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Modeling of sesame seed dehydration energy requirements by a soft-computing approach

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Abstract

Thermodynamic models and Soft-computing method of Neural Network (NN) were used for computation of sesame seed dehydration energy (heat and entropy). The NN method for prediction of the Equilibrium Moisture Content (*EMC*) of sesame seed was utilized. The heat of sorption of sesame seed is predicted by a mathematical model. After well training of the NN model, predictive power of the model was found to be high (R^2=0.99). A regression model was also developed for prediction of entropy of sorption. At moisture content of about 11% (d.b.) the heat and entropy of sorption of sesame seed were decreased, smoothly, and they became highest at moisture content of about 8% (d.b.). Dehydration energy values of sesame seeds was very low compared with the other agricultural products. Computation of dehydration energy would be useful in the simulation of dried sesame seed storage.

Keywords: Entropy; Heat, Neural Network; Sesame seed; Sorption isotherm

Introduction

Sesame (*Sesamum indicum L.*) is one of the oldest cultivated plants in the world. Sesame seed is harvested either for the whole seed used in baking, for confectionery purposes, cake, and flour, or for cooking-oil extraction. Sesame seed contains approximately 45% by weight of oil, compared to 20% of seed weight for soybeans, and 25% protein. It is a good source of essential amino acids and minerals. It is also consumed for its medicinal qualities. Since sesame seed is more sensitive to high drying and storage temperature, it dries indoor with either natural or forced convection air. Sun drying is a well known, popular, and inexpensive method to reduce moisture contents of agricultural products, which prevents deterioration within the time that is considered as the safe storage period. Availability of such information is vital for understanding the drying process of sesame seed. Effective design of drying and storage systems for sesame seed also needs knowledge of their thermodynamic properties. Determining the end point to which the seeds must be dried in order to achieve a stable product with optimal moisture content is very important and also this is necessary for energy consumed to remove a given amount of moisture from the seeds. One of the most important aspects of drying and storage technology, especially for industrial processes, is modeling of the thermodynamic properties. This would allow engineers to choose the most appropriate method of drying and storage for a given product as well as to choose suitable operating conditions. Moisture content and temperature of sesame seed affect its storage life. Increasing these factors causes an increase in sesame seed respiration and enzymes production resulting in a decrease in seed storage and germination (Copeland and McDonald, 1995). Equilibrium Moisture Content (*EMC)* is a durability index and any change in quality of food and agricultural products during packaging and storage is crucially important (Veltchev and Menkov, 2000). Fundamental relationship between *EMC* and water activity of food and agricultural products is known as sorption isotherms. Sorption characteristics of food and agricultural products are used for designing, modeling and optimizing some processes such as drying, aeration and storage (Labuza, 1975; Bala, 1997). Energy consumption in drying process with regard to final equilibrium moisture content is an index for selection of dryer or type of drying process. Considering high moisture content of seed at harvesting time ,Safe storage and keeping the quality of harvested sesame seeds, is very important. Equilibrium moisture content (*EMC*) of food or agricultural products is defined as their moisture content in equilibrium with environmental temperature and relative humidity. *EMC* is an important parameter in studying the drying process. Studies have proved that, if the two mentioned environmental factors are not controlled, the mold activities increase (Brooker et al., 1992). Many studies have been conducted to propose several isotherm models for food and agricultural products (Kaymak-Ertekin and Gedik, 2004; Phomkong et al., 2006; Janjai et al., 2006). Isotherms of food and agricultural products are usually sigmoid-shape curves difficult to draw and manipulate. Several complex mathematical models have been developed to predict these curves (Bala, 1997). For estimation of parameters of these predictive models, non-linear direct optimization technique is required. Such estimations limit the accuracy and the shape of the model isotherms and also the reliability of predictions over the whole range of water activity. Neural network can be a good alternative for this

Table 1. Input parameters for NNs and their boundaries for prediction of equilibrium moisture content of sesame seed

Input Parameters	Maximum	Minimum	Levels
Water Activity (%)	98	55	7
Air Temperature (°C)	75	45	4

purpose. Neural network (NN) is a soft computing method and consists of neurons, which have been related with special arrangement. Neurons are in layers and every network includes some neurons in input, output and hidden layers. Algorithms and architectures of neural networks are different through variation in neuron model and relationship between neurons of layers, and their related weights. Purpose of learning process in neural networks is weights updating, so that with presenting set of inputs, desired outputs are obtained. Heat equation is proposed to use in the calculation of sesame seed heat of sorption while both the heat and entropy equations are essential to calculate the humidity during simulation of stored dried sesame seed. If neural network models are developed using experimental *EMC* data of sesame seed, the developed models can be used for more precise prediction by computer. This can also be used to predict the heat and entropy more accurately for modeling and simulation of drying, packaging and storage of sesame seed. Heat of sorption is an important parameter for drying and a measure of the water-solid binding strength. It can be used to determine the energy requirements and show the state of water within the dried sesame seed. Moisture content level of sesame seed at which the heat of sorption reaches the value of latent heat of sorption is often considered as the indication of the amount of bound water existing in the sesame seed (Wang and Brennan, 1991). The objectives of this study were to apply neural network method for modeling of sesame seed dehydration energy requirements, to find an improved empirical model for the heat of sorption and also to find a new empirical model for the entropy of sesame seed based on the NN method.

Material and methods

Experiments

Sesame seed samples were supplied from Kerman province, Iran. To establish a fix relative humidity at water activity domain of 55-98%, seven salt saturated solutions were utilized. Creation of such air relative humidity by the salt saturated solutions has been reported through the literature (Bala, 1997). Water activity values were also checked using a hygrometer. Gravimetric method was utilized for determination of the samples *EMC*; as it has high precision and dose not need a complex implement (Spiess and Wolf, 1983). Sesame seed samples were placed into a decicator and kept for six weeks while they weighted every single day. Equilibrium was derived when the difference of any successive weighing was lower than 0.001 g (Gabas et al., 1999). The temperature needed for the experiments was provided using an incubator with an electrical heater and an electronic temperature controller to maintain the temperature. An electric fan was fitted to circulate the air inside the sample box to accelerate moisture transfer between the sesame seed samples and air inside the sample box. Three to four weeks were needed for the sesame seed samples to be reached equilibrium. All the experiments were conducted in three replications.

Soft computing approach (structures and modeling)

Neural networks of Feed forward Back Propagation (FFBP) and Cascade Forward Back Propagation (CFBP) neural networks were utilized for training the experimental data set. Feed Forward Back Propagation consists of input, hidden and output layers. Back propagation (BP) learning algorithm was used for learning these networks. During training this network, calculations were carried out from input layer of network toward output layer, and error values were then propagated to prior layers. Cascade Forward Back Propagation neural network is similar to FFBP neural network in using the BP algorithm for weights updating, but the main symptom of this network is that each layer of neurons related to all previous layer of neurons. Two training algorithms including Bayesian regulation (BR) back propagation and Levenberg-Marquardt (LM) algorithms were used for updating neural network weights. Considering and applying the two inputs in all experiments, the *EMC* values were derived for different conditions. Networks with two neurons in input layer (water activity and temperature) and one neuron in output layer (*EMC*) were designed. Boundaries and levels of input parameters are shown in Table 1. Neural network toolbox (ver. 4.1) of Matlab software was used in this study. Threshold functions of LOGSIG, TANSIG and PURELIN were used to reach the optimized status (Demuth and Beale, 2003). Experimental data of 45, 55 and 75 °C selected for training network with suitable topology and training algorithm. The data obtained from experiment of 65 °C was also used for testing the trained network. The following criterion of root mean square error has defined to minimize the training error (Demuth and Beale, 2003):

$$MSE = \frac{1}{MN}\sum_{p=1}^{M}\sum_{i=1}^{N}(S_{ip} - T_{ip})^2 , \quad (1)$$

where MSE is the mean square error, S_{ip} is network output in *i*th neuron and *p*th pattern, T_{ip} is target output at *i*th neuron and *p*th pattern, N is number of output neurons and M is number of training patterns. To optimize the selected networks from prior stage, the secondary criteria were used as follows:

$$R^2 = 1 - \frac{\sum_{k=1}^{n}[S_k - T_k]}{\sum_{k=1}^{n}[S_k - \frac{\sum_{k=1}^{n} S_k}{n}]} \quad (2)$$

$$E_{mr} = \frac{100}{n}\sum_{k=1}^{n}\left|\frac{S_k - T_k}{T_k}\right| \quad (3)$$

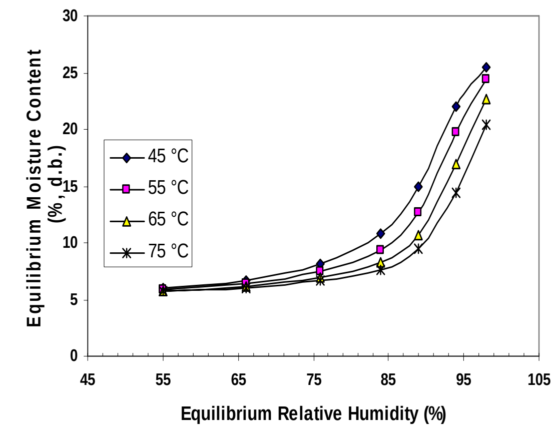

Fig 1. Experimental values of equilibrium moisture content as a function of temperature and water activity of sesame seed

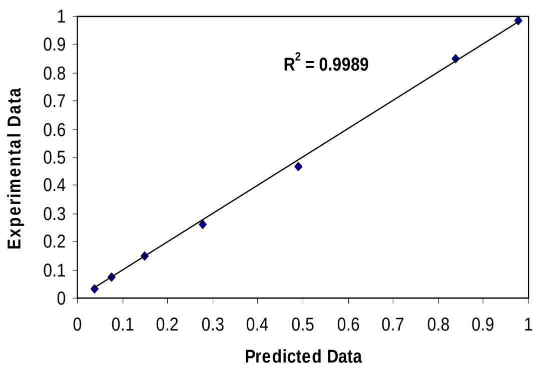

Fig 2. Predicted values of *EMC* of sesame seed using NNs versus experimental values for testing data set (65 °C)

(4) $$SE = \sum_{k=1}^{n} \sqrt{\frac{(S_k - T_k)^2}{d.f.}} ,$$

where R^2 is the determination coefficient, E_{mr} the mean relative error, SE the standard error, S_k the network output for *k*th pattern, T_k the target output for *k*th pattern, $d.f.$, degree of freedom and n the number of training patterns. To increase the accuracy and processing velocity of neural networks, input data was normalized at boundary of [0, 1].

Theoretical principles

The heat of sorption can be calculated by the following equation (Phomkong et al., 2006):

(5) $$\frac{\partial \ln(RH)}{\partial T_{ab}} = \frac{\Delta H}{R_o T_{ab}^2} ,$$

where RH is the relative humidity (%), T_{ab} is the absolute temperature (K), ΔH is the heat of sorption (kJ mol^{-1}) R_o is the universal gas constant (8.315 kJ kmol^{-1} K^{-1}). Integrating Eq. (5) and assuming that the heat of sorption (ΔH) is independent of temperature, the following equation is obtained:

(6) $$-\ln(RH) = (\frac{\Delta H}{R_o})\frac{1}{T_{ab}} - \frac{\Delta S}{R_o} .$$

When ln(RH) are plotted against $1/T_{ab}$, a straight line graph is obtained with the y-intercept of $\Delta S/R_o$. From the values of this y-intercept and R_o, ΔH and ΔS can be computed.

Results and Discussion

Sorption isotherm of sesame seed was determined using experimental method. The average of sesame seed *EMC* in three replications as well as water activities of salt saturated solutions is shown in Fig. 1. These curves are the moisture sorption isotherm of sesame seed at four temperature levels of 45, 55, 65 and 75°C in the range of 55 to 98 % relative humidity. Increasing air temperature in a specified water activity decreased the *EMC*. Increasing in water activity caused an increase in sesame seed *EMC* at all air temperatures because the seeds are quite small in size. FFBP and CFBP neural networks were used for mapping between inputs and outputs of patterns. Various compositions of threshold functions were used in layers. Several topologies were tested and the best results which used from each network, training algorithm and threshold functions are represented in Table 2. The best results were belonged to FFBP network, LOGSIG-LOGSIG-LOGSIG threshold function and 2-4-2-1 topology. This composition produced MSE=0.0000506, R^2 =0.9989, E_{mr} =1.341% and SE =0.394 converged in 23 epochs. The R^2 of optimized NN plotted in Fig. 2. Equilibrium moisture contents values of sesame seed at the four temperature levels (45, 55, 65 and 75°C) and five moisture levels (8, 11, 14, 17 and 20%) were computed using the optimized neural network model. Values of ln(RH) versus function of 1/T_{ab} were plotted for sesame seed at constant moisture content (Fig. 3). These values were predicted by the optimized NN. The slope of the plotted lines at constant moisture contents were the heat of sorption of sesame seed. The slopes were calculated by linear regression analysis. The heat of sorption for sesame seed at different moisture contents is presented in Fig. 4. The heat of sorption of sesame seed was decreased with increasing in its moisture content at low moisture content level, water was absorbed on the most accessible locations on the exterior surface of sesame seed. As the moisture content of sesame seed increased the solid material swells and therefore, new high-energy sites are opened up for water to get bound to. This causes the heat of sorption of sesame seed to increase along with decreasing moisture content. This trend is similar to those reported in studies on agricultural, food and medicinal products (Lahsasni et al., 2004; Phomkong et al., 2006). The heat of sorption was found to be fittted a power law

Table 2. Training algorithm for different neurons and hidden layers for networks

Network Type	Learning Algorithm	Threshold Function	No. of Layers and Neurons	*MSE*	R^2	E_{mr}	*SE*	Epoch
FFBP	LM	LOGSIG -LOGSIG - LOGSIG	2-4-2-1	0.0000506	0.9989	1.341	0.394	23
	BR	LOGSIG - LOGSIG - PURELIN	2-4-3-1	0.0000986	0.9933	4.503	0.703	34
CFBP	LM	TANSIG– LOGSIG –LOGSIG	2-3-2-1	0.0000854	0.9951	3.887	0.536	46
	BR	TANSIG - LOGSIG - PURELIN	2-4-3-1	0.000866	0.9892	6.984	0.931	41

Table 3. Maximum value of sesame seed heat of sorption compared with other agricultural products

Sample Type	***EMC* (%, d.b.)**	**Heat of Sorption (kJ mol^{-1})**	**Reference**
Sesame seed	8	3.32	This Study
Mango	30	18	Janjai *et al.* (2007)
Longan	40	19.5	Janjai *et al.* (2006)

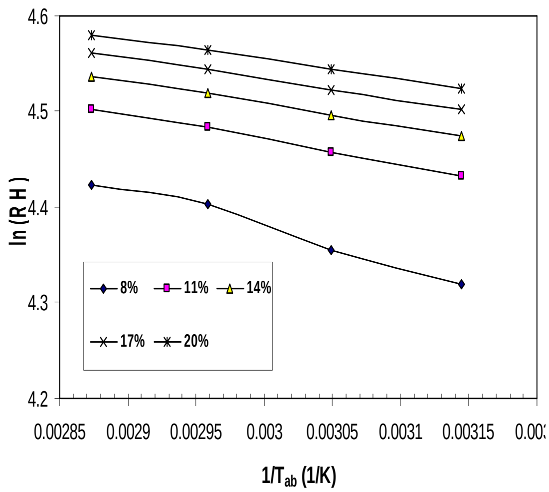

Fig 3. Neural network method for computing of ln(RH) as a function of $1/T_{ab}$ at different moisture content for sesame seed

Realtion. The following equation was developed for sesame seed:

$$\Delta H = 16.333 EMC^{-0.7789} \quad (7)$$

$$R^2 = 0.9924$$

This relation showed that the heat of sorption of sesame seed increases following a power model. This relation has a better fit than the exponential relation previously developed by Janjai et al. (2006) for Longan. The maximum values of heat of sorption of some agricultural products that reported by researchers compared with sesame seed in this study and represented in Table 3. The lower values of heat of sorption of sesame seed have been compared to some other agricultural products might be due to the smaller size of the sesame seed. The heat of sorption of sesame seed is significantly low, while its equilibrium moisture content is lower than 11% (d.b.). This can be explained by the fact that at moisture content of about 11% (d.b.) the water is loosely bound in sesame seed. This implies that sesame seed needs less energy at low moisture content (about 8% d.b.) for drying and low energy at lower moisture contents is needed, especially for storage. Entropy of sorption of sesame seed is presented in Fig. 4. It is a

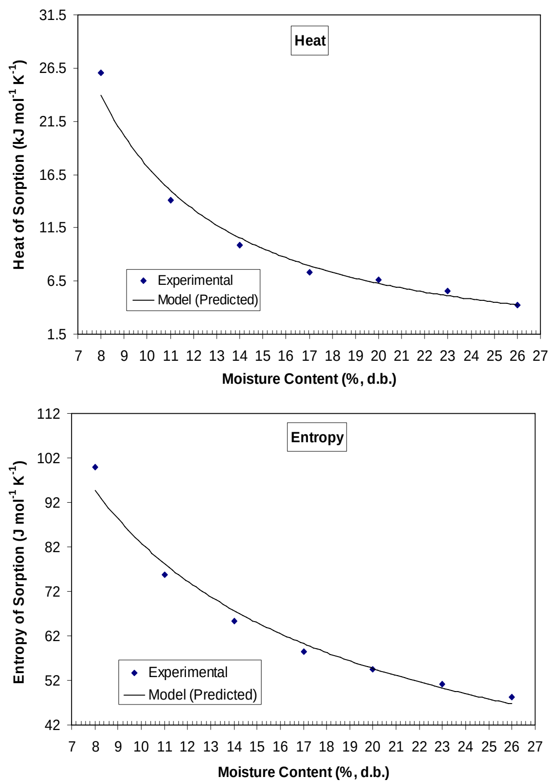

Fig 4. Experimental values and power model of sesame seed heat and entropy of sorption at different equilibrium moisture contents

function of moisture content and the following power model is fitted to the data:

$$\Delta S = 55.87 EMC^{-0.092} \quad (8)$$

$$R^2 = 0.9811$$

Fitted curves for prediction of entropy of sesame seed have good values compared to experimental one. These results proved that the entropy of sesame seed was decreased with increase in moisture content. Similar trends reported on the entropy of cassava, melon seed and potato (McMinn and Magee, 2003; Aviara and Ajibola, 2002). The derived equations for heat and entropy of sorption are necessary for calculation of humidity during storage of sesame seed. These results showed that the NN method has adequate accuracy to develop precise equations for sesame seed heat and entropy of sorption modeling.

Conclusions

Soft computing method of neural network (NN) is used for prediction of sorption isotherms of sesame seed and then dehydration energy modeling of sesame seed carried out using obtained results. The following conclusions can be drawn from the experiments: The best neural network model produced *MSE*=0.0000506, R^2 =0.9989, E_{mr} =1.341% and SE =0.394 for prediction of equilibrium moisture content. The sesame seed heat of sorption computed by the thermodynamic equations. This method proved that, the relation between moisture content and heat and entropy of sorption in sesame seed is a power model. The heat of sorption of sesame seed characterized by a power model, developed in this study with R^2 above 0.99. Entropy of sorption of sesame seed was also determined by a power model. The power model for sesame seed has R^2 above 0.98. The power equation for heat and entropy of sesame seed showed that the heat of sorption increases following a power relationship. The heat of sorption of sesame seed is significantly low, while its equilibrium moisture content is 8 % (d.b.). This can be explained by the fact that at the moisture content of 8 % (d.b.) in sesame seed, the water is loosely bound in sesame seed. The low values of sesame seed heat of sorption compared with some other agricultural products might be due to the small size of the sesame seed. This implies that sesame seed needs less energy at low moisture content (about 11% d.b.) for drying and storage.

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