Acta Sci. Pol., Technol. Aliment. 11(2) 2012, 137-149
pISSN 1644-0730 eISSN 1889-9594 www.food.actapol.net/

MODELLING MOISTURE DIFFUSIVITY OF POMEGRANATE SEED CULTIVARS UNDER FIXED, SEMI FLUIDIZED AND FLUIDIZED BED USING MATHEMATICAL AND NEURAL NETWORK METHODS

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ABSTRACT

Background. Modelling moisture diffusivity of pomegranate cultivars is considered to be a major aspect of the drying process optimization. Its goal is mainly to apply the optimum drying method and conditions in which the final product meets the required standards. Temperature is the major parameter which affects the moisture diffusivity. This parameter is not equal for different cultivars of pomegranate. So modelling of moisture diffusivity is important in designing, optimizing and adjusting the dryer system.
Material and methods. This research studied thin layer drying of three cultivars of pomegranate seeds (Alak, Siah and Malas) under fixed, semi fluidized and fluidized bed conditions. Drying process of samples was implemented at 50, 60, 70 and 80°C air temperature levels. Second law of Fick in diffusion was utilized to compute the effective moisture diffusivity (D_{eff}) of the seeds. Linear and artificial neural networks (ANNs) also were used to model D_{eff} of seeds.
Results. Maximum and minimum values of the D_{eff} were related to malas and alak cultivars, respectively. Three linear models were found to fit the experimental data with average R^2 = 0.9350, 0.9320 and 0.9400 for Alak, Siah and Malas cultivars, respectively. The best results for neural network were related to feed forward neural network with training algorithm of Levenberg-Marquardt was appertained to the topology of 3-4-3-1 and threshold function of LOGSIG. By the use of this structure, R^2 = 0.9972 was determined.
Conclusion. A direct relationship was found between D_{eff} and thickness of fleshy section of the seeds. The Siah cultivar has the highest value of D_{eff}. This is due to higher volume of fleshy section of the siah cultivar. Cultivar type and air velocity have the highest and the least effect on D_{eff}, respectively.

Key words: fluidized bed drying, moisture diffusivity, pomegranate, artificial neural network

INTRODUCTION

Pomegranate (*Punica granatum* L.) is one of the most important fruits of subtropical regions of Iran. Nutritional and therapeutic values, versatile adaptability and better keeping quality are the reasons for its cultivation in the country [Khoshnam et al. 2007]. Pomegranate seeds (arils) are the only edible portion of the fruit. Pomegranate seeds are consumed as fresh or dried form. Many domestic and wild cultivars of pomegranate have been found in Iran. Some of the best pomegranate cultivars which are cultivated in Iran are Alak, Siah and Malas. Alak cultivar is used as fresh fruit. Siah cultivar is used in pharmaceutical industries and jounce of malas cultivar is consumed as a delicious beverage [Mansouri et al. 2010].

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Pomegranate seeds due to high moisture content are very sensitive to microbial spoilage. Therefore drying the seeds is necessary in order to obtain safe storage [Doymaz 2007]. The main purpose production of dried pomegranate seeds is utilization of salted seeds as a nibbling snack [Kingsly 2006]. Dried pomegranate seeds are also a good source of minerals and vitamins. The most important process of pomegranate seeds is drying, because the quality of dried seeds depends on this process [Bialonska 2009]. Sun drying is a common method to remove the moisture of pomegranate seeds. By the use of this method, moisture transfer rate from product is very low; therefore sun drying is time consuming [Kingsly 2007]. Applying of sun drying causes contamination of product with insects and dust, also the drying process strongly depends on weather condition [Doymaz and Pala 2002].

Fluidized bed drying is one of the best methods in dehydration of high moisture products. This method can improve the quality of final product, such as: colour, taste, and nutritional content [Alibas 2007]. Moreover, this method can increase the moisture removal rate [Sacilik 2007].

Fluidization includes minimum fluidized bed (semi fluidized bed) and bubbling fluidized bed. Fixed bed is before minimum fluidized bed and transportation phenomenon occurs after bubbling fluidized bed [Amiri Chayjan et al. 2009 a, Kunii and Levenspiel 1991]. Fluidization state increases heat and mass transfer between wet material and drying air [Arumuganathan et al. 2009, Gazor and Mohsenimanesh 2010].

Effective moisture diffusivity (D_{eff}) is an important index in modelling, designing and optimizing of a drying process. Effective moisture diffusivity value determines the mass transfer rate from product in drying process [Hashemi et al. 2009].

Numerous mathematical models have been developed for predicting of D_{eff} values by many researchers [Aghbashlo et al. 2011, Amiri Chayjan et al. 2011]. This estimation method reduces the accuracy of the D_{eff} as well as the reliability of the predictions over the whole range of input parameters. Therefore, finding an alternative computational method to establish a new relationship between D_{eff} and input parameters in order to increase the accuracy and reliability of predictions is necessary. Artificial neural networks (ANNs) can be a suitable method for this purpose.

ANNs is one of the soft computing approaches. It is constructed from simple processing units named neurons. ANNs discovers the relationships between input and output parameters through learning process. By use of this method a mapping is created between input and output variables. Input data processing is carried out in hidden and output layers. Training process of network, finally terminates to learning [Chayjan and Esna-Ashari]. Many experimental patterns can be used to train the network. During training process, the network weights between layers are improved until the error between predicted and experimental values is reduced to a defined number. With the aforesaid conditions, learning process occurs. Trained ANN can be utilized for output prediction of a new unknown pattern [Zhang et al. 2002].

Although many studies have been accomplished about modelling effective moisture diffusivity for different food and agricultural products, nevertheless no study has been conducted about mathematical and artificial neural network modelling of pomegranate seed cultivars drying in semi fluidized and fluidized bed conditions. Additionally, effective moisture diffusivity of pomegranate seed cultivars under these conditions is not available.

The main goals of this study were: 1) mathematical modelling of effective moisture diffusivity of pomegranate seed cultivars under fixed, semi fluidized and fluidized bed drying, 2) artificial neural network modelling of effective moisture diffusivity of pomegranate seed cultivars, 3) evaluating the relationship between effective moisture diffusivity and input parameters such as bed condition, air temperature and some physical properties of the seeds and 4) study on the importance degree of the input parameters on effective moisture diffusivity using artificial neural network.

MATERIAL AND METHODS

Drying apparatus. Drying experiments were performed using a laboratory fluidized bed dryer (Fig. 1). A centrifugal fan with an electrical motor (0.375 kW) supplied the required air flow. A heat supply unit with six electrical heating elements (2 kW) was designed to heat the input air to an adjusted temperature level. Drum type drying chamber has the diameter and

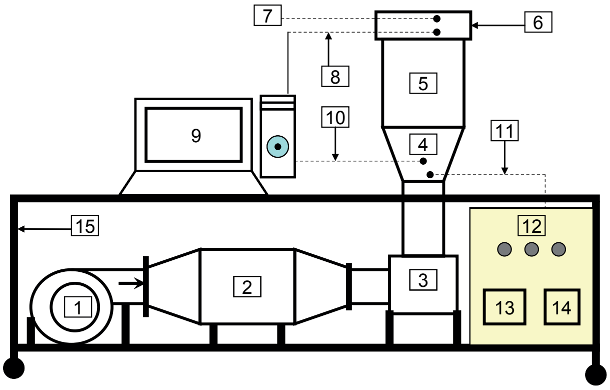

Fig. 1. Experimental fluidized bed dryer: 1 – fan and electrical motor inverter, 2 – electrical heater, 3 – mixing chamber, 4 – diffuser, 5 – drying chamber, 6 – chamber cap, 7 – air velocity sensor, 8 – outlet air temperature recorder, 9 – computer, 10 – input air temperature recorder, 11 – thermocouple, 12 – electrical panel, 13 – thermostat, 14 – inverter, 15 – chassis

height of 150 mm and 320 mm, respectively. Temperature control of input air was conducted by a thermostat with ±0.1°C accuracy (Atbin mega, made in Iran). Input air flow control was carried out by an inverter with ±0.1 Hz accuracy (Vincker VSD2, made in Taiwan). Air temperature was recorded using a thermometer with type k sensor and accuracy of ±0.1°C (Lutron TM-903, made in Taiwan). Air relative humidity was measure by a hygrometer with accuracy of ±3% RH (Lutron TM-903, made in Taiwan), respectively. Measuring and recording of fluidization curve components (air velocity against pressure drop) was performed using Standard ST-8897 (made in China). Accuracy of this device in measuring differential pressure and air velocity was ±0.1 Pa and ±0.1 m/s, respectively.

Drying experiments. With regard to thin layer drying condition and the dryer chamber area, about 40 g pomegranate seed was used in drying tests. Some physical property values of the pomegranate seed samples are shown in Table 1. Each fluidization curve has a minimum fluidized bed which its pressure drop against air velocity is maximum value. Therefore this point, as well two others (before and after it) were selected as drying points. To attain these experimental points, an inverter was used to gradually increase the fan speed.

Fresh pomegranate seeds were collected after cutting the pomegranate fruits. The seed samples were stored in a refrigerator at 3 ±1°C. Air relative humidity and ambient air temperature during drying changed from 20 to 35% and 25 to 29°C, respectively. Inlet air temperature to the drying chamber was recorded during the experiments using a thermometer with accuracy of ±0.1°C (Lutron TM-903, made in Taiwan). Four air temperature levels of 50, 60, 70, and 80°C were selected to apply in the experiments. Moreover, with respect to three air velocities, 12 experiments were totally performed for each cultivar. The sample weight during the experiments was recorded using a digital balance (AND GF-6000, made in Japan) with ±0.01 g accuracy. Initial moisture content of pomegranate seeds was determined using gravimetric method at 70°C for 24 h [AOAC 2002]. Initial moisture content of three pomegranate cultivars of Alak, Siah and Malas was 2.74, 2.80 and 3.09 (d.b.), respectively. Final moisture content of all cultivars after drying process was about 0.09 (d.b.).

Table 1. The measured physical properties of the pomegranate seed cultivars

Properties	Alak		Siah		Malas	
	seed	kernel	seed	kernel	seed	kernel
Geometrical mean diameter, m	0.0043	0.0039	0.0082	0.0041	0.0076	0.0040
Sphericity, %	59	52	77	58	73	55
Particle density, kg/m^3	1 228	1 188	1 186	1 212	1 127	973
Bulk density, kg/m^3	523	502	555	541	605	492
Porosity, %	57.4	57.7	53.2	55.4	46.3	49.4

Effective moisture diffusivity. Second low of Fick in diffusion with sphere geometry is used for computing of effective moisture diffusivity. It was assumed the seed shrinkage after drying process is negligible and distribution of initial moisture is uniform. Fick's equation for computing effective moisture diffusivity of pomegranate seeds is as follows:

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

where:

MR – moisture ratio,
M – moisture content at any time, d.b.,
M_e – equilibrium moisture content, d.b.,
M_0 – initial moisture content, d.b.,
n – number of terms taken into consideration,
t – drying time, s,
D_{eff} – effective moisture diffusivity, m^2/s,
r – radius of kernel, m.

Drying of pomegranate seeds was performed in a long drying period. Therefore according to Kingsly and Singh [2007] the first term of Eq. (1) was considered in calculations. The relationship was simplified as follow:

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

After linearization of Eq. (2):

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \left(\frac{6}{\pi^2}\right) - \left(\frac{-D_{eff} \pi^2 t}{r^2}\right) \quad (3)$$

Artificial neural networks modelling. Feed and cascade forward neural networks were utilized in this study. There are two types of multi layer perceptron (MLP) neural network. Two learning algorithms of Bayesian regulation (BR) and Levenberg-Marquardt (LM) were also used. Feed forward neural network (FFNN) comprises one input layer, one or two hidden layers and one output layer [Demuth et al. 2007]. For training this structure, back propagation (BP) algorithm was implemented. In the updating process, the weight coefficients were updated using learning rules. During network training, computations were conducted from input toward output layers of the network and error values were propagated to previous layers. Cascade forward neural network (CFNN) is similar to FFNN in weights updating, but the main difference between these networks is in the relationship between neurons.

Network topologies with three neurons in input layer (input air temperature, air velocity and cultivar) and one neuron in output layer (D_{eff}) were considered. Neural network topology and connection weights between input and output parameters are indicated in Figure 2. Input variable levels and boundaries are presented in Table 2. Data analysis was accomplished using neural network toolbox (ver. 5) of Matlab software. Three transfer functions were employed to achieve the optimized network structure [Demuth et al. 2007]:

$$Y_j = X_j \quad \text{(PURELIN)} \quad (4)$$

$$Y_j = \frac{2}{(1 + \exp(-2X_j)) - 1} \quad \text{(TANSIG)} \quad (5)$$

$$Y_j = \frac{1}{1 + \exp(-X_j)} \quad \text{(LOGSIG)} \quad (6)$$

where X_j is calculated as follow:

$$X_j = \sum_{i=1}^{m} W_{ij} \times Y_i + b_j \quad (7)$$

where:

m – number of output layer neurons,
W_{ij} – weight of between i-th and j-th layers,
Y_i – j-th output neuron,
X_i – j-th input neuron,
b_j – bias of j-th neuron for FFNN and CFNN networks.

About 75% of the experimental data were separated for network training to find suitable structure. Mean square error (MSE) should be minimized in the learning process. MSE is defined as follow [Demuth et al. 2007]:

$$MSE = \frac{1}{mq} \sum_{p=1}^{m} \sum_{i=1}^{q} (S_{ip} - T_{ip})^2 \quad (8)$$

where:

S_{ip} – network output in i-th neuron and p-th pattern,
T_{ip} – target output at i-th neuron and p-th pattern,
q – number of output neurons,
m – number of training patterns.

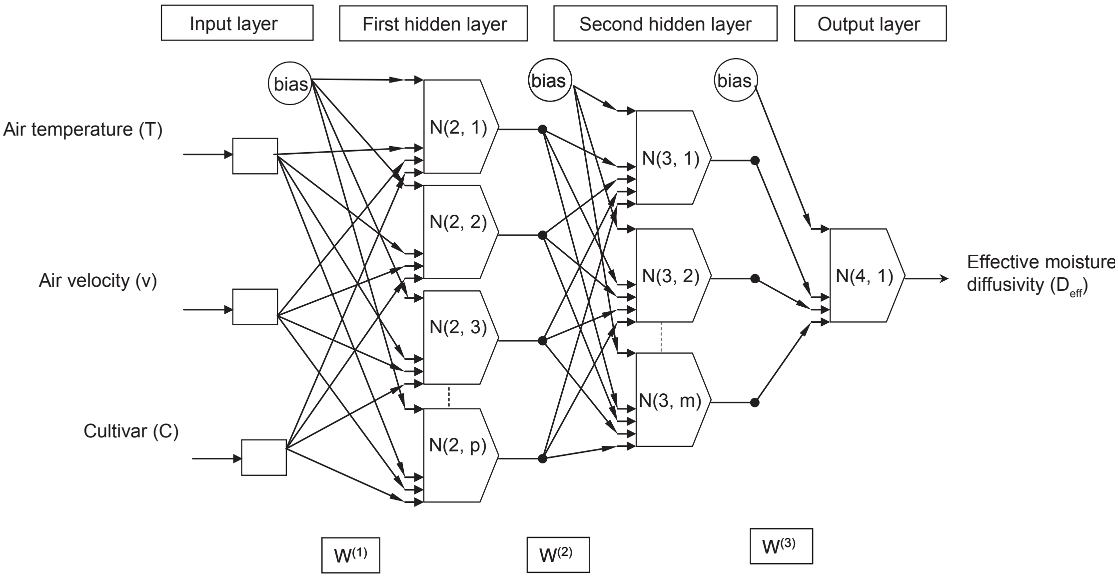

Fig. 2. Artificial neural network topology for modelling effective moisture diffusivity of pomegranate seed cultivars

Table 2. Input parameters for artificial neural networks and their boundaries for the prediction of effective moisture diffusivity of pomegranate seed cultivars

Input variables	Lower limit	Upper limit	Number of levels
Input air temperature, °C	50	80	4
Air velocity m/s	1.34	4.42	3
Cultivar	–	–	3

Many other indices were used to optimize the applied network. These indices are as follows:

$$R^2 = 1 - \frac{\sum_{k=1}^{m}[S_k - T_k]}{\sum_{k=1}^{m}[S_k - \frac{\sum_{k=1}^{n} S_k}{n}]} \tag{9}$$

$$E_{mr} = \frac{100}{n}\sum_{k=1}^{m}\left|\frac{S_k - T_k}{T_k}\right| \tag{10}$$

$$SD_{mr} = \sqrt{\frac{\sum_{k=1}^{n}\left(\left|\frac{S_k - T_k}{T_k}\right| - \overline{\left|\frac{S_k - T_k}{T_k}\right|}\right)}{n-1}} \tag{11}$$

where:
R^2 – determination coefficient,
E_{mr} – mean relative error,
SD_{mr} – standard deviation of mean absolute error,
S_k – network output for k-th pattern,
T_k – target output for k-th pattern,
n – number of training patterns.

To increase processing velocity and accuracy of network, input and output data were normalized at domain of [0, 1].

RESULTS AND DISCUSSION

Fluidization curves. Minimum fluidized bed of three pomegranate cultivars was determined by plotting the fluidization curve (Fig. 3). Minimum air velocity of Alak, Siah and Malas cultivars at this point was 2.67, 2.79 and 2.49 m/s, respectively. The pressure drop of these cultivars in minimum fluidized bed condition (point B) was 0.064, 0.060 and 0.056 kPa, respectively. Also two other points for all cultivars were selected in fixed and fluidized bed boundaries

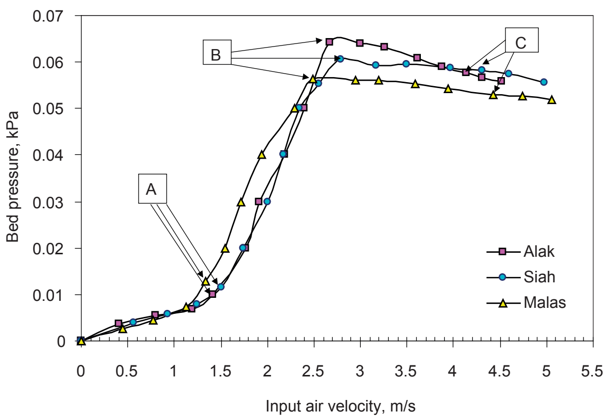

Fig. 3. Fluidization curve of pomegranate seed cultivars and selected points for modelling: A – fixed bed, B – semi fluidized bed, C – fluidized bed

(points A and C in Figure 3). Bed pressure of all pomegranate seed cultivars in minimum fluidized bed condition (point A in Figure 3) was maximum value. A good form of fluidization in terms of perfect golf stream in the seed bed was clearly observed. Accordingly a smooth fluidization with a low fluctuation and without slug formation was attained. As can be seen in Figure 3, an increasing mode for all cultivars is achieved between input air velocity and bed pressure until minimum fluidized bed point. After reaching this point, generally the pressure drop was decreased. This range was considered as fluidized bed. These results are similar to the other products such as canola [Gazor and Mohsenimanesh 2010], millet, barley, paddy and soya bean [Khoshtaghaza and Chayjan 2007] and potato slices [Chayjan et al. 2012].

Mathematical modelling of D_{eff}. Values of ln(MR) against drying time (hour) were plotted for all the cultivars and drying conditions. These curves for Alak cultivar have been presented in Figure 4. Similar trend was observed for the other cultivars. With regard to fit the linear models to these data, drying process of pomegranate seeds was conducted as liquid diffusion. With respect to the equivalent diameter of pomegranate seeds was small (4.34, 7.59 and 8.18 mm for Alak, Siah and Malas cultivars, respectively), one falling period observed in drying of pomegranate seeds. These curve slopes were proportionally increased with increase in temperature level. The effect of air velocity

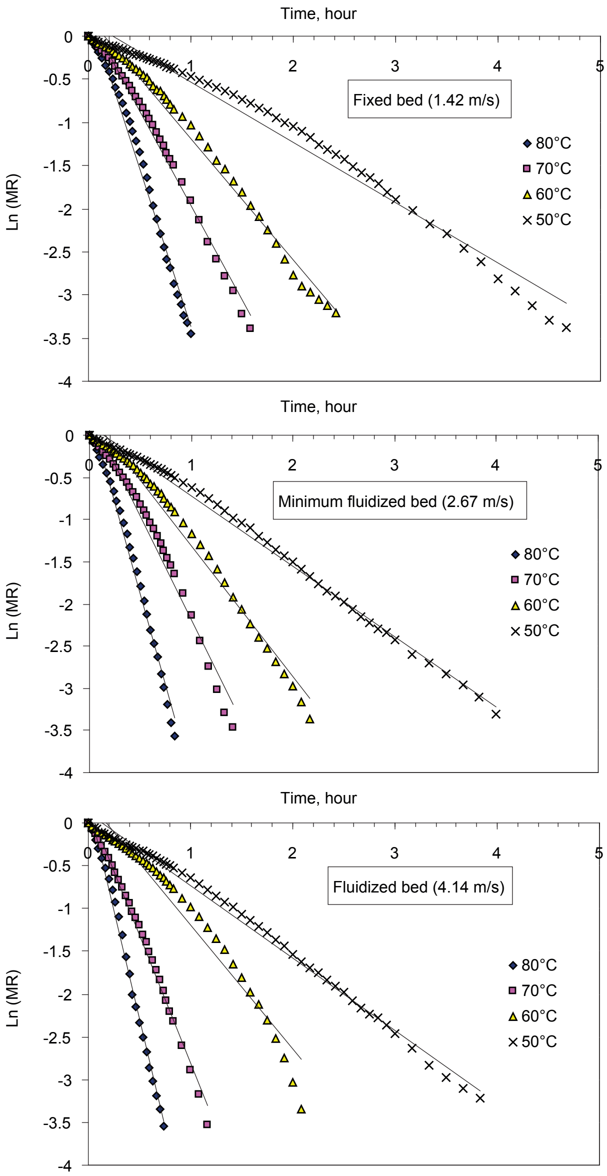

Fig. 4. Ln (MR) against drying time (hour) for thin-layer drying of pomegranate seeds (alak cultivar) in fixed, semi fluidized and fluidized bed conditions

(bed condition) on D_{eff} value is less than air temperature (Fig. 5). Change in bed condition at low air temperatures has not got significant effect on D_{eff} value.

Maximum and minimum values of D_{eff} for three pomegranate cultivars are given in Table 3. Maximum values of D_{eff} for all cultivars were calculated in fluidized bed condition and 80°C. Minimum values of D_{eff}

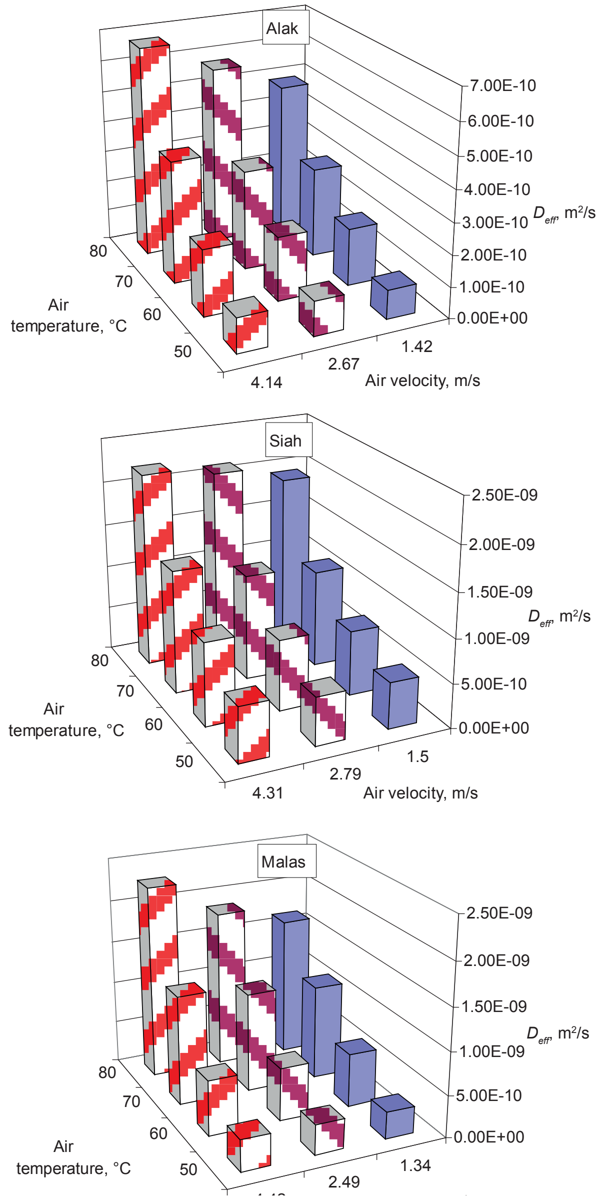

Fig. 5. Effective moisture diffusivity of pomegranate seed cultivars

for all cultivars were computed in fixed bed condition and 50°C. These results proved that the fluidized bed condition can be more effective in high temperature convective drying. But at low temperature levels, no significant difference was observed among three bed conditions. This result can cause lower energy utilization by heater and electrical motor and less drying

Table 3. Maximum and minimum values of effective moisture diffusivity of pomegranate seed cultivars and their related input temperatures and air velocities

Cultivar	D_{eff} m²/s		Air velocity m/s		Air temperature °C	
	minimum	maximum	minimum	maximum	minimum	maximum
Alak	9.27×10^{-11}	6.75×10^{-10}	1.42	4.14	50	80
Siah	5.28×10^{-10}	2.21×10^{-9}	1.5	4.31	50	80
Malas	3.13×10^{-10}	2.28×10^{-9}	1.34	4.42	50	80

losses in product. Similar results are reported in drying of carrot and potato slices [Aghbashlo et al. 2011, Chayjan et al. 2012]. The computed values of D_{eff} for all pomegranate seed cultivars are in domain of 10^{-9}-10^{-11} m²/s for the drying of food and agricultural materials [Aghbashlo et al. 2011, Chayjan et al. 2012, Kingsley et al. 2007]. The results showed that the Siah cultivar has the highest value of D_{eff}. A pomegranate seed included two parts, fleshy and woody. Woody part is kernel of seed and its moisture content level is very low. The fleshy section is high moisture content and is around the kernel. Thickness of fleshy section of seed cultivars is different. Generally higher volume of fleshy section can affect on D_{eff}. Figure 6 revealed that a direct relationship exists between D_{eff} and volume of seed fleshy section. This can be due to higher capacity

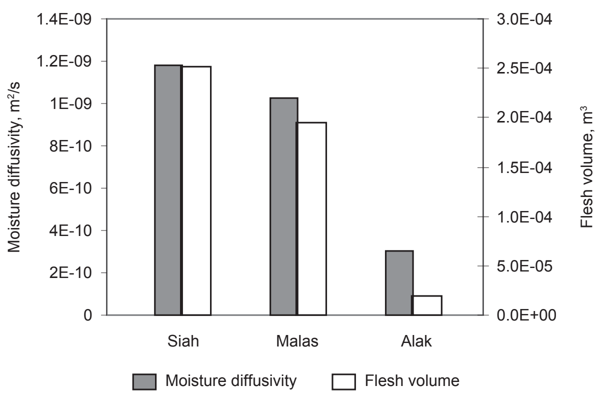

Fig. 6. Variations of D_{eff} for different pomegranate cultivars and flesh volume of the seed

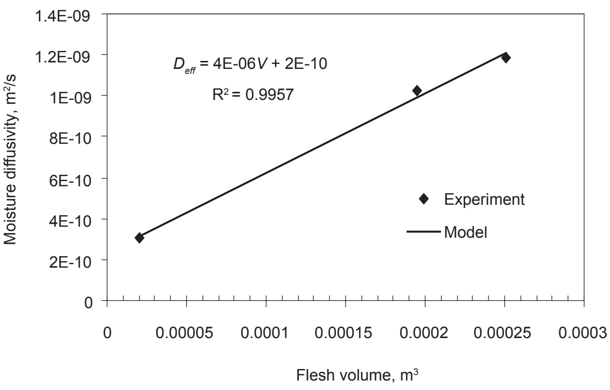

Fig. 7. Relationship between D_{eff} of different pomegranate cultivars and flesh volume of the seed

of mass transfer for the higher fleshy cultivar (Siah). Accordingly the D_{eff} values of siah cultivar are almost higher in all drying conditions. A relationship between D_{eff} and fleshy part volume of the seed for all cultivars is presented in Figure 7.

Air temperature has more effect on D_{eff} values of pomegranate seeds compared to air velocity, especially in higher temperature levels. Using linear regression analyses, three models were fitted to the D_{eff} values of three pomegranate cultivars based on input temperature and bed conditions (air velocity). Fitted models and corresponding R^2 values are represented in Table 4. Similar results concerning influence of input temperature on D_{eff} during convective drying

Table 4. Mathematical models fitted to experimental values of effective moisture diffusivity for three pomegranate cultivars

Cultivar	Model	R^2	E_{mr}	SD_{mr}
Alak	$D_{eff} = 3.1\times10^{-11}\ V + 1.6\times10^{-11}\ T - 8\times10^{-10}$	0.9350	19.81	13.85
Siah	$D_{eff} = 7.8\times10^{-11}\ V + 5\times10^{-11}\ T - 2\times10^{-9}$	0.9320	30.12	16.92
Malas	$D_{eff} = 7.3\times10^{-11}\ V + 5.3\times10^{-11}\ T - 3\times10^{-9}$	0.9400	58.43	55.54

Table 5. Best selected topologies including training algorithm, different layers and neurons for FFNN and CFNN

Network	Training algorithm	Threshold function	Number of layers and neurons	MSE	R^2	E_{mr}	SD_{EMR}	Epoch
FFNN	LM	TANSIG	3-3-2-1	0.00127	0.9858	8.03	7.735	32
		LOGSIG	3-4-3-1	0.00004	0.9972	5.58	5.68	46
		TANSIG-LOGSIG-LOGSIG	3-3-2-1	0.00015	0.9966	6.72	7.65	13
	BR	LOGSIG	3-3-2-1	0.00032	0.9969	7.08	6.46	70
		TANSIG	3-3-3-1	0.00051	0.9957	9.24	15.11	43
		TANSIG-LOGSIG-PURELIN	3-4-3-1	0.00080	0.9865	9.38	11.67	26
CFNN	LM	TANSIG	3-3-2-1	0.00003	0.9936	9.72	13.22	17
		LOGSIG	3-3-3-1	0.00008	0.9959	9.98	12.87	15
		TANSIG-LOGSIG-TANSIG	3-3-3-1	0.00011	0.9813	10.16	11.41	29
	BR	TANSIG	3-5-3-1	0.00541	0.9074	20.39	21.50	42
		LOGSIG	3-4-2-1	0.00463	0.9213	19.56	18.96	21
		TANSIG-LOGSIG-LOGSIG	3-3-2-1	0.00296	0.9733	15.54	23.77	34

have been reported for tomato [Doymaz 2007], peach [Kingsley et al. 2007] and corn [Amiri Chayjan et al. 2011].

Neural network modelling of D_{eff}. Two strategies of similar and various threshold functions for all layers were utilized to study effect of different threshold functions on FFNN and CFNN outputs (Table 5). Both strategies, as well as learning algorithms of LM and BR, were used for training of FFNN and CFNN networks. Several topologies were selected as the best results from each network, training algorithm and threshold functions (Table 5).

The best results for FFNN belonged to 3-4-3-1 topology and LOGSIG threshold function with LM algorithm in the first strategy. This structure generated $MSE = 0.00004$, $R^2 = 0.9972$ and $E_{mr} = 5.58$ converged in 46 epochs. The best result for the second strategy of FFNN with LM algorithm is belonged to 3-3-2-1 topology and threshold functions of TANSIG-LOGSIG-LOGSIG. This structure generated MSE = 0.00015, $E_{mr} = 5.72$ and $R^2 = 0.9966$.

The best results for CFNN belonged to topology of 3-3-3-1 with LM algorithm, threshold function of LOGSIG and the first strategy. This composition output was $E_{mr} = 9.98$ and $R^2 = 0.9959$ at 15 training epochs. CFNN with the second strategy, LM algorithm, topology of 3-3-3-1 and threshold functions of TANSIG-LOGSIG-TANSIG presented the output of $MSE = 0.00011$, $E_{mr} = 10.16$ and $R^2 = 0.9813$.

With respect to the obtained results, the first strategy of FFNN, LM algorithm with LOGSIG threshold function and 3-4-3-1 topology has presented the best performance. Real and predicted values of D_{eff} and real errors are shown in Figure 8. Training and testing *MSE* for patterns are also presented in Figure 9. The results indicated that the E_{mr} of this network is the least value, so this network was selected as an optimized structure. Output demonstration of Matlab software for this optimized network is depicted in Figure 10.

Weight matrices of optimized network between layers and biases are as follows:

(Weight matrix between layer 1 and layer 2)

$$IW\ \{2, 1\} = \begin{bmatrix} 2.19 & 4.05 & 8.74 \\ 0.48 & -0.09 & -1.61 \\ -16.33 & -2.89 & 0.75 \\ -2.44 & 2.89 & -8.69 \end{bmatrix}$$

(Weight matrix between layers 2 and 3)

$$LW\ \{3, 2\} = \begin{bmatrix} -1.33 & 0.14 & 4.88 & -0.73 \\ -3.26 & 3.28 & 1.36 & -3.17 \\ 6.37 & 4.08 & -1.85 & -0.57 \end{bmatrix}$$

Weight matrix between layers 3 and 4)

$$LW\ \{4, 3\} = [7.86\ \ -11.65\ \ -1.13]$$

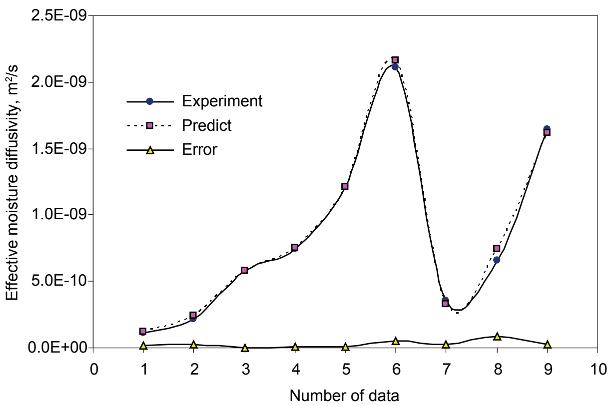

Fig. 8. Predicted values of D_{eff} using ANNs against real values and real error

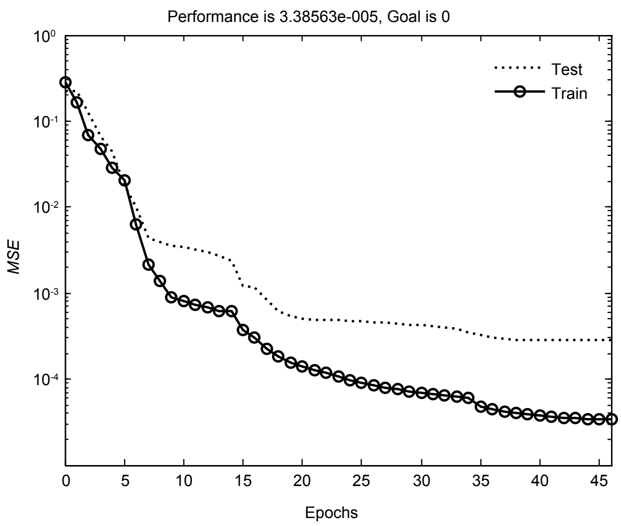

Fig. 9. Mean square error of training and testing patterns for the optimized ANN

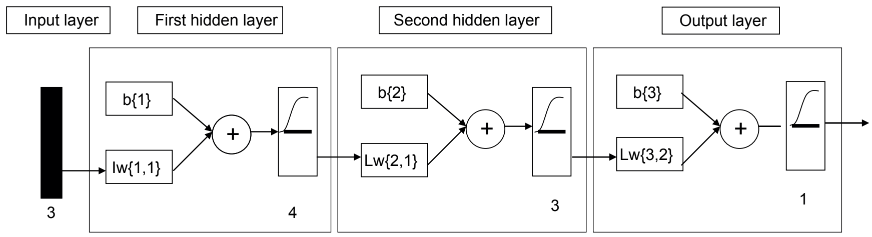

Fig. 10. Output demonstration of optimized network using Matlab software: IW and LW – weight matrices, b – bias matrices

$$(\text{Bias to layer 2})\ \text{b}\ \{2\} = \begin{bmatrix} -15.70 \\ 1.24 \\ 5.03 \\ -5.21 \end{bmatrix}$$

$$(\text{Bias to layer 3})\ \text{b}\ \{3\} = \begin{bmatrix} 6.89 \\ -1.60 \\ 5.48 \end{bmatrix}$$

$$(\text{Bias to layer 4})\ \text{b}\ \{4\} = [0.47].$$

The average values of two indices for the optimized ANN and mathematical model are depicted in Figure 11. A significant difference has been observed between mathematical model and the optimized ANN results in R^2 value. The average value of R^2 value for mathematical model was 0.9357 and for optimized ANN was 0.9972 (Fig. 11 A). Mean relative error produced by the optimized ANN (5.58%) is less than mean relative error of the mathematical model (36.12 in Figure 11 B).

Mohapatra and Rao [2005] recommended to E_{mr} of a model which has been fitted to the experimental data should always be lower than 10%, therefore, the optimized ANN model is reliable to predict D_{eff} values for entire range of input parameters. Due to the mathematical models can not predict the D_{eff} of pomegranate seed cultivars with an acceptable accuracy, but the optimized ANN predicted the D_{eff} of pomegranate seed cultivars with suitable SD_{EMR} value around the E_{MR}. These results showed that the overtraining for the optimized ANN has not occurred and SD_{EMR} with E_{mr} are the proper indices for comparing of the two methods. Moreover, accuracy of MSE and R^2 values has been controlled by E_{mr} and SD_{EMR}. Aghbashlo et al. [2008] predicted the D_{eff} of berberis fruit in convective drying with R^2 = 0.9570 using a complex mathematical model. D_{eff} of carrot in a semi-industrial continuous band dryer was determined using a statistical model with R^2 = 0.9831 [Aghbashlo et al. 2011].

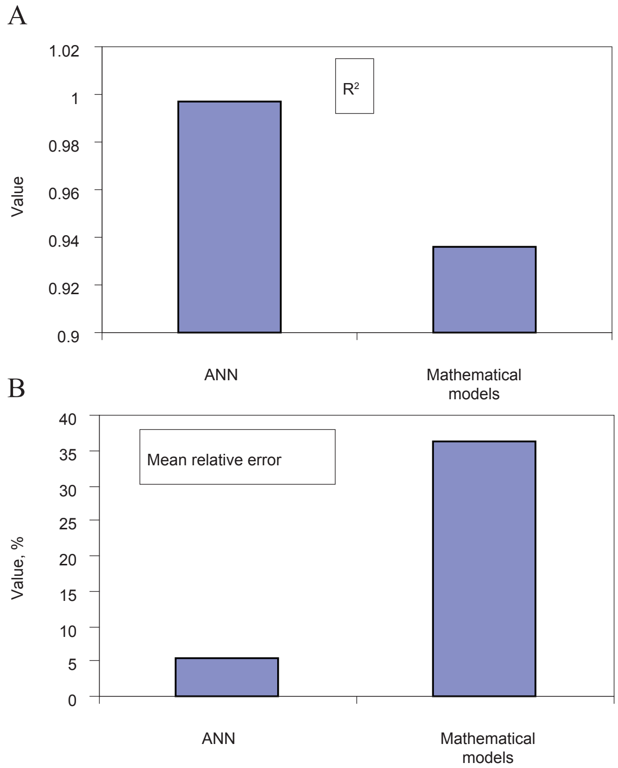

Fig. 11. Average values of the optimized ANN and mathematical models for prediction of D_{eff} values of pomegranate seed cultivars: A – determination coefficient, B – mean relative error

To study importance of input parameters on D_{eff} of pomegranate seed cultivars, consecutive omitting

Table 6. Results of consecutive omitting method of input parameters on output of optimized neural network

Omitted parameter	*MSE*	R^2	E_{mr}	SD_{EMR}	Epoch
Air temperature	0.04683	0	109	126	12
Air velocity	0.00332	0.9649	18.33	17.02	19
Cultivar	0.03582	0	127	153	28

method of input parameters was applied. In this method, after deleting one of the input parameters from the optimized network, the answer was compared to the other results. The most important parameter causes further decrease in R^2 values and further increase in error values (Table 6). Hence the cultivar type was selected as the most important parameter which affects the D_{eff} value. This is due to difference in tissue, flesh volume and kernel size of cultivars. Air temperature has the second-rate influence on D_{eff}. Air velocity has not got a significant effect on D_{eff} values, because the error values were not significant compared to the original state. In study of modelling and optimizing of four dependent parameters of quality, kinetic, performance and energy of rough rice drying with seven independent variables in fixed bed using ANNs method, input air temperature was found as the most important factor affecting all the independent variables. Also ambient air temperature and relative humidity had the least effects [Amiri Chayjan et al. 2009 b].

CONCLUSION

Mathematical and artificial neural network (ANNs) approaches were used to predict the effective moisture diffusivity (*EMC*) of three pomegranate seed cultivars through three independent parameters including cultivar type, drying air temperature and air velocity and then effect of input parameters on D_{eff} of the seeds was studied using obtained results. The following conclusions can be drawn from the study:

1. Drying results of three pomegranate seed cultivars in fixed, semi fluidized and fluidized bed conditions indicated that the effective moisture diffusivity for the seed cultivars varied between 2.28×10^{-9} and 9.27×10^{-11} values. Moreover, increase in input air temperature for each air velocity (bed condition) caused an intensive increase in D_{eff} values, however increase in air velocity in each air temperature level (except for 80°C) had no significant effect on D_{eff} value.
2. The average R^2 and E_{mr} values for regression analysis with linear model were calculated 0.9357 and %36.12, respectively. The optimized ANN for data training was FFNN with LM algorithm and LOGSIG threshold function, four neurons for the first hidden layer and three neurons for the second hidden layer. The R^2 and E_{mr} values using ANN were 0.9972 and %5.58, respectively.
3. Results showed that the siah cultivar has the highest value of D_{eff}. This is due to higher volume of fleshy section f the siah cultivar. A direct relationship was found between D_{eff} and volume of seed fleshy section. Accordingly the D_{eff} values of siah cultivar are almost highest in all drying conditions.
4. Study on the optimized ANN showed that the cultivar type was the most important parameter which affects the D_{eff} value. Air temperature has the second-rate influence on D_{eff}. Air velocity has not got a significant effect on D_{eff} values.

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MODELOWANIE WSPÓŁCZYNNIKA DYFUZJI WODY W WARSTWIE NIERUCHOMEJ, PÓŁFLUIDALNEJ I FLUIDALNEJ NASION GRANATU Z WYKORZYSTANIEM METOD MATEMATYCZNYCH I SIECI NEURONOWYCH

STRESZCZENIE

Wstęp. Modelowanie współczynnika dyfuzji wody w nasionach granatu różnych odmian jest podstawą optymalizacji suszenia nasion. Cele optymalizacji to przede wszystkim wyznaczenie najlepszej metody i parametrów suszenia, które zapewnią właściwą jakość suszu. Na dyfuzję wody w nasionach najbardziej wpływa temperatura. Najkorzystniejsza wartość tego parametru jest różna dla różnych odmian granatu. Dlatego modelowanie współczynnika dyfuzji wody jest istotne z punktu widzenia projektowania, optymalizacji i regulacji suszarek.

Materiał i metody. W badaniach analizowano suszenie w cienkiej warstwie nieruchomej, półfluidalnej i fluidalnej nasion granatu z trzech odmian (Alak, Siah i Malas). Próbki suszono powietrzem o temperaturze

50, 60, 70 i 80°C. Do wyznaczania wartości współczynnika dyfuzji wody (D_{eff}) wykorzystano drugie prawo dyfuzji Ficka. Do modelowania D_{eff} zastosowano również zależność liniową oraz sztuczne sieci neuronowe.
Wyniki. Maksymalne i minimalne wartości D_{eff} są związane z odmianami odpowiednio Malas i Alak. Trzy modele liniowe dopasowano do danych eksperymentalnych, uzyskując wartości R^2 równe 0,9350, 0,9320 i 0,9400 odpowiednio dla odmian Alak, Siah i Malas. Najlepsze wyniki modelowania z użyciem sztucznych sieci neuronowych uzyskano dla sieci o działaniu wyprzedzającym z algorytmem uczącym Levenberga-Marquardta o typologii 3-4-3-1 z funkcją progową LOGSIG. Ta struktura dała dopasowanie z R^2 równym 0,9972.
Wnioski. Znaleziono zależność funkcyjną między D_{eff} a grubością części miękkiej nasion. Siah ma największą wartość D_{eff} ze względu na większą objętość części miękkiej tej odmiany nasion. Rodzaj odmiany oraz prędkość przepływu powietrza suszącego mają odpowiednio największy i najmniejszy wpływ na D_{eff}.

Słowa kluczowe: suszenie w złożu fluidalnym, współczynnik dyfuzji wody, nasiona granatu, sztuczne sieci neuronowe

Received – Przyjęto: 22.11.2011 Accepted for print – Zaakceptowano do druku: 19.12.2011

For citation – Do cytowania

Chayjan Amiri R., Salari K., Barikloo H., 2012. Modelling moisture diffusivity of pomegranate seed cultivars under fixed, semi fluidized and fluidized bed using mathematical and neural network methods. Acta Sci. Pol., Technol. Aliment. 11(2), 137-149.