and do not include the interaction effect of other related parameters. Thus, it is important for researchers to find a model that incorporates a large number of variables. This problem can be overcome by using the soft computing methods, the same as artificial neural networks. It has been reported that for complex systems like drying process, where a mechanistic description of the dependency between dependent and independent variables is either unknown or very complex, neural networks performed better than mechanistic models (Chegini et al., 2008; Erenturk and Erenturk, 2007; Farkas et al., 2000; Khazaei et al., 2008; Mittal and Zhang, 2000). ANN is especially useful in modelling complex non-linear, multi-dimensional functional relationships (Chegini et al., 2008; Khazaei et al., 2008). One of the characteristics of ANN is its ability to learn the relationship between dependent and independent variables through the data rather than assuming the functional form of the relationship (Chegini et al., 2008; Kaminski et al., 1998; Khazaei et al., 2008). ANN is able to learn the dependency between dependent and independent variables with any degree of complexity. More details of ANN can be found in published papers (Chegini et al., 2008; Khazaei et al., 2008).

The specific objectives of this study were 1) to determine the natural drying kinetics of sesame seeds, under both natural convection and forced convection air, 2) mathematical modelling of thin layer drying of sesame seeds, 3) to develop an ANN model for the prediction of moisture ratio of sesame seeds, as a function of drying time and drying method, and 4) to compare the performance of the ANN model with that of the mathematical models.

## MATERIALS AND METHODS

**Sample preparation.** The sesame seeds (SS) used in this study were obtained from a local market in Tehran, Iran. The seeds contain 56.87% crude fat, 23.04% crude protein, 13.25% carbohydrate, 3.52% ash and 3.40% moisture. They were cleaned manually by removing all the foreign matter such as stones, dirt and broken seeds. The initial moisture content of seeds was determined by using the ASAE standard oven method (4) and it was found to be 3.5% (d.b).

The size of the randomly selected 100 seeds was determined from the main dimensions. For each seed, the length, width and thickness were measured by using a micrometer gauge reading at 0.01 mm. The geometric mean diameter ($G_{md}$), sphericity ($\phi$), volume (V), and surface area (S) of the seeds were calculated by using the following relationships (Altuntas et al., 2005; Tunde-Akintunde and Akintunde, 2004; Verma and Prasad, 1999):

$$G_{md} = (LWT_k)^{1/3}, \quad \phi = \frac{G_{md}}{L} \tag{4}$$

$$V = \frac{\pi}{6} G_{md}^{\ 3}, \qquad S = \pi G_{md}^{\ 2} \tag{5}$$

Other physical properties like 100-seed mass, true density, bulk density and porosity of SS were determined using the methods cited by other researchers (Altuntas et al., 2005; Mwithiga and Sifuna, 2006). All the physical properties of seeds were investigated at the moisture content of 3.5% (d.b.).

**Drying tests.** The drying tests were conducted for studying the thin-layer drying characteristics of sesame seeds (SS), under indoor drying with both natural and forced convection air. The drying experiments were performed during July and August 2005 in Pakdasht, Iran, with minimum and maximum air temperatures of around 32 and 36°C over a one day drying cycle with relatively low air humidity, which never exceed 40%.

In this study, SS of the average initial moisture content of around 50.8% (d.b.) were dried to the final moisture content of about 3.0-3.7% (d.b.). The wet samples of the seeds were dried under indoor drying with both natural convection (NC) and forced convection (FC) air. A schematic diagram of the experimental set-up for indoor drying of SS with forced convection air is shown in *Figure 2*. According to *Figure 2*, for drying SS under indoor drying with natural convection condition, the windows of the room were closed and the cooler systems was turned off. During the FC drying experiments, the mean values of temperature and the relative humidity of air ranged from 25 to 29°C and from 35 to 40%, respectively. Corresponding values for the NC drying experiments were within the range of 32 to 36°C and 30 to 35%, respectively.

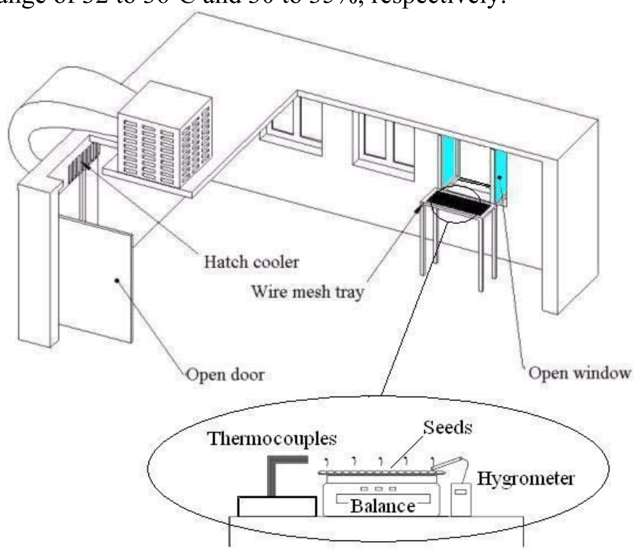


**Fig. 2 - Flow diagram of indoor natural drying of sesame seeds under forced convection air**

Wire mesh trays of 150 mm in diameter and 70 mm in depth were used, on which to place the seed samples. The trays were placed reasonably above a high steel frame, to ensure a reasonable level of air circulation under and around the SS. The air temperatures, relative humidity and air velocity just above the samples bed surface were measured during the experiments. The air velocity was measured by using a digital anemometer (TESTO, 405-VI, Taipei, Taiwan), being in the measurement range of 0–15 m/s. In all FC drying tests, the air velocity just above the samples bed was constant and was equal to 1.1 m/s. A thermo hygrometer (Extech 444731, Shenzhen, China) was used to measure air temperature and relative humidity.

For each drying test, a sample of 30 g of moist seeds was evenly spread on the wire mesh baskets as thin-layer with the thickness of approximately 0.4 cm. The moisture loss content of the samples was accomplished by periodical weight of the mass, using a digital balance, having an accuracy of 0.01 g. Seed samples were weighed at various time intervals, ranging from 5 min at the beginning of the drying to 80 min during the last stage of the process. The instantaneous moisture content (dry basis) of seeds was calculated. The drying process was continued until no further changes in their mass were observed. Each experiment was replicated three times and the average values were used for analysis.

**Mathematical Modelling.** For the both FC and NC drying methods, the curve fitting computations were done by using the Khazaei and Peleg models. The parameters of the mathematical models were estimated by using a nonlinear regression procedure performed using the SigmaPlot software (SigmaPlot 6.0 scientific graphing software from SPSS Inc., Chicago). The suitability of the models was evaluated and compared by using the coefficient of determination, $R^2$, and Root Mean Square Error, RMSE (Chegini et al., 2008; Sacilik et al., 2006). The higher values for $R^2$ and the lower value for RMSE the better is goodness of fit (Akpinar et al., 2006; Togrul, and Pehlivan, 2004).

**Neural networks model development.** Using the drying tests, 32 patterns were obtained, each with three components ($X_1$, $X_2$, $Y_1$), which were used for training and testing the neural networks. Two of the components were the input variables (drying method and drying time), whereas the last component was the output variable, representing the moisture content (*Figure 3*). The 32 patterns were randomly divided into 22 and 10 data sets for training and testing the neural networks, respectively.

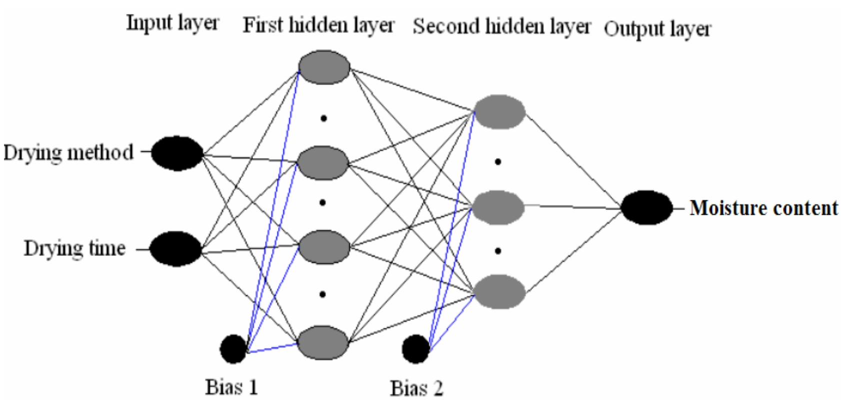


**Fig. 3 - ANN model used for sesame moisture ratio prediction**

A supervised artificial neural network (ANN) trained by back-propagation algorithms was developed to predict moisture content based on the two input variables. The back-propagation algorithm was implemented by using the ANN Toolbox of the MATLAB computer-aided design software (The MathWorks Inc., Natick, MA).

The neural networks with various structures were investigated, including 3- and 4-layer with different number of neurons in each hidden layer, different values of learning rate and momentum, and different transfer function (sigmoid, linear and hyperbolic tangent). The best ANN structure was selected on the basis of the lowest error on the training and verification of ANN. The best ANN model and optimum values of network parameters were obtained by trial and error. The performances of the various ANN configurations were compared using the coefficient of determination ($R^2$) and the root mean square error, RMSE, (Chegini et al., 2008; Khazaei et al., 2008). The final network was selected on the basis of the lowest error on test sets of data.

## RESULTS AND DISCUSSION

**Physical Properties.** The dimensional properties of sesame seeds (SS) were given in *Table 1*. The length of seeds ranged from 2.61 to 3.77 mm, width ranged from 1.40 to 2.05 mm and thickness ranged from 0.66 to 1.01 mm. The geometric mean diameter ranged from 1.42 to 1.91 mm while the sphericity of seeds ranged from 0.45 to 0.59. The relationships between length, width, thickness and geometric mean diameter were given by the following equation:

$$L = 1.788 \times W = 3.76 \times T_k = 1.886 \times G_{md} \quad (6)$$

The sesame seeds used in this study had a true density of 1230–1234 kg/$m^3$. The mean value of volume to surface area ratio (V/S) of a single seed was found to be 2.8x$10^{-4}$ m from Eqs. [5]. Based on the equivalent dimensions given in Table 1, the mean value of surface area per unit mass (specific surface area) of seeds was equal to 2.74 $mm^2$/mg. The physical properties of the sesame seeds used in this study are in general agreement with those reported by Tunde-Akintunde and Akintunde (2004).

**Table 1 - Some physical properties of sesame seeds**

| Parameter | Mean | Min | Max | SD |
|---|---|---|---|---|
| Length L , (mm) | 3.14 | 2.61 | 3.77 | 0.20 |
| Width W, (mm) | 1.76 | 1.4 | 2.05 | 0.11 |
| Thickness $T_k$, (mm) | 0.84 | 0.66 | 1.01 | 0.07 |
| Geometric mean diameter, (mm) | 1.67 | 1.42 | 1.91 | 0.09 |
| Sphericity, (%) | 0.53 | 0.45 | 0.59 | 0.02 |
| Mass of 100 seeds, (g) | 0.275 | 0.143 | 0.296 | 0.02 |
| Surface area, ($mm^2$) | 8.77 | 6.41 | 11.50 | 0.95 |
| Volume of a single seed, ($mm^3$) | 2.47 | 1.54 | 3.69 | 0.39 |
| Volume per unit surface area, ($mm^3/mm^2$) | 0.28 | 0.24 | 0.32 | 0.01 |
| Bulk density, (kg/$m^3$) | 577 | 575 | 579 | 1.30 |
| True density, (kg/$m^3$) | 1231 | 1230 | 1234 | 2.40 |
| Porosity, (%) | 53.1 | 53.0 | 53.2 | 0.01 |

**Drying characteristics.** The drying curves for thin layer drying of sesame seeds under indoor drying with both natural convection (NC) and forced convection (FC) conditions are shown in *Figure 4*. The SS of average initial moisture content of around 50.8% (d.b.) were dried at the final moisture content of about 3.0-3.7% (d.b.), until no further changes in their mass were observed. It is evident from the curves that the moisture content decreases continuously with the drying time. It can be seen that the drying curve consists in an initial fast reduction in moisture (first phase), followed by a constant drying rate period (relaxation phase).

During the FC experiments, the time to reach the final moisture content of 3.0% was found to be 400 min. The same moisture content of sesame seeds was found to achieve its equilibrium moisture content (3.7%) after 900 min, when seeds were dried by using the NC method. Thus, the FC drying times were around 55% shorter than the NC air-drying times.

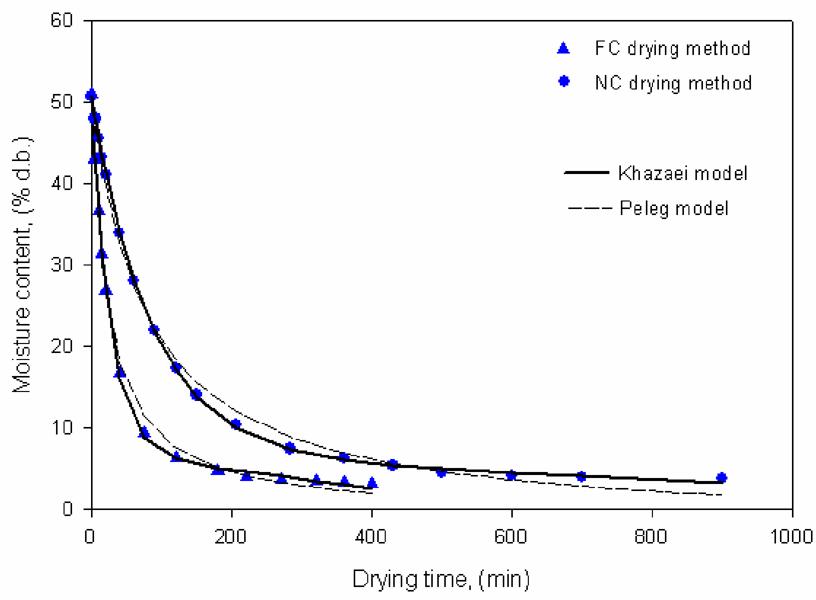


**Fig. 4 - Comparison of the thin layer drying characteristics of sesame seeds in drying by FC and NC methods**

Data on moisture content versus drying time were fitted into the Peleg's and Khazaei models for both NC and FC drying methods. *Table 2* presents the results of non-linear regression analysis of fitting the two models to the experimental data and the comparison criteria used to evaluate goodness of fit namely, $R^2$ and RMSE. Both Peleg's and Khazaei models have provided an excellent fit to the experimental data with a value for $R^2$ greater than 0.996, indicating a good fit. However, the values for RMSE obtained from the Khazaei model were significantly less, as compared to those obtained from the Peleg model. Figure 4 suggests the experimental moisture contents fitted with the Peleg's and Khazaei models for both NC and FC drying conditions. It is clear that there was a good conformity between experimental and predicted moisture content data, by using the Khazaei model.

**Table 2 - Parameter estimation and curve fitting criteria for the Peleg's and the newly developed model for thin layer natural drying of SS**

| Model | Drying method | Parameters | | | | $R^2$ | RMSE |
|---|---|---|---|---|---|---|---|
| | | $M_o$ (% d.b) | $M_{rel}$ (% d.b) | $T_{rel}$ (min) | $K_{rel}$ (% d.b $min^{-1}$) | | |
| Khazaei | FC | 50.8 | 43.861 | 26.18 | 0.0113 | 0.9993 | 0.379 |
| | NC | 50.8 | 43.799 | 84.746 | 0.0041 | 0.9996 | 0.297 |
| Peleg | | $K_1$, (min $\%^{-1}$db) | | $K_2$, ($\%^{-1}$d.b) | | | |
| | FC | 0.445 | | 0.0193 | | 0.996 | 1.02 |
| | NC | 1.444 | | 0.0188 | | 0.996 | 1.08 |

The moisture content evolution in time is the first indication of how and to what extent the drying process is going on. It is used as an element of comparison. The drying rate, *dM/dt*, as a function of time or moisture content, is also an important parameter. The changes in the drying rates of sesame seeds versus moisture content are shown in *Figure 5*. It is apparent that the drying rate decreases continuously with improving the drying time. The results were generally in agreement with some literature studies on drying various food products (*Doymaz, 2006; Kashaninejad et al., 2007; Lahsasni et al., 2004; Togrul and Pehlivan, 2004*). In *Figure 5*, data on the drying rate, at the very beginning times of drying (i.e., at t =0 min) were obtained from the first derivative of the Peleg's equation (*Eq. [2]*) as following (*Turhan et al., 2002*):

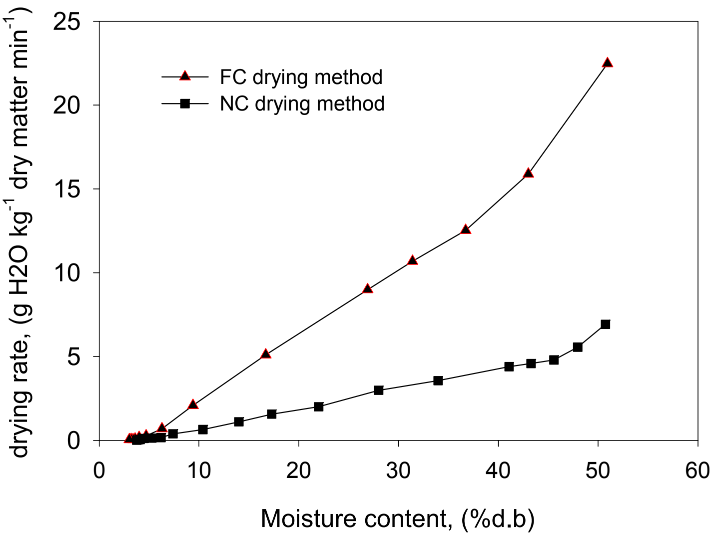


**Fig. 5 - Variation of the drying rate of the sesame seeds versus moisture content**

$$(\frac{dM}{dt})_{t=0} = -\frac{1}{K_1} \quad (7)$$

The Peleg drying rate constant $K_1$ is a constant related to mass transfer rate, e.g., the lower the $K_1$, the higher the initial drying rate. The SS dried by using FC and NC methods exhibited statistically significant differences in $K_1$ (Table 2). The drying rate of SS dried by FC and NC methods at the very beginning times of drying were equal to 22.47 and 6.9 (g H2O/kg dry matter $min^{-1}$), respectively. According to Eq. [8], the mean drying rates of SS dried by the FC and NC methods were equal to 1.2 and 0.5 (g H2O/kg dry matter $min^{-1}$), respectively.

$$\text{Mean drying rate} = \frac{M_e - M_o}{\text{Total drying time}} \quad (8)$$

As indicated in *Figure 5*, there is no constant drying rate period in the drying of SS and the two drying operations are seen to occur in the falling rate period. During the falling rate period, the drying rate decreases continuously with decreasing moisture content and increasing drying time. These results are in agreement with the observations of earlier researchers of other seeds and grains (Doymaz, 2006). According to Figure 5, the free water dries during a first short period and subsequently, the intermolecular water dries during longer periods. At the beginning of drying, free water was available and the rate of drying was controlled by free water on the surface or outer layers of seeds. The drying rate then decreased lower than the first stage of the drying period. At this stage, water was no longer free; water in seeds was held by molecular adsorption and capillary condensation. It can, therefore, be considered a diffusion-controlled process, in which the rate of moisture removal is limited by diffusion of moisture from inside to the surface of the product. Previous studies have also showed that drying biological material is a diffusion-controlled process and may be represented by the Fick's law.

As expected, the rate of drying sesame seeds under the FC drying method was much higher than that at the NC method (*Figure 5*). It is evident that the influence of drying conditions on the drying rate is markedly higher when moisture is higher (*Figure 5*). At the moisture content of less than 7% (d.b), there is no difference in the drying rates between the two drying methods, indicating the significance of internal resistance to mass transfer at the low water content in the material.

**Calculation of effective diffusivity of sesame seeds.** The Fick's second law of diffusion (*Eq. [1]*) was used to calculate the effective water diffusivity of SS, under FC and NC drying conditions. Other researchers have also reported similar methods for determining the diffusion coefficient of white rice and wheat kernels (Kang and Delwiche, 2000; Steffe, 1980). For long drying periods, the Fick's second law equation (*Eq. [1]*) can be further simplified to only the first term of the series and the moisture ratio *Mr* was reduced to $M_t/M_o$, because $M_e$

was relatively small compared to $M_t$ and $M_o$ (Doymaz, 2006). Then, *Eq. [1]* can be written in logarithmic form of (Kang and Delwiche, 2000; Steffe, 1980):

$$\ln\frac{M_t}{M_o} = \ln\frac{6}{\pi^2} - (\frac{\pi^2 D_{ef}\, t}{R_e^2}) \qquad (9)$$

The diffusion coefficient can be calculated from the slope of the left-hand side of *Eq. [9]* versus time (*Fig. 6*). It is expected that a plot of *ln(Mr)* versus drying time gives a straight line with a slope of (Kashaninejad et al., 2007):

$$\text{Slope} = -\frac{\pi^2 D_{ef}}{R_e^2} \qquad (10)$$

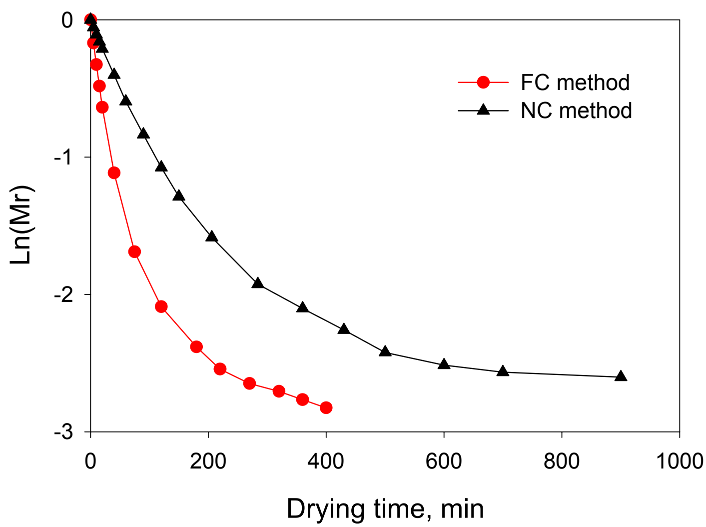


**Fig. 6 - Comparison of Ln(Mr) versus drying time for sesame seeds**

It is evident from *Fig. 6* that *Eq. [9]* is valid for ln(Mr) < -1.3 (Mr<0.3) and not in the practical range of drying high moisture seeds. Then, the complete series of the Fick's second law equation (*Eq. [1]*) would be required for this work, but this includes numerous shortcomings previously listed by Giner and Mascheroni (2001). Marquez et al. (2006) have also reported similar limitations of *Eq. [9]* for drying rose hip fruits. In spite of this limitation, the diffusion coefficient of many grains and fruits, such as amaranth, wheat, chestnuts, hull-less seed pumpkin, pistachio nuts, and black grapes have been successfully predicted by using this simplified form of the Fick's second law, *Eq. [9]*, (Doymaz, 2006; Gaston et al., 2004; Kashaninejad et al., 2007).

The calculated values of the effective diffusion coefficient, $D_{ef}$, of sesame seeds for the FC and NC drying conditions were $3.1\times10^{-11}$ and $1.1\times10^{-11}$ $m^2/s$, respectively. The value of $D_{ef}$ for the FC drying method was 2.8 times higher than that for the NC method. The values of $D_{ef}$ lay within the range of $10^{-11}$ to $10^{-9}$ $m^2$/s for food materials dried by using the conventional and solar drying methods (Doymaz, 2006).

During the falling rate period and with continuous decrease of the drying rate, there also appears a resistance to water vapour diffusion (Khazaei et al., 2008; Toure and Nkembo, 2004). The overall resistance to diffusion, $R_{ds}$, is characterized by the following equation (Khazaei et al., 2008; Toure and Nkembo, 2004):

$$Ln(M_R) = -\frac{S}{mR_{ds}}.t \qquad (11)$$

where $R_{ds}$ is the overall resistance to diffusion ($m^2$ s/kg). From *Eq. [11]*, the resistance to diffusion can be determined by the slope of the straight line obtained by plotting the experimental data from *Ln(Mr)* as a function of drying time (*Fig. 6*). The overall resistance to diffusion of sesame seeds, dried by the FC and NC drying methods, were calculated equal to $70.8\times10^5$ and $19.6\times10^6$ $m^2$ s/kg, respectively. As expected, the drying method had a significant effect on the resistance to diffusion.

**Neural networks modelling.** In this study, an ANN model was developed to predict the moisture content of sesame seeds based on the drying time and drying method. The training error associated with different one- and two-hidden layer ANN configurations are presented in *Figure 7*. It is evident that the learning ability of the two hidden layers networks was significantly higher than that for one-hidden layer. This indicates that increasing the number of hidden layers has increased the learning capability of the networks. In addition, the number of neurons in each hidden layer had a significant effect on learning performances of the ANN models. The number of neurons within each hidden layer can be varied based on the complexity of the problem and data set. However, a well-trained ANN model is the key to build an ANN model to be able to predict precisely outputs.

Among the various structures, models of good training performance were produced by the 2-13-9-1 (RMSE of 0.0097), 2-15-5-1 (RMSE of 0.0101), 2-6-3-1 (RMSE of 0.0101), and 2-12-3-1 (RMSE of 0.0179) structures with hyperbolic tangent transfer function in the hidden and output layers. Indeed, a well-trained ANN model is the key to design and analyse the input and output relations.

In order to avoid possible overtraining, the aim is to obtain an ANN model with a minimal dimension and minimum errors in training and testing. In this study, the most suitable ANN for correlating the moisture content with drying time and drying method was selected as 2-6-3-1. For this structure, the best combinations of the ANN parameters that were used for predicting the moisture ratio are shown in *Table 3*. These results confirm that given sufficient hidden units, multi-layer feed-forward network architectures can approximate virtually any function of interest to any desired degree of accuracy.

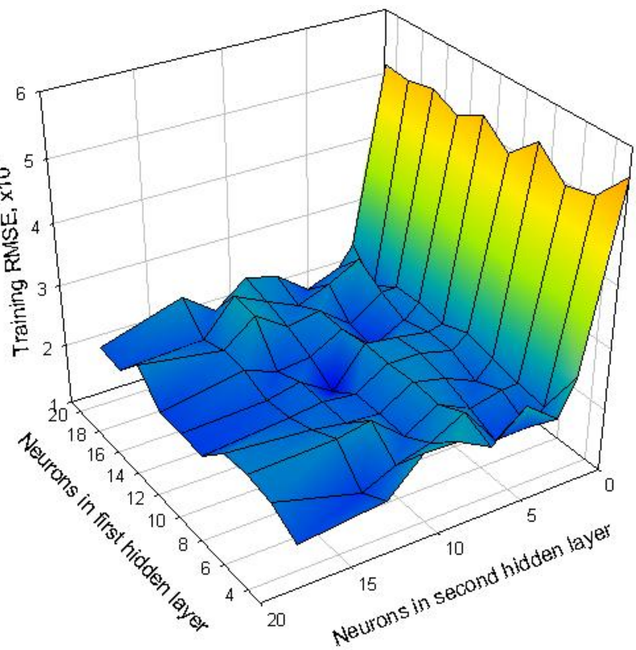


**Fig. 7 - Learning ability of ANN as a function of number of hidden layers and number of neurons within each hidden layer (with hyperbolic tangent transfer function)**

**Table 3 - The optimum values of the ANN parameters used to predict the moisture content of sesame seeds**

| Optimum | | | Transfer function | Mean value | | | | Number of epochs |
|---|---|---|---|---|---|---|---|---|
| MLP structure | Learning rate | Momentum | | Training RMSE | Testing RMSE | Testing mean relative error | $R^2$ | |
| 2-6-3-1 | 0.5 | 0.7 | Tanh | 0.0165 | 0.0192 | 2.63% | 0.998 | 24000 |

*Figure 8* shows that the RMS error is represented as a function of the number of epochs for the final structure, 2-6-3-1. As it can be seen, the training of the model was successfully accomplished. The error on training data generally decreases with increasing the number of epochs, with an initial large drop in error, which slows down as the network begins to learn the patterns representing the data set (Figure 8). However, if training is allowed to continue beyond the point at which the error reaches the global minima, over-fitting (or overtraining) may arise, where memorization of the training data occurs. Because of this over-fitting, if a network performance is monitored by training data alone, the network will

perform with little error on the training data but will not be able to generalize well for the testing data. In several neural network applications, this has been handled by monitoring test set performance during training and picking the network where performance on the test set was optimal *(Chegini et al., 2008; Khazaei et al., 2008; Uno et al., 2005*). In this study, the optimal network prediction was found at epochs near to $24 \times 10^3$. This result implies that the designed ANN was able to properly learn the relationship between the input and output parameters.

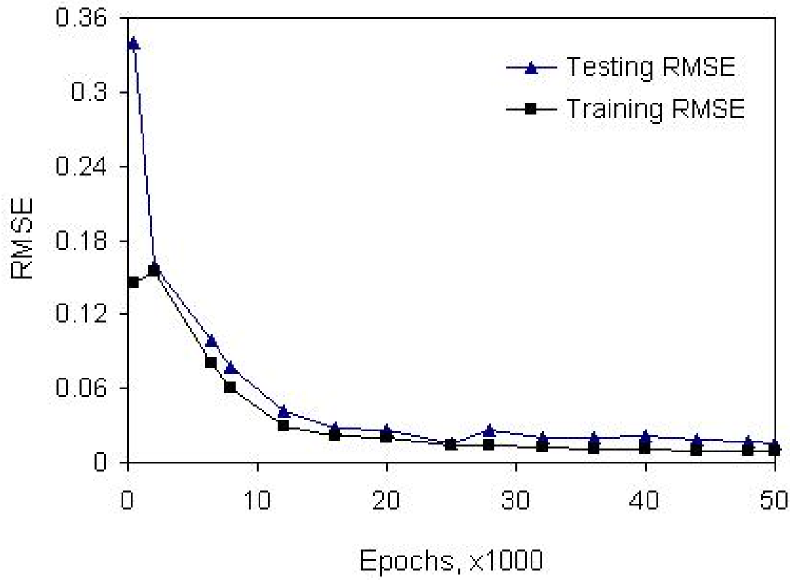


**Fig. 8 - Convergence of the Mean Root Square Errors during training of the final selected ANN**

To reveal the credibility of prediction from the optimal ANN model presented in *Table 3*, predicted versus the actual values of moisture content were plotted in *Figure 9*. The results demonstrated a very good agreement between the predicted and the desired values of moisture content, $R^2$=0.999. For the final network, the RMSE and MRE between predicted and measured data were lower than 0.0116 and 1.73%, respectively. Ideally, the RMSE and MRE values should be close to zero, indicating that, on average, there is no difference between predicted and measured values. These results demonstrate that the ANN model used in this study can potentially be used to estimate the drying kinetics of sesame seeds.

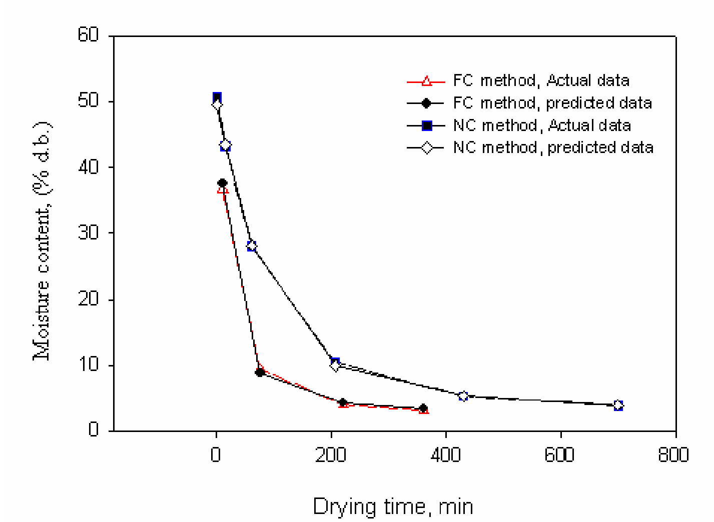


**Fig. 9 - Ten samples of data on moisture content, predicted by using the ANN model versus actual data**

The results obtained from this study also showed that the learning rate and momentum values have significantly affected the ANN performance. As it is clear from *Table 3*, a small learning rate and a large momentum were desirable, so that the achieved results be as precise as possible. A problem during the training of ANN is the choice of a suitable learning rate and momentum (Chegini et al., 2008; Khazaei et al., 2008). At learning an ANN, the proper selection of learning rate and momentum are very important to obtain a satisfactory ANN training (Anderson, 1995). An improper selection will result in more time for the training process, a poor ANN performance and sometimes, an unsatisfactory performance. The values of 0.5 for the learning rate and 0.7 for momentum were desirable so that the achieved training results were as precise as possible.

Here it is possible to compare the prediction ability of the ANN models, developed in this study, with that for the mathematical drying models reported in Table 2. The results indicated that the use of the ANN model resulted in higher $R^2$ and lower RMSE and MRE values in predicting the moisture content of SS. A simple ANN model instead of two new developed models / or Logarithmic model (two models for FC and NC drying methods) is more powerful for accurate prediction of drying kinetics of sesame seeds. This provides the gradual possibility of establishment of a unique powerful model, which can be of paramount importance in the automatic control system. Further, the prediction by a well-trained ANN is normally faster than by the mathematical models.

## CONCLUSIONS

The time needed to dry sesame seeds, with the initial moisture content of 50.8% d.b, in drying by the NC and FC methods, was of 400 and 900 min, respectively. The drying rates of sesame seeds at the very beginning times of drying were equal to 22.47 and 6.9 (g H2O $kg^{-1}$ dry matter $min^{-1}$) for the FC and NC drying methods, respectively.

The calculated values of the effective diffusion coefficient, $D_e$, of sesame seeds for the FC and NC drying methods were $3.1\times10^{-11}$ and $1.1\times10^{-11}$ $m^2/s$, respectively.

Both the Khazaei and Peleg's models were suitable for predicting the moisture content of sesame seeds. However, the Khazaei model gave better fit to the drying data.

The ANN model was capable of predicting the moisture content with an $R^2$ of 0.999, RMSE of less than 0.0116 and MRE about 1.73%. Therefore, the ANN represented the drying characteristics better than the mathematical models.

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