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Investigating the effect of microwave power on moisture diffusivity and drying kinetics of faba beans: An experimental and modeling study

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ABSTRACT

In this research, the influence of microwave power on drying behavior and moisture diffusivity of faba bean (dehulled) was investigated. The fresh samples were dried as single layers at four different power levels (220, 330, 440, and 550 W). The results showed that the processing time was significantly decreased with increasing power ($p<0.05$). Six kinetic models were examined to simulate the experimental drying kinetics and the Midilli model showed the best performance. The average values of effective moisture diffusivity were calculated to be in the range of 1.92×10^{-9} m^2/s to 5.16×10^{-9} m^2/s, and increased significantly with increasing microwave power ($p<0.05$). The average rehydration ratio of dried faba beans changed from 239.12% to 325.05%, and increased with increasing microwave power. In addition, in this study a genetic algorithm-artificial neural network method was used for prediction of the moisture ratio of faba beans. This network structure has two inputs of microwave power and treatment time. The optimal network contained 10 neurons in hidden later was able to predict the moisture ratio of faba beans with a coefficient of determination (r) of 0.994. Sensitivity analysis results showed that treatment time is the most sensitive factor in predicting the moisture ratio of faba beans. In summary, the predictions of the genetic algorithm-artificial neural network model have high agreement with the testing datasets and they are useful for understanding and controlling the factors affecting the drying rate of faba beans during microwave drying.

1. INTRODUCTION

Legume crops, a sustainable source of high-protein food, are grown widely throughout the world. Among legumes, faba bean (*Vicia faba* L.), also known as fava bean, broad bean, and horse bean, is one of the oldest crops cultivated worldwide [1]. Probably faba beans are one of the best-performing crops under global warming and climate change scenarios because of their unique ability to excel under almost all types of climatic conditions coupled with their wide adaptability to a range of soil environments [2]. Faba bean, a nutritious leguminous cool tolerant crop, is widely cultivated throughout the world. Southwestern Asia, China, Ethiopia, Australia, and France are the main producers of faba beans. Faba beans are a rich source of lysine-rich proteins, carbohydrates, minerals, vitamins, and numerous bioactive compounds [3]. There is growing interest in pulses such as faba bean for the development of foods with enhanced nutrition, functionality, and health benefits [4]. Faba beans can be used as a vegetable, green or dried, fresh, or cooked/canned [2, 5].

Drying is the most popular technique for food preservation, which involves the removal of moisture to extend the shelf life of food products and help prevent microbial and enzymatic deterioration [6, 7]. Conventional thermal processing methods, such as hot-air drying are fundamentally based on the principle of heat conduction and convection, where thermal energy is transferred from the surface of the material to its interior [8, 9]. As an efficient thermal processing method, microwave heating has faster heating rates and high energy efficiency compared to conventional processing methods [10]. Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz, which can penetrate the material being processed and cause polar molecules, such as water, in the material to rotate violently and collide with each other, generating volumetric heat under the alternating microwave field [8]. Microwaves are based on dielectric heating by electromagnetic waves and offer advantages such as lower drying temperatures, faster drying speeds, more uniform energy distribution throughout the material, shorter drying times, and better quality of the final product [11].

The most common artificial neural network (ANN) architecture is associated with the general multi-layer perceptron, which consists of an input layer, a hidden layer, and an output layer with different numbers of neurons in each layer. The optimization of ANN parameters can be improved using genetic algorithms and stochastic global search algorithms, thereby achieving better performance. Genetic algorithms simulate the survival of the fittest principle of nature and search for an objective function that serves the natural optimization. Genetic algorithms are used for optimization based on weights and biases obtained ANN. Genetic algorithm–artificial neural network (GA-ANN) model is a useful tool for fruit and vegetable monitoring, crop grading and classification, drying rate modeling, and prediction and modeling of food quality attributes [12, 13]. Taheri-Garavand, *et al.* [14] confirmed that with an optimized ANN topology using genetic algorithm, the intelligent model may show a good ability to predict the moisture content of Savory leaves.

Increased consumption of pulses worldwide is driven in part by growing consumer demand for new foods with enhanced nutrition and health benefits. Pulses such as faba bean have significant potential in the development of value-added foods and ingredients [4]. In recent years, microwave drying has received increasing attention. Currently, most microwave heating research has primarily focused on investigating the effects of microwave power and duration on various materials [15-17]. Therefore, the main objectives of this study were to investigate and mathematical modeling of microwave drying curves and moisture diffusivity of dehulled faba beans. In addition, the GA-ANN method was used for prediction of the moisture ratio of faba beans.

2. Material and methods

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2.1. Drying experiments and measurements

Fresh faba bean pods (*Vicia faba* L.) harvested from farms located in Hamedan, Iran were purchased, removed their pods, and stored in a refrigerator at 6°C.

Before to each drying experiment, about 60 g of the faba beans was taken out of the refrigerator, washed with water, placed at the ambient temperature for 30 min for temperature stabilization and hand hulled.

A domestic microwave oven (Gplus, Model; GMW-M425S.MIS00, Goldiran Industries Co., Iran) was used to dry the dehulled faba beans. The experiments were carried out at different microwave powers of 220, 330, 440, and 550 W. The samples were uniformly distributed as a single layer on a tray inside the microwave oven and moisture loss was monitored accurately to 0.01 g (laboratory scale, LutronGM-300p, Taiwan) at regular time intervals of 20 s. It is worth noting that each drying experiment was replicated three times and the average values were used.

2.2. Mathematical modeling of drying kinetics

For mathematical modeling of the experimental drying curves, first of all, the moisture ratio (MR) was calculated by using Eq. (1):

$$MR = \frac{M}{M_0} \quad (1)$$

Then, the 6 commonly used semi-theoretical mathematical models including Quadratic (Eq. 2), Page (Eq. 3), Newton (Eq. 4), Midilli (Eq. 5), Logarithmic (Eq. 6), and Henderson and Pabis (Eq. 7) were fitted to the experimental MR results using Matlab software (version R2012a) and applying nonlinear regression method.

$$MR = a+bx+cx^2 \quad (2)$$

$$MR = exp(-kt^n) \quad (3)$$

$$MR = exp(-kt) \quad (4)$$

$$MR = a\,exp(-kt^n)+bt \quad (5)$$

$$MR = a\,exp(-kt)+c \quad (6)$$

$$MR = a\,exp(-kt) \quad (7)$$

Where MR and t are moisture ratio and treatment time, respectively. Also, the a, b, c, k, and n are coefficients of models. The accuracy of the models was evaluated by using three well-known statistical criteria including sum of squared error (SSE), coefficient of determination (r), and root mean square error (RMSE) defined as follows [18]:

$$MSE = \frac{\sum_{i=1}^{N}(O_i - T_i)^2}{N} \quad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - T_i)^2}{N}} \quad (9)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|O_i - T_i| \quad (10)$$

$$SE = \frac{\sigma}{\sqrt{N}} \quad (11)$$

$$r = \sqrt{1 - \frac{\sum_{i=1}^{N}[O_i - T_i]^2}{\sum_{i=1}^{N}[O_i - T_m]^2}} \quad (12)$$

Where O_i is the ith actual value, T_i is the ith predicted value, N is the number of data, σ is the standard deviation, and T_m is given by:

$$T_m = \frac{\sum_{i=1}^{N} O_i}{N} \quad (13)$$

2.3. Determination of effective moisture diffusivity coefficient

Thin layer drying of agricultural products can be described by one-dimensional diffusion and using Fick's second law. The effective moisture diffusivity coefficient (D_{eff}) of fresh faba beans during microwave drying was estimated following the procedure described by Salehi, *et al.* [10] and Azimi-Nejadian and

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Hoseini [17]. By plotting the experimental data in terms of ln(MR) against the process time (t), a straight line was obtained for each experiment and the effective diffusivity was calculated as follows (Eq. 14):

$$D_{eff} = -\frac{L^2 \times S}{\pi^2} \tag{14}$$

Where D_{eff} is the effective moisture diffusivity coefficient (m^2/s), S is the slope of the line, and L is the thickness of samples.

2.4. Rehydration ratio

The mass change of dried faba beans after rehydration was calculated following the procedure described by Salehi, *et al.* [19]. The dried faba beans were submerged in 250 ml glass beakers containing distilled water at 90°C. The beakers were transferred into the water bath (R.J42, Pars Azma, Iran) and the rehydration process (cooking process) was conducted at 90°C. The cooked faba beans mass after the rehydration time (3 h) was recorded by a laboratory balance (LutronGM-300p, Taiwan). The rehydration percent of dried faba beans was calculated as the ratio of the weight of cooked faba beans divided by the weight of dried faba beans × 100.

2.5. Genetic algorithm–artificial neural network (GA-ANN) modeling

In this study, the Neurosolution software (release 5, NeuroDimension, Inc., USA) was used for making the GA-ANN model. The microwave power and treatment time (2 inputs) were used as inputs and moisture ratio data of faba beans were used as output. The experimental data order was first randomized and then total data were randomly separated into 3 partitions: training (30%), validating (20%), and testing data (50%). The testing data were used for the prediction of the trained network performance on unseen data. In the hidden layers and output layer a sigmoid activation function was used (due to the highest r-values in comparison to the other functions, hyperbolic tangent and a linear) (Eq. 15).

$$f(x) = \frac{1}{1 + e^{-x}} \tag{15}$$

The Levenberg–Marquardt (LM) optimization method was applied to network training. The crossover probability and the mutation probability operators were adjusted equal to 0.9 and 0.01, respectively. Also, a sensitivity analysis was done to supply the measure of relative significance between the inputs of the ANN model and to show how the model output changed in response to input changes.

2.6. Statistical analysis

The obtained data from the experiments was statistically analyzed using SPSS 21 software. The Duncan multiple range test was practiced and significance was assumed at $p < 0.05$.

3. Results and Discussion

3.1. Drying characteristics

Typical drying curves of the dehulled faba beans at different power levels are shown in Figure 1. The minimum process duration of the dehulled faba beans was obtained for the power level of 550 W while the maximum value belonged to the microwave power of 220 W. The higher power enhances both kinetic energy and absorbed energy causing more vapor pressure difference between the center and surface of the samples and consequently increasing the moisture removal rates [17]. In this study, the high moisture content of the dehulled faba beans caused high friction against the bipolar rotation and subsequently high levels of heat inside the slices. The phenomenon resulted in quick vapor movement and forced the water to be diffused towards the slice's surface. Maleki, *et al.* [20] investigated the effective parameters in drying rate of faba beans. Their results show that the shortest drying time of faba beans during hot-air drying was 29 min (at 75°C and air velocity=2 m/s).

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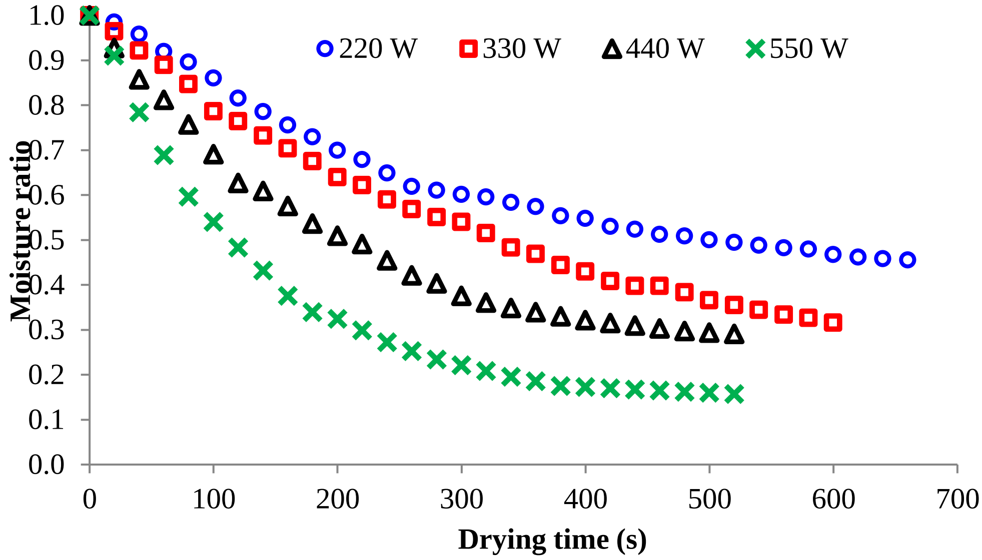

Figure 1. Typical moisture removal curves for microwave-dried dehulled faba beans at different power levels.

3.2. Evaluation of mathematical thin-layer models

The kinetic assessment of a reaction involves the study of the rate and mechanism by which one chemical species is converted to another. For most food products, time-dependent relationships are described using zero-order or first-order models [21, 22]. The obtained experimental moisture ratio values were fitted to the mathematical thin layer models and the results of statistical analysis are presented in Table 1. From the result and based on the statistical criteria including SSE, r, and RMSE, of all the practiced models, the Midilli model was found as the more suitable model to describe the microwave thin layer drying curves of the dehulled faba beans.

Table 1. The statistical analysis of the practiced thin-layer models for prediction of the faba beans drying curves (microwave power=330 W)

Model name	Sum of squared error	Coefficient of determination	Root mean squared error
Quadratic	0.0022	0.9989	0.0088
Page	0.0013	0.9993	0.0067
Newton	0.0188	0.9909	0.0250
Midilli	0.0007	0.9996	0.0049
Logarithmic	0.0008	0.9996	0.0055
Henderson and Pabis	0.0082	0.9960	0.0169

The drying constant and coefficient for the Midilli model obtained from fitting the moisture removal curves at different microwave power levels are shown in Table 2. Furthermore, to examine the Midilli model capability to simulate the drying curves, the experimental moisture ratio data was compared with those estimated by the model, and the results for one randomly selected drying curve are shown in Figure 2. As can be seen from this figure, the points were generally banded around the 45° straight line declaring that the Midilli model had a good capability to describe the microwave drying behavior of the faba beans. The purpose of Kusuma, *et al.* [23] study was to evaluate the drying of clove leaves with microwave-assisted drying using six mathematical models. Their results showed that the Midilli model became the most accurate model to show the drying characteristics of clove leaves compared to 5 other confirmed mathematical models with SSE values ranging from 0.0001 - 0.0034.

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Table 2. The constants and coefficients of the Midilli model obtained for drying curve fitting of the faba beans

Microwave power	a	k	n	b	Sum of squared error	Coefficient of determination	Root mean squared error
220 W	1.0170	0.1321	1.0800	0.0273	0.0035	0.9981	0.0108
330 W	0.9988	0.1333	1.0061	0.0068	0.0017	0.9993	0.0076
440 W	0.9996	0.2257	1.0197	0.0182	0.0015	0.9994	0.0080
550 W	1.0053	0.3402	1.0320	0.0180	0.0013	0.9996	0.0074

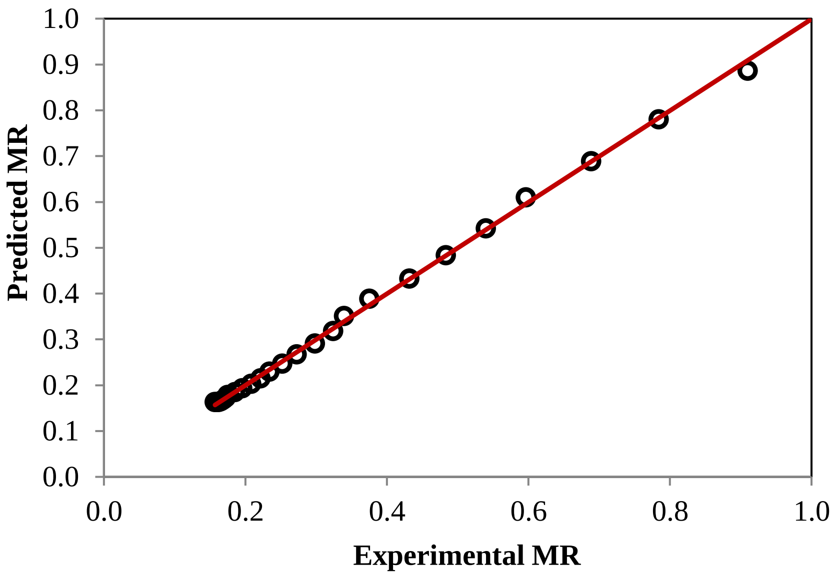

Figure 2. Comparison between experimental data and predicted moisture ratios (MR) values by Midilli model (microwave power=550 W)

3.3. Effective moisture diffusivity coefficient

Microwave technology has been widely applied in food processing and food service due to its efficacy and safety [16]. The calculated average values for the effective moisture diffusivity coefficient of the faba beans at various microwave power levels from plotting the graph of ln(MR) versus process time and using Eq. (14) are presented in Table 3. Based on statistical analysis, microwave power has a significant effect on moisture diffusivity ($p < 0.05$), and an increase in power increases the moisture diffusivity coefficient. As the results show, the moisture diffusivity changed from 1.92×10^{-9} m^2/s to 5.16×10^{-9} m^2/s. Azimi-Nejadian and Hoseini [17] found that increasing microwave power increases the temperature within the sample during drying, decreases the water viscosity, results in more water activity, and consequently leads to eased diffusion of the water molecules. Maleki, *et al.* [20] investigated the effective parameters in hot-air drying process of faba beans. Their results show that the highest moisture diffusivity of faba beans during hot-air drying was 4.53×10^{-8} m^2/s. The changes in effective moisture diffusivity and activation energy during drying of apple in a microwave and an oven were studied by Hashemi, *et al.* [24]. Their results showed that increasing microwave power increased the drying rate and effective moisture diffusivity. Also, two-stage drying results in better moisture removal.

Table 3. The values of effective moisture diffusivity coefficient values for the faba beans under microwave power drying

Microwave power	Effective moisture diffusivity coefficient (m^2/s)	Coefficient of determination
220 W	$1.92\times10^{-9}\pm7.62\times10^{-11}$ d	0.9834
330 W	$2.98\times10^{-9}\pm2.09\times10^{-10}$ c	0.9976
440 W	$3.92\times10^{-9}\pm2.03\times10^{-10}$ b	0.9862
550 W	$5.16\times10^{-9}\pm4.38\times10^{-10}$ a	0.9667

3.4. Rehydration ratio

During the drying process, as the moisture content of the material decreases, changes such as the destruction of the internal pore structure occur, which in severe cases leads to volume contraction of the material [25]. Rehydration capacity is a crucial characteristic of dehydrated foods. The porous structure of the material directly influences its characteristics such as rehydration capacity, hardness, and crispness. The calculated average values for the rehydration ratio of the dried faba beans at various microwave power levels are presented in Table 4. Based on statistical analysis, microwave power has a significant effect on the rehydration ratio ($p < 0.05$), and an increase in power increases the rehydration ratio of dried faba beans. As the results show, increasing microwave power from 220 W to 550 W increased the rehydration ratio from 239.12% to 325.05%. Salehi, *et al.* [5] investigated the effect of ultrasonic pretreatment on the rehydration ratio of cooked faba beans. Their results showed that the mean rehydration ratio of dried faba beans after cooking significantly increased from 308.4 % to 327.1 % when the extension of processing time increased from 0 to 15 min ($p < 0.05$).

Table 4. The rehydration ratio values for the faba beans under microwave drying

Microwave power	Rehydration ratio (%)
220 W	239.12±7.98 c
330 W	282.09±6.93 b
440 W	294.62±2.93 b
550 W	325.05±10.75 a

3.5. Genetic algorithm–artificial neural network (GA-ANN) modeling results

The genetic algorithm is applicable to solve a variety of optimization problems specifically the discontinuous, no differentiable, stochastic or highly nonlinear objective function [12]. In this study, the GA-ANN model was developed for the estimation of the moisture ratio of faba beans during microwave drying. In this research, the ANN model was trained using the genetic algorithm to find the best network structure. It was found that GA-ANN with 10 neurons in 1 hidden layer could estimate moisture ratio with a high r-value (r=0.994). The calculated r-values for the estimation of moisture ratio during microwave drying of faba beans show a high correlation between estimated and experimental values. Parvaneh, *et al.* [26] used olfaction machine and ANN method to assess the freshness of chicken meat. Their results showed that an optimal ANN with a general structure of 10-6-3 could determine the freshness of chicken meat at different storage dates.

The error values (MSE, NMSE, and MAE) calculated by the optimized GA-ANN model for prediction of the moisture ratio of faba beans during microwave drying are reported in Table 5. In addition, the estimation performance of the GA-ANN model for unseen data of moisture ratio is presented in Figure 3. As can be seen from this figure, the points were generally banded around the 45° straight line declaring that the GA-ANN model had a good capability to describe the microwave drying behavior of the faba beans. The results showed that a satisfactory agreement between the predicted and experimental data could be achieved by using the GA–ANN model. Taheri-Garavand, *et al.* [14] used the GA–ANN method to predict the moisture content of savory leaves during the drying process under different drying conditions. The results showed that the optimized GA-ANN had two hidden layers, with 9 and 17 neurons in the first and second hidden layers, respectively. The MSE value (0.000095) and r-value (0.999) of the GA–ANN experiment showed that it could

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accurately predict the moisture content based on the input variables. In another study, Maftoonazad, *et al.* [27] used ANN technique to predict mass transfer during the osmotic dehydration of black fig fruits in a ternary system. Their results showed that a properly trained ANN model was more accurate than a response surface methodology model in predicting this parameter.

Table 5. Error values calculated by optimized genetic algorithm–artificial neural network model for estimation of moisture ratio of faba beans during microwave drying

Performance	Moisture ratio
Mean squared error (MSE)	0.00062
Normalized mean squared error (NMSE)	0.01251
Mean absolute error (MAE)	0.01932
Minimum absolute error	0.00001
Maximum absolute error	0.08874
Correlation coefficient (r)	0.99377

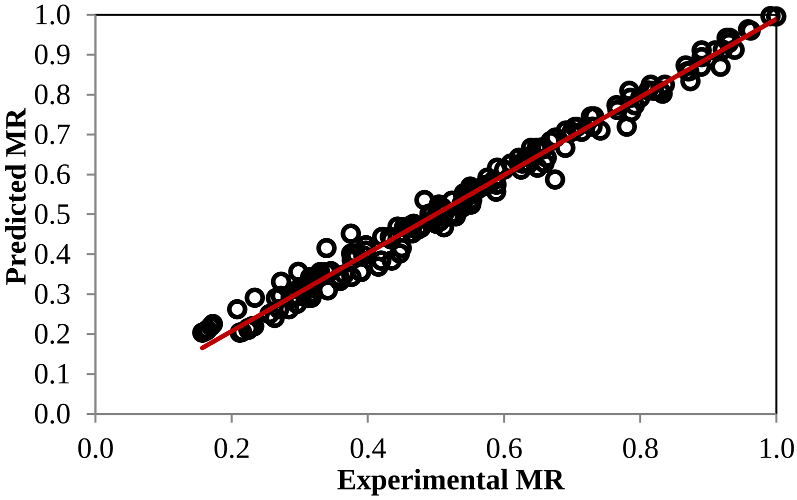

Figure 3. Comparison between experimental data and predicted moisture ratios (MR) values by genetic algorithm–artificial neural network model

The best GA-ANN network weight and bias values for moisture ratio changes of faba beans during microwave drying are reported in Table 6, which could be used in a computer program for the prediction of this parameter. Kalathingal, *et al.* [28] integrated a ANN with a genetic algorithm to predict the optimized process parameters required for fluidized bed drying of green tea leaves. Their network had one layer each for input and output with a linear activation function and two hidden layers with a sigmoid function. Their results showed that the weights and bias values of the trained ANN were used by the genetic algorithm to estimate a fitness function that maximized the total phenolic content and minimized the drying time and total color difference.

The results indicated that the developed GA-ANN drying model can efficiently estimate the moisture ratio of faba beans during microwave drying. Also, in this study the sensitivity analysis was used to examine the sensitiveness of GA-ANN structures toward various inputs (Figure 4). Sensitivity analysis results demonstrated that the treatment time was the major sensitive input for the estimation of moisture ratio of faba beans during microwave drying.

Table 6. The weight and bias data of the best model structure for estimation of moisture ratio.

Hidden neurons	Bias	Input neurons		Output neuron
		Microwave power (W)	Treatment time (min)	Moisture ratio
1	-1.2458	0.6739	-24.8332	14.2091
2	-0.5395	0.2143	3.5352	-8.3790
3	-7.1327	5.7902	0.3979	-4.0351

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4	-0.8388	6.5620	7.3833	-4.9471
5	2.0536	-6.9468	-0.7186	2.2697
6	-0.1076	-3.9393	5.2421	1.0975
7	-0.5459	1.3343	0.4717	1.5311
8	0.0827	-0.9229	-0.4489	-1.0586
9	-0.0319	1.1414	0.4141	1.6961
10	-1.3950	6.5081	4.8930	4.9697
Bias				3.3939

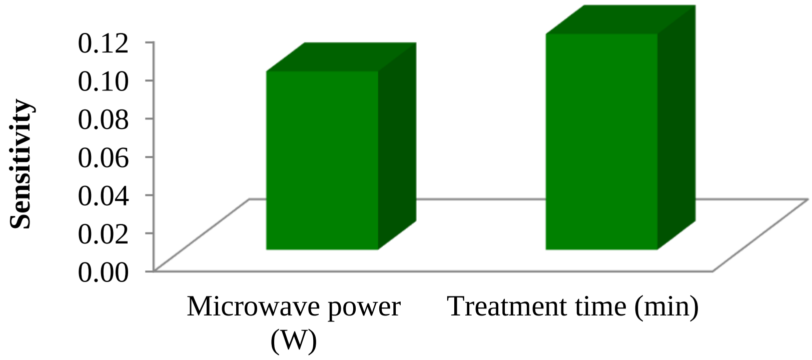

Figure 4. Sensitivity analysis result for estimation of moisture ratio of faba beans during microwave drying.

4. Conclusion

In this study, the influences of microwave power level on drying characteristics of single thin layer drying of dehulled faba beans via a microwave oven dryer were investigated. The curves of moisture removal rate included a short accelerating rate period in the beginning followed by a long falling rate period. The minimum process duration of the dehulled faba beans was obtained for the power level of 550 W while the maximum value belonged to the microwave power of 220 W. Among different mathematical models fitted to the experimental moisture ratio data, the Midilli model was found as the best one to describe the curves. By increasing the microwave power level from 220 W to 550 W, the effective moisture diffusivity coefficient significantly increased from 1.92×10^{-9} m^2/s to 5.16×10^{-9} m^2/s ($p < 0.05$). Based on statistical analysis, microwave power has a significant effect on the rehydration ratio ($p < 0.05$), and an increase in power increases the rehydration ratio of dried faba beans. The optimal network with a general structure of 2-10-1 was constructed to estimate the moisture ratio of faba beans during microwave drying. The modeling results indicated that the GA-ANN approach could give a good estimation of the moisture ratio of faba beans during drying. Overall, the use of new modeling approaches such as GA-ANN is recommended to investigate the drying kinetics of other agricultural products.

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بررسی تأثیر توان مایکروویو بر نفوذ رطوبت و سینتیک خشک شدن باقلا: مطالعه آزمایشگاهی و مدل‌سازی

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چکیده

در این پژوهش، تأثیر توان مایکروویو بر رفتار خشک‌شدن و نفوذ رطوبت باقلا (بدون پوست) بررسی شد. نمونه‌های تازه به‌صورت تک لایه در چهار سطح توان مختلف (۲۲۰، ۳۳۰، ۴۴۰ و ۵۵۰ وات) خشک شدند. نتایج نشان داد که زمان فرآیند به‌طور معنی‌داری با افزایش توان، کاهش می‌یابد ($p<۰/۰۵$). شش مدل سینتیکی برای شبیه‌سازی سینتیک خشک‌کردن آزمایشگاهی بررسی شدند و مدل میدیلی بهترین عملکرد را نشان داد. میانگین نفوذ مؤثر رطوبت در محدوده $۱/۹۲\times۱۰^{-۹}$ مترمربع بر ثانیه تا $۵/۱۶\times۱۰^{-۹}$ مترمربع بر ثانیه محاسبه شد و با افزایش توان مایکروویو به‌طور معنی‌داری افزایش یافت ($p<۰/۰۵$). میانگین نسبت آبگیری مجدد باقلای خشک‌شده از ۲۳۹/۱۲ درصد به ۳۲۵/۰۵ درصد تغییر کرد و با افزایش توان مایکروویو افزایش یافت. همچنین در این مطالعه از روش الگوریتم ژنتیک-شبکه عصبی مصنوعی برای پیش‌بینی نسبت رطوبت باقلا استفاده شد. ساختار این شبکه دو ورودی توان مایکروویو و زمان تیماردهی داشت. شبکه بهینه دارای ۱۰ نورون در لایه پنهان قادر به پیش‌بینی نسبت رطوبت باقلا با ضریب تبیین برابر ۰/۹۹۴ بود. نتایج آنالیز حساسیت نشان داد که زمان تیماردهی حساس‌ترین عامل در پیش‌بینی نسبت رطوبت باقلا است. در مجموع، پیش‌بینی‌های مدل الگوریتم ژنتیک-شبکه عصبی مصنوعی با مجموعه داده‌های ارزیابی مطابقت زیادی داشت و برای درک و کنترل عوامل مؤثر بر سرعت خشک‌شدن باقلا در طول خشک‌کردن با مایکروویو مفید است.