Kinetics and Artificial Neural Network Prediction of Pistachio Drying in an Infrared Assisted Solar Dryer

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ABSTRACT

To explain the drying behavior of pistachio nuts in an infrared assisted solar dryer, nine mathematical models were fitted to the experimental data and their comparison criteria were calculated. Meanwhile, different Artificial Neural Networks (ANNs) were tested to obtain the best network for final moisture content prediction. The results showed that drying time shortened by 30% when the air temperature raised from 45 to 65ºC. Increasing the IR power to 500 W caused a 45% reduction in drying time. The Henderson and Pabis model was selected as the best mathematical model to describe the drying behavior of pistachio nuts. Among the networks, Levenberg–Marquardt back-propagation training algorithm presented the best fit to the drying data with RMSE of 0.0035 and R^2 of 0.999 for the training and RMSE of 0.0038 and R^2 of 0.996 for the testing. Based on RMSE criteria, the ANN modeling yielded a more accurate prediction compared to all of the empirical equations.

Keywords: Infrared; Mathematical Modeling; Artificial Neural Network; Pistachio Nut; Solar Dryer.

INTRODUCTION

Pistachio (*Pistachio Vera* L.) is one of the most important nuts in the world. Pistachio nut because of its high nutritional properties and favorable taste is mainly consumed as raw, salted or roasted. Meanwhile, pistachio nuts are widely used in food industries such as snack foods, ice cream, and pastry (Kashaninejad *et al.*, 2006).

Due to high initial moisture content of pistachio nuts after harvesting (about 40 to 50% (db)) a drying operation to appropriate moisture content (5 to 7% (db)) is needed before storage (Kouchakzadeh and Tavakoli, 2011). Since the quality of final product is profoundly affected by drying method, drying is one of the most important stages in pistachio production (Kashani Nejad *et al.*, 2003). A number of researchers have studied different dryers for pistachio drying (Kouchakzadeh, 2013; Özahi and Demir, 2015). Solar drying is a well-known method for agricultural products drying and is increasingly used as an alternative to the industrial hot air dryers which are the most conventional drying devices. Solar dryers have advantages over both traditional open sun drying (eg. shorter drying time, lower product losses and higher quality) and industrial hot air dryers (eg. higher energy efficiency and lower environmental pollution).

A technique to heat transfer is infrared (IR) radiation. IR is an electromagnetic wave with the wavelength of 700 nm to1 mm. IR electromagnetic energy particles attack the surface of the products to be warmed after which conduction takes over. To avoid material surface burning or hardening, applying an air flow with IR radiation is usually recommended. IR dryer has been investigated as a method used for increasing energy

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efficiency, improving product quality and reducing drying time (Shi *et al.*, 2008; Wang and Sheng, 2006).

Mathematical modeling using empirical correlation method is usually applied to describe drying behavior of agricultural products. Although this method gives very accurate results for each experiment, but the equation is not valid for other conditions and there is no way to obtain a general equation for a range of drying parameters (Movagharnejad and Nikzad, 2007). Artificial Neural Network (ANN) is a suitable modeling method for bio-processes, which are complex to describe applying the mathematical approaches. ANN is a black box which indirectly considers the effect of independent variables on targets, with no dependence on any assumption or special condition. Since ANN provides new ideas for its strong function of nonlinear mapping, parallel processing and self-learning (Gupta *et al.*, 2009), the response time achieved in ANN method is shorter than mathematical modeling methods.

The present study was focused on investigation of Akbari variety pistachio drying behavior in an IR assisted solar dryer. Although many mathematical and ANN models have been presented by researchers to describe drying kinetics of various agricultural products (Huang and Chen, 2015; Zhou and Jin, 2016), there is no known model available for pistachio drying in an IR assisted solar dryer. Furthermore, a comparative study for prediction of pistachio drying characteristics using mathematical correlation and ANN method has been conducted at different drying conditions.

2. MATERIALS and METHODS

2.1 Dryer Description

A schematic view of the designed IR assisted solar dryer which was constructed in department of Biosystems engineering, Shahid Bahonar University of Kerman, Iran, is given in figure 1. The dryer was comprised of solar air collector, drying chamber, IR lamps, auxiliary electrical heater and fan. The solar collector chamber was constructed from wood (1.5 cm thickness). A fined-perforated aluminum plate (3 mm thickness) and a transparent glass sheet (6 mm thickness) were used as the collector absorber and cover, respectively. The sides and bottom walls of the solar collector were insulated by a glass wool sheet (2.5 cm thickness). Two 500 W electrical heaters were installed at the collector outlet to work as the auxiliary heater. In order to reduce air temperature variations during the tests, the heaters were located in a heat storage box which was constructed from perforated clay bricks. The drying chamber was a wooden cabinet whose walls were completely insulated by glass wool and in which a base for the product tray was deployed. Top wall of the drying chamber contained two lamp holders for installing IR lamps above the product tray (with 30 cm distance). The fan was powered by a 12 V battery and provided a forced-air flow through the dryer components.

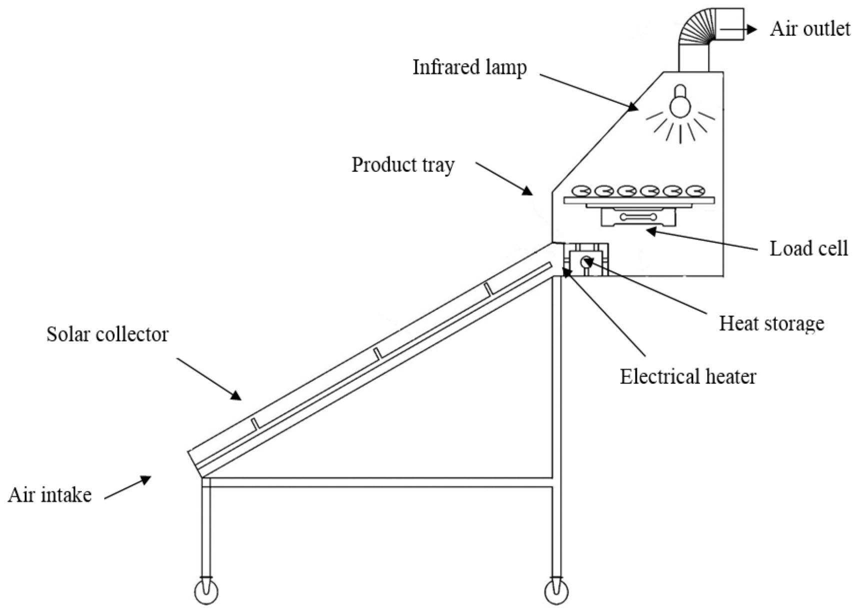

Figure 1. Schematic view of the IR assisted solar dryer

2.2 Experimental Procedure

The tests were conducted during November 2013, from 9 am to 3 pm in Kerman City, Iran. At each test, 0.5 kg fresh hulled pistachio nut was spread on the product tray located in the drying chamber under the exposure to the infrared radiation. The drying process was carried out at a constant air flow rate of 0.042 kg/s and the experiment factors were: drying air temperature at three levels (45, 55 and 65 ^oC) and power of IR lamps at three levels (0, 250 and 500 W). Meanwhile, product weight, solar radiation intensity, ambient and drying air temperature were measured during the tests. All the data were recorded at time intervals of 30 minutes during the test period.

2.3 Instrumentation

Two load cells (OBU-1, Bongshin Co., Korea) were used to measure the product weight changes during the drying period. The load cells data were monitored and recorded on a computer employing a load cell transmitter (TM 1020, TIKA Eng. Co., Iran) interface. Ambient and drying air temperatures were measured by means of two temperature sensors (SMT 160, TIKA Eng. Co., Iran) which were located outside the solar collector chamber and before the product tray, respectively. An AVR control system (Iran Electronic Co., Iran) was used to control, display and record the temperature data. To measure the solar radiation intensity on the collector a solar power meter (TES 1333R, TES Corp., Taiwan) was installed where its sensor was parallel to the solar collector surface.

2.4 Mathematical Modeling

To find a suitable equation for describing drying behavior of pistachio in the IR assisted solar dryer, the drying curves were fitted with 9 equations (table 1). For this purpose, moisture ratio (MR) expression was obtained using the following equation:

$$MR = \frac{(M - M_e)}{(M_i - M_e)} \quad (1)$$

Where M, is the moisture content at each time, M_i, is the initial moisture content, M_e, is the equilibrium moisture content. The equilibrium moisture content is the moisture content at which the pistachio is neither gaining nor losing moisture; this however, is a dynamic equilibrium and changes with relative humidity and temperature. Since M_e value is relatively small compared with M and M_i values, a number of researchers made the assumption of $M_e = 0$ and so they used the simplified equation of $MR=M/M_o$ instead of equation 1 (Vijayan *et al.*, 2016; Zhu *et al.*, 2015). But, the observations of Al-mahasneh *et al.*, indicated that this simplification is not appropriate and taking the value of equilibrium moisture content could achieve more accurate results than the zero value (Al-Mahasneh *et al.*, 2013). Therefore, in the present study the value of M_e was determined at the end of each test. The moisture content at which moisture desorption (drying rate) was small and negligible during a specific period was taken as the equilibrium moisture content (Aguirre-Loredo et al., 2016; Li et al., 2011). SPSS (Statistical Package for Social Science) was employed for the non-linear regression analysis. To select the best fitted model, the statistical parameters such as reduced chi-square (χ^2), root mean square error (RMSE), mean bias error (MBE) and t-stat value as well as coefficient of determination (R^2) were calculated as follows (Mortezapour *et al.*, 2014; Vijayan *et al.*, 2016):

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

$$MBE = \frac{\sum_{i=1}^{N}(MR_{\exp.i} - MR_{pre.i})}{N} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp.i} - MR_{pre.i})^2}{N}} \quad (4)$$

$$t-value = \sqrt{\left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]} \quad (5)$$

Where $MR_{exp,i}$ is the ith experimental moisture ratio, $MR_{pre,i}$ is the ith predicted moisture ratio, N is the number of observations and z is the number of model constants. The model which has the highest values of R^2 and lowest values of χ^2, RMSE, MBE and t-stat shows the best fit.

Table 1.Mathematical models applied to the drying curves of pistachio

Model name	Model expression	Reference
Lewis	$MR = \exp(-kt)$ *	(Bruce, 1985)
Page	$MR = \exp(-kt^n)$	(Agrawal and Singh, 1977)
Henderson and Pabis	$MR = a.\exp(-kt)$	(Chhinman, 1984)
Logarithmic	$MR = a.\exp(-kt) + c$	(Togrul and Pehlivan, 2002)
Two-term	$MR = a.\exp(-k_0 t) + b.\exp(-k_1 t)$	(Henderson, 1974)
Modified Henderson and Pabis	$MR = a.\exp(-kt) + b.\exp(-gt) + c.\exp(-ht)$	(Karathanos, 1999)
Verma et al.	$MR = a.\exp(-kt) + (1-a).\exp(-gt)$	(Verma *et al.*, 1985)
Geometric	$MR = at^{-n}$	(Chandra and Singh, 1995)
Midilli et al.	$MR = a.\exp(-kt^n) + bt$	(Midilli *et al.*, 2002)

*. k, n, a, k_0, k_1, b, g, h and c are empirical constants of the drying models.

2.5 Artificial Neural Network Description

In this study, ANN was used to apply a more comprehensive method for drying behavior description. The first step in creating a successful neural network is the network architecture. Since Multi-Layer Perceptron (MLP) networks are one of the most successful neural network architectures for prediction and process modeling, in this study, MLP network was selected. The number of neurons in input and output layers depends on independent and dependent variables, respectively (Movagharnejad and Nikzad, 2007), so in the first layer of the present network there were three neurons as inputs, including: IR power, drying temperature and drying time. In the last layer moisture content was considered as the network output and the optimum number of neurons in the hidden layer was determined through trial and error, based on the lowest observed training error. The complexity of the problem under investigation is a determinant factor for the number of hidden layers and their neurons (Izadifar and Jahromi, 2007). The network structure is given in figure 2. In order to achieve the best prediction of moisture content, different networks with various training algorithms and transfer functions were examined in MATLAB (7.14 ver.) by means of neural network toolbox. In early stopping technique (improving generalization method) the available data is randomly divided into training (70%), validation (15%) and test (15%) subsets. The networks performance was evaluated by RMSE and R^2 criteria. Appropriate values for the network training parameters indicated good training and values of validating parameters show the reliability of network for prediction.

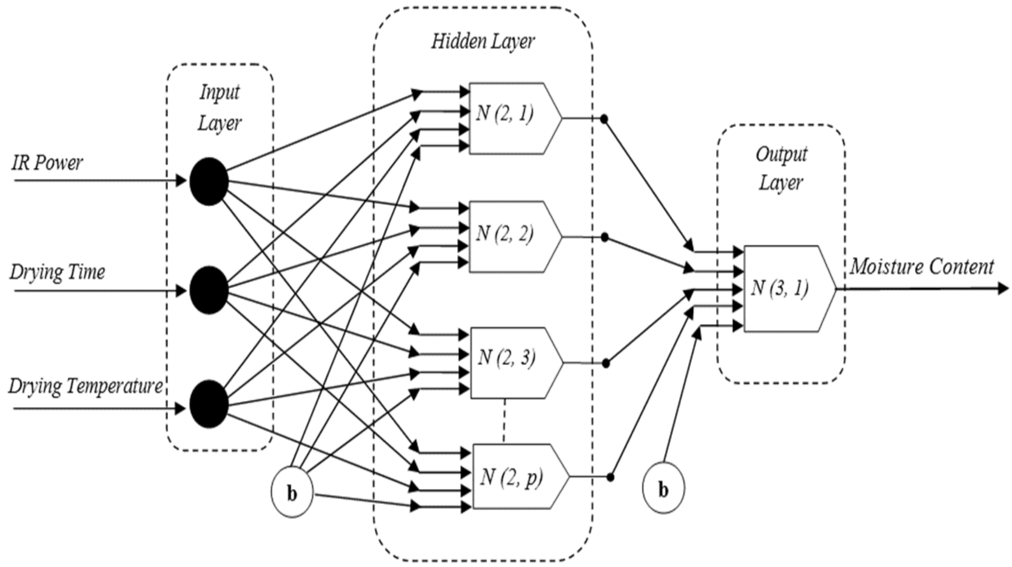

Figure 2. The network structure used for moisture content prediction

3. Results and Discussion

During the experiment period, the ambient temperature ranged from 19 to 26 ^{O}C which its highest value was at 2 pm. The solar radiation intensity variations were between 650 and 870 W/m^2 which its maximum value was observed at noon.

Moisture ratio variations as a function of drying time at the different drying treatments were shown in figure3. It is clear that higher drying temperatures led to higher water removal rates and consequently, resulted in a significant reduction in drying time (P<0.05). It was observed that drying time decreased by 30% when raising the air temperature from 45 to 65 ºC. Similar results were reported by previous researchers (Fu and Chen, 2015; Rodríguez *et al.*, 2014; Tanaka *et al.*, 2015). Figure 3 also illustrates that IR radiation intensity could significantly shorten the drying time (P<0.05) and increases the water removal rate. Since heat transfer rate and consequently, product temperature increases with IR radiation, a higher mass transfer and water evaporation rate occurs. The results show that increasing the IR power from 0 to 500 W led to a 45% reduction in drying time. This finding agrees with the previous researches (Nowak and Lewicki, 2004; Pathare and Sharma, 2006; Sharma *et al.*, 2005).

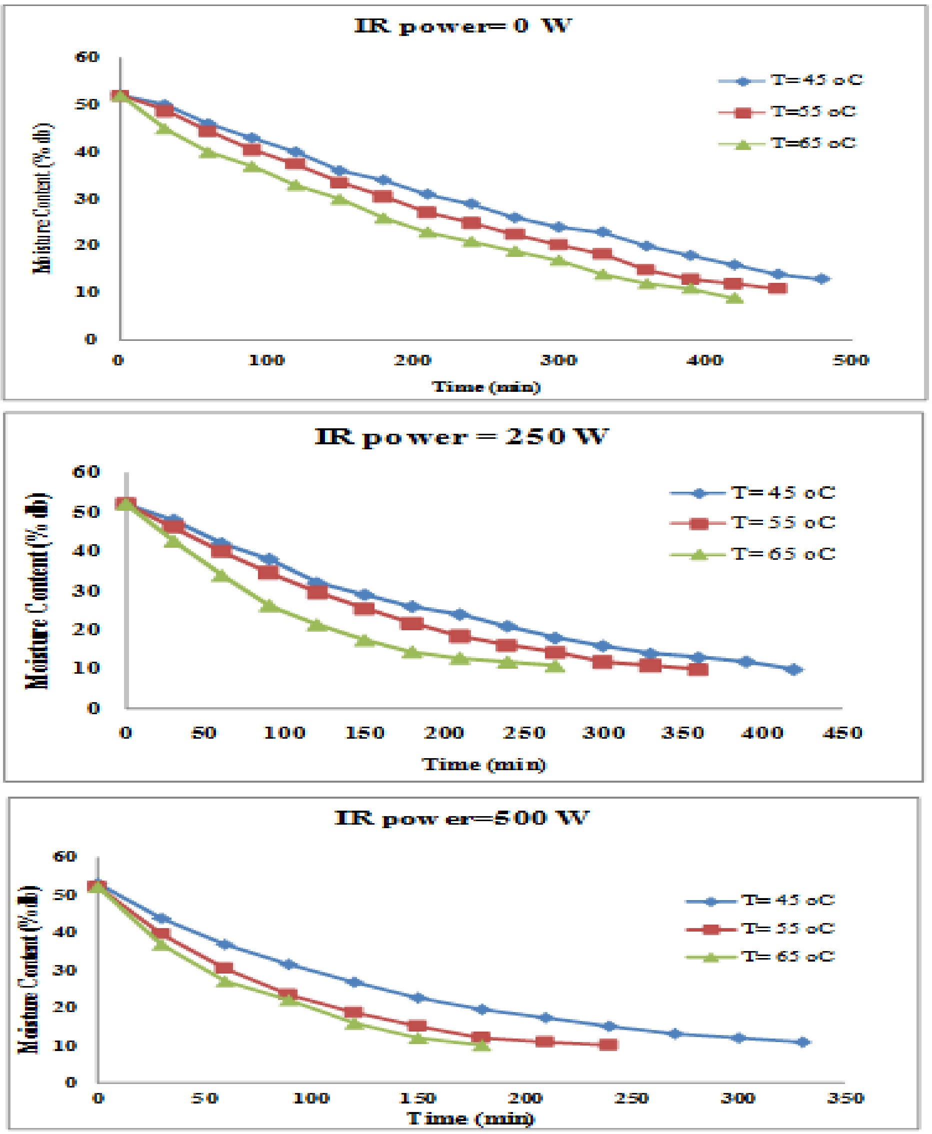

Figure 3. Variations of moisture content during drying period at different drying air temperatures (T) and IR powers

The average values of coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE), mean bias error (MBE) and t-stat for different models are given in table 2. The results show that the values of R^2, χ^2, RMSE, MBE and t-stat ranged from 0.931, 0.0005, 0.016, 0.012 and 1.170 to 0.999, 12.765, 1.398, 1.275 and 2.364, respectively. It can be seen from table 2, the highest R^2 values were observed with the Page and the Henderson and Pabis models. But the Henderson and Pabis presents lower χ^2, RMSE, MBE and t-value compared with the Page model. Therefore, the Henderson and Pabis could be selected as the model to describe the drying behavior of pistachio in the IR assisted solar dryer. The results of (Kouchakzadeh, 2013) showed that the Page model was the most suitable for describing drying curve of pistachios under ultrasound-assisted sun drying. While, the Logarithmic model was the best one for open sun drying of pistachios without ultrasound power. Kashaninejad et al. have selected the Page model as the most suitable for describing the drying behavior of the pistachio nuts in a hot air dryer (Kashaninejad *et al.*, 2007). Table 3 shows the values of the constants for Henderson and Pabis model.

Table 2. Results of statistical analysis for different drying models

Model	R^2	RMSE	χ^2	MBE	t-value
lewis	0.9961	0.03762	0.000938	0.03313	
Page	0.9975	0.03071	0.000903	0.02571	1.590788
Henderson and Pabis	0.9994	0.01612	0.000507	0.01214	1.189605
Logarithmic	0.9965	0.02367	0.001901	0.01979	1.583788
Two-term	0.9962	0.05312	0.00932	0.04863	2.364426
Modified Henderson and Pabis	0.9314	1.39749	12.76481	1.27468	2.312406
Verma *et al.*	0.9963	0.09367	0.009912	0.075155	1.396978
Geometric	0.9551	0.07643	0.01523	0.057158	1.17069
Midilli et al.	0.9712	0.09176	0.09815	0.0694592	1.203852

Table 3. The calculated constants for Hendesron and Pabis model

IR Power (W)	Air Temperature (°C)	Model Constants	
0	45	k=0.004	a=1.007
	55	k=0.004	a=1.021
	65	k=0.005	a=1.011
250	45	k=0.005	a=1.004
	55	k=0.006	a=1.021
	65	k=0.007	a=1.002
400	45	k=0.007	a=0.991
	55	k=0.009	a=0.973
	65	k=0.009	a=0.968

To validate the selected model, predicted moisture ratio by the Henderson and Pabis model was plotted versus measured moisture ratio (see fig. 4). The data are generally banded around the straight line which means that there is a good agreement between predicted and measured moisture rations.

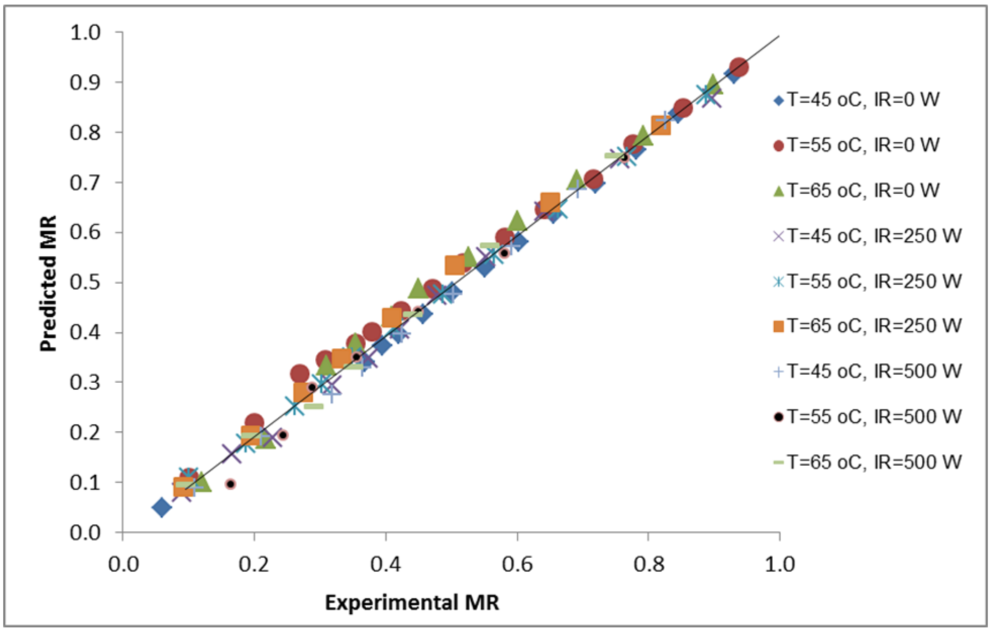

Figure 4. Predicted MR from the Henderson and Pabis model versus experimental MR at different drying air Temperatures (T) and IR powers

Different ANNs with various training algorithms and transfer functions were tested to obtain the best network for final moisture content prediction (Table 4). Performance analysis of different transfer functions (logarithmic sigmoid, tangential type sigmoid and radial basis) with various training algorithms was evaluated and the RMSE of the tests for different numbers of hidden units in the experiments is given in Table 5. Clearly, training and validation errors as well as R^2 values indicated good training and reliability of the network for the prediction. Applying many trial-and-error tests, the best ANN was obtained with three layers (3 inputs, 40 hidden nodes and 1 output) having RMSE of 0.0035 and R^2 of 0.999 for the training. Levenberg–Marquardt back-propagation training algorithm and radial basis transfer function were used in this network.

Table 4. Network characteristics used for the prediction process

	variables	Value/type
1	Type of network	Feedforward
2	Number of input neurons	3
3	Number of output neurons	1
4	Number of neurons in hidden layer	40
5	Number of hidden layers	1
6	Input layer transfer function	Linear
7	output layer transfer function	Linear
8	hidden layer transfer function	Radial basis
9	Combination of inputs	Weighted sum of the inputs plus the bias
10	Status of data	Normalized in [-1 1]
11	Performance function of network	RMSE
12	Values for performance function	10^{-6}
13	Training algorithm	Levenberg–Marquardt back-propagation algorithm

Table 5. Performance analysis of the selected network with different transfer functions and training algorithms

	logsig						*Tansig*								*Radbas*			
	Trainlm		***Traingd***		***Trainbr***		***Trainlm***		***Traingd***		***Trainbr***		***Trainlm***		***Traingd***		***Trainbr***	
	RMSE	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*	R^2
5	0.0422	0.9863	0.4171	0.6568	0.0359	0.9883	0.0527	0.9852	0.3393	0.7588	0.0290	0.9919	0.0575	0.9885	0.3900	0.8465	0.0317	0.9907
10	0.0184	0.9929	0.3237	0.8473	0.0198	0.9929	0.0292	0.9917	0.2783	0.8685	0.0188	0.9925	0.0298	0.9943	0.3055	0.8023	0.0205	0.9923
15	0.0132	0.9933	0.3998	0.7418	0.0163	0.9933	0.0130	0.9937	0.2177	0.8926	0.0169	0.9941	0.0146	0.9949	0.3473	0.9375	0.0189	0.9938
20	0.0122	0.9946	0.2653	0.8521	0.0178	0.9928	0.0116	0.9945	0.2005	0.9079	0.0179	0.9938	0.0102	0.9955	0.3045	0.9689	0.0168	0.9954
25	0.0091	0.9957	0.2605	0.8658	0.0169	0.9939	0.0118	0.9944	0.2978	0.8071	0.0188	0.9925	0.0066	0.9960	0.2761	0.9438	0.0188	0.9940
30	0.0101	0.9942	0.2421	0.8837	0.0176	0.9932	0.0091	0.9951	0.1913	0.9219	0.0187	0.9933	0.0049	0.9972	0.2611	0.9562	0.0216	0.9931
40	0.0060	0.9969	0.2507	0.8730	0.0168	0.9945	0.0046	0.9973	0.1719	0.9392	0.0192	0.9931	0.0035	0.9995	0.2390	0.9545	0.0182	0.9945

The average RMSE of the neural networks with 40 neurons in the hidden layer (0.0035) means that the results of the neural network models appear to be appropriate. In order to avoid complicated neural network structure, no further search was made by more different numbers of hidden layers. Furthermore, based on RMSE criteria, comparison of tables 2 and 4 clearly shows that the results of the ANN model are more accurate than each of the empirical equations.

Fig. 5 and Fig. 6 show the variation and histogram of errors between targets and outputs of the selected network, respectively. It is clear from figure 5 that a good agreement between predicted and target moisture contents was achieved using ANN method. The histogram of errors indicates that errors well distributed normally about zero in the range of -0.1and 0.1.

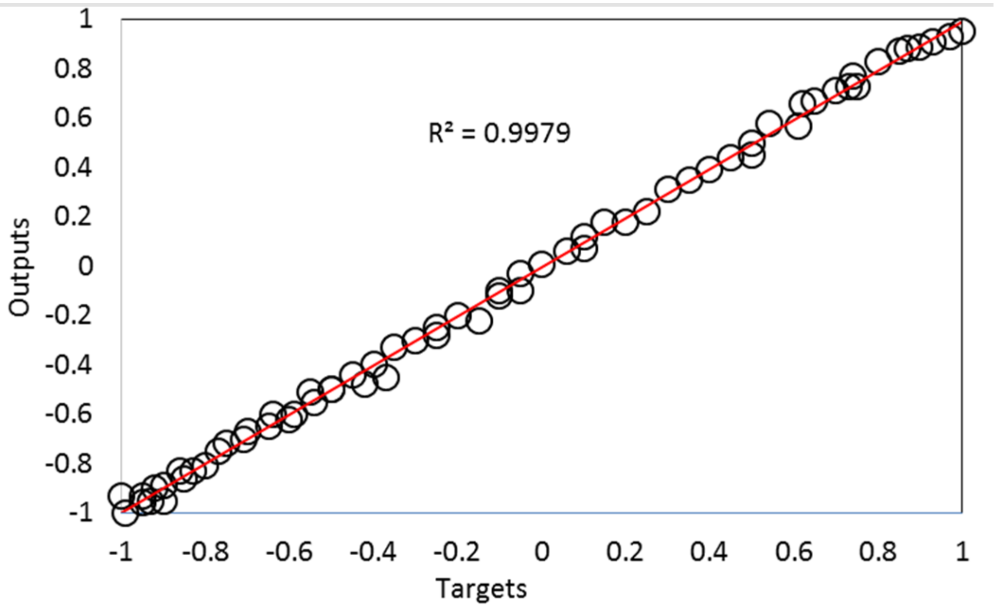

Figure 5. Variation of targets versus outputs of the selected network

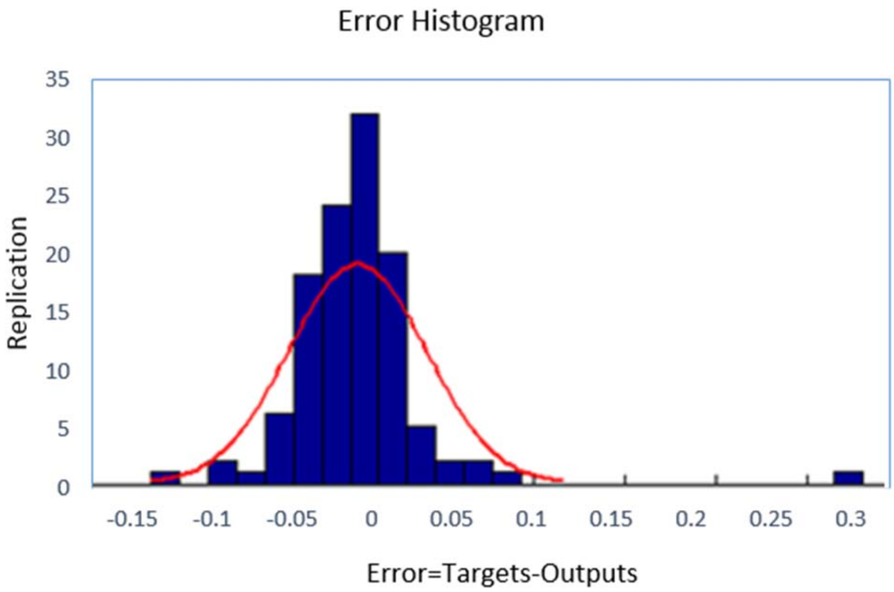

Figure 6. The error histogram between targets and outputs of the selected network

4. CONCLUSION

Drying behavior of pistachio in IR assisted solar dryer was studied in the present study. It was deduced that

1- Drying time shortened by 30% when air temperature raised from 45 to 65°C.

2- Increasing the IR power from 0 to 500 W caused a 45 % reduction in drying time.

3- In order to explain the drying behavior of the pistachio and develop a mathematical model, nine models were fitted to the experimental data and their constants and comparison criteria were calculated.

4- The Henderson and Pabis model presented the best agreement with the experimental data (having the highest R^2 of 0.999 and the lowest χ^2, RMSE, MBE and t-stat values of 0.0005, 0.0161, 0.012 and 1.189, respectively).

5- The best ANN was obtained with 3 inputs, 40 hidden nodes and 1 output, having RMSE of 0.0035 and R^2 of 0.999 for the training and RMSE of 0.0038 and R^2 of 0.998 for the testing.

6- Based on RMSE criteria, the ANN model results are more accurate compared with the empirical equations.

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التنبؤ بالشبكة العصبية والحركية الاصطناعية لتجفيف الفستق الحلبي

باستخدام المجفف الشمسي بمساعدة الأشعة تحت الحمراء

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ملخص

لشرح سلوك الفستق الحلبي خلال التجفيف بواسطة التجفيف الشمسي بمشاهدة الاشعة تحت الحمراء ، تم استخدام تسعة نماذج رياضيه تم تركيبها على البيانات التجريبية وتم حساب معاير المقارنة الخاصة بها، وفي الوقت نفسه تم اختيار الشبكات العصبية الاصطناعية (ANN'S)للحصول على افضل محتوى متوقع للرطوبة النهائية. اظهرت النتائج ان وقت التجفيف تم تقصيره بنسبة 30% عندما ارتفعت حرارة الجو من 45 ^{0} الى 65 ^{0} وعندما تم زيادة قوة الاشعة تحت الحمراء الى 50 واط ادى ذلك الى انخفاض 45% من وقت التجفيف. تم اختيار نموذج هندرسون وبابيس كأفضل نموذج رياضي لوصف سلوك تجفيف الفستق الحلبي ومن بين الشبكات قدمت خوارزمية تدريب ليفنبيرغ –ماركاردت للانتشار الخلفي افضل ملائمه بيانات التجفيف باستخدام RMSE (0.0035) و R2 (0.999) للتدريب RMSE (0.0038) و R2 (0.996) للاختبار واستنادا الى معايير RMSE اسفرت نماذج الشبكة ANN عن توقع اكثر دقه مقارنه بجميع المعادلات التجريبية.

الكلمات الدالة: الأشعة تحت الحمراء، الفستق الحلبي، المجفف الشمسي.

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