Optimization of Almond Kernels Drying under Infrared-vacuum Condition with Microwave Pretreatment using Response Surface Method and Genetic Algorithm

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ABSTRACT

The aim of this study was optimization of almond kernels drying with infrared-vacuum dryer and microwave pretreatment using Response Surface Methodology (RSM) and Genetic Algorithm (GA). The almond kernels were dried as thin layer with air temperatures of 30, 45 and 75°C vacuum pressures of 20, 40 and 60 kPa and microwave powers of 270, 450, and 630W. Design expert software was used to generate the experimental designs, statistical analysis, and regression models. The results showed that the optimum point for drying of almond kernels under infrared-vacuum dryer and microwave pretreatment with RSM method and considering the minimum value of shrinkage, energy consumption, and total color change as well as the maximum value of effective moisture diffusivity can be achieved at air temperature of 45°C, vacuum pressure of 34.04 kPa, and microwave power of 270W with 68% desirability and optimum point with GA method can be obtained at air temperature of 45°C, vacuum pressure of 34.05 kPa and microwave power of 270W.

Keywords: *Amygdales Communist* L., Color change, Energy consumption, Moisture diffusivity, Shrinkage.

INTRODUCTION

Almond (*Amygdales Communist* L.) is a member of Rosaceae family. Almonds are relatively high in terms of oil content; with values ranging from 36 to 60% of kernel dry mass (Abdallah *et al.,* 1998; Guadagni *et al.,* 1978). Most of the fatty acids in almond oil (approximately 90%) are unsaturated, with the ratio of monounsaturated to diunsaturated ranging from 2:1 to almost 5:1, respectively (Abdallah *et al.,* 1998). In 2012, world production of almond was about 1,530,271 tones, out of which Iran produced about 100,000 tons (FAO, 2012). Almond has an antioxidant nutrient value because it has good amounts of vitamin E, selenium, and essential fatty acids.

Drying process is very important in almond production processing. This process must be carried out in a way that not only protects the food against corruption, but also the least damage affects quality of the product, including color, flavor, texture, and nutritional value of the food.

Vacuum is often employed as a process for removing bulk and absorbed water from the product. Combined with heat, vacuum can be considered as an effective method for drying. High degrees of dryness can be attained at relatively low temperatures. This allows for fast and effective drying of temperature-sensitive products. Lower moisture content can be achieved through the utilization of vacuum and heat in comparison to the utilization of heat alone (particularly with parts that are porous or

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have a very high surface area). Additionally, drying under a vacuum can prevent oxidation of sensitive products that cannot be dried in the presence of air. Vacuum drying systems can also recover the solvent that is removed from the product, in the case of need. Often, the intended part for drying is placed into the vacuum drying chamber.

Microwave drying is a newly added technique to the already existing drying techniques, in comparison to convective air-drying (cabinet, flat bed, tunnel), spray, vacuum, foam mat, and freeze-drying (Prabhanjan *et al.*, 1995). The conversion of microwave energy into heat in the food is due to the presence of water. The drying time can be greatly reduced (Sharma and Prasad, 2001) and the quality of the ultimate product is ensured (Yongsawatdigul and Gunasekaran, 1996) by applying microwave energy to dried material. A vacuum-infrared dryer with microwave pretreatment combines the advantages of both microwave heating and vacuum drying (Calin-Sanchez *et al.,* 2011).

Several researchers have indeed combined the advantages of Far Infrared (FIR) drying with that of vacuum drying to dry several food products. Swasdisevi *et al.* (2007) investigated far infrared radiation drying of Cavendish banana slices under vacuum. The results revealed that the vacuum pressure, temperature, and thickness had significant effects on the drying kinetics and various qualities of the dried banana viz. color, hardness, and shrinkage. In addition, the optimum condition for infrared-vacuum drying was at temperature of 50°C, pressure of 5 kPa, and thickness of 2 mm. Mongpraneet *et al.* (2002) examined the drying behavior of the leaf parts of welsh onion undergoing combined far infrared and vacuum drying. The results showed that the radiation intensity levels dramatically influenced the drying rate and the dried product qualities.

Optimization of all aspects of a product is an effective strategy for accomplishing successful development of the product (Deshpande *et al.,* 2008).

As an important point in the statistical design of experiments, the Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response (Montgomery, 2005).

Genetic Algorithm (GA) is a combinatorial optimization technique, which searches for an optimal value of a complex objective function by simulation of the biological evolutionary process based, as in genetics, on crossover and mutation (Izadifar and Zolghadri Jahromi, 2007). Selection, crossover and mutation are the basic operators involved in GA. The process involved in GA optimization problems is based on that of natural evolution and broadly works as: (1) Randomly generating an initial population of potential solutions; (2) Evaluating the suitability or 'fitness' of each solution; (3) Selecting two solutions biased in favor of fitness; (4) Crossovering the solutions at a random point on the string to produce two new solutions; (5) Mutating the new solutions based on a mutation probability, and (6) Returning to stage two.

In the previous study by Nazghelichi *et al.* (2011), an integrated response surface methodology and genetic algorithm was recommended for developing Artificial Neural Networks (ANNs) with great chances to be an optimal one. The integrated RSM and GA approaches have been shown to be useful tools to find the global optimum ANN topology for prediction of the energy and exergy during fluidized bed drying which is considered as a tedious and time-consuming task.

Applying microwave energy during the whole process of drying causes energy losses and reduction of the product quality, therefore, applying microwave energy in the specified periods of drying process was proposed as a new method in this study. As far as the above literature review shows, no study has been reported about optimization of almond kernels drying under infrared-

vacuum condition. This study was carried out to ascertain the possibility of supplementing RSM and GA for the optimization of almond kernels drying under infrared-vacuum condition with microwave pretreatment.

MATERIALS AND METHODS

Sample Preparation

Fresh almond kernels were obtained from a field located in Asadabad (Hamedan Province), Iran; and stored in a refrigerator at $4\pm1°C$ for experiments. The initial moisture content of almond kernels was determined by drying 20 g of the sample in an oven at $105\pm1°C$ until constant weight was attained (Valverde *et al.*, 2006). Experiments were replicated three times. The initial moisture content of almond kernels was observed to be 0.47 (g $_{water}$ g^{-1} $_{dry}$ $_{solid}$).

Drying Equipment

Drying of almond kernels was conducted in a laboratory infrared-vacuum dryer with microwave pretreatment (Figure 1), developed in Biosystems Engineering Department, Bu-Ali Sina University, Hamedam, Iran .

A microwave oven (Sharp R959SLMA, Thailand) was used as the pre-treatment dryer. The cylindrical chamber was 20 cm in diameter and 30 cm in height. The dryer mainly consisted of four basic units: vacuum chamber, vacuum pump, infrared lamp, and electrical heaters controlling temperature of the drying chamber. Infrared lamp heater (100W) was used to heat the vacuum chamber and chamber air temperature was controlled via a temperature control unit with type k sensor and the accuracy of $\pm0.1°C$ (Lutron TM-903, Taiwan). Vacuum condition was created by a vacuum pump (DV-285N-250- PLATINUM, USA). In order to define and maintain absolute pressure during the experiments with an accuracy of 0.001 bar, a pressure controller (Sensys PSCH0001 BCIJ, Korea) was used. During the experiments, ambient temperature, relative humidity, inlet and outlet temperatures of drying air and vacuum pressure in dryer chamber were recorded. Relative humidity and the air temperature were logged on by a hygrometer with accuracy of ±3% RH (Lutron TM-903, Taiwan).

Experimental Procedure

Drying experiments were performed at the drying air temperatures of 45, 60, and 75°C, microwave powers of 270, 450, and 630W, and vacuum pressures of 20, 40, and 60 kPa.
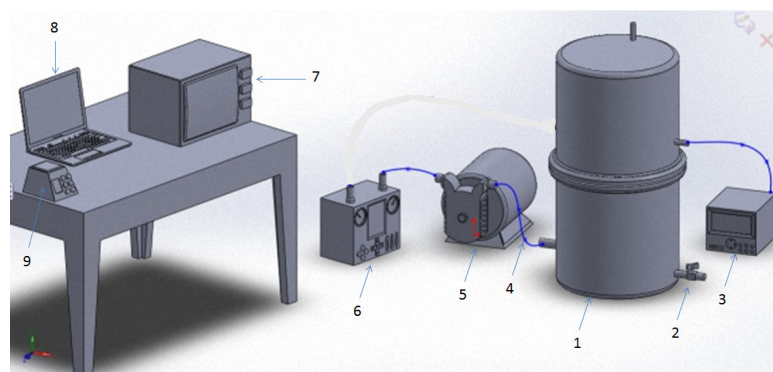
Figure 1. Schematic diagram of infrared-vacuum dryer with microwave pretreatment: (1) Dryer chamber; (2) Vacuum break up valve; (3) Thermometer; (4) Suction pipe; (5) Vacuum pump; (6) Pressure controller; (7) Microwave oven; (8) Computer, and (9) Digital balance.

Microwave powers were used alternatively as the pre-treatment drying and were applied every 20 seconds interval between infrared-vacuum conditions. When the dryer received a steady state condition, the samples (about 45 g) were spread on a tray. Weight loss of samples was measured and recorded every 20 seconds in the microwave dryer and every 300 seconds in the infrared-vacuum dryer. Drying time was defined as the time required for reducing moisture content of the samples to 0.1 g $_{water}$ g^{-1} $_{dry\ solid}$.

Shrinkage

Shrinkage occurs when water is removed from the cell and air takes its place. To measure shrinkage of the product at the beginning and end of each experiment by a digital caliper, the three basic diameters were measured.

Volume of almond kernels before drying (initial volume) was computed using Equation (1):

$$V_0 = \frac{4}{3}\pi(\frac{D}{2})^3 \qquad (1)$$

Where, V_0 is the initial volume before drying (m^3) and D is the geometric mean diameter (m). D was calculated using Equation (2):

$$D = \sqrt[3]{abc} \qquad (2)$$

Where a, b and c are the major, intermediate, and minor diameters (m), respectively.

Shrinkage was obtained using Equation (3).

$$S_b(\%) = \frac{(V_0 - V)}{V_0} \times 100 \qquad (3)$$

Where, V is the secondary volume or after drying and S_b is shrinkage percent.

Volume after drying was determined in the same way as the initial volume. Five replications were performed on samples with the same moisture content (Figiel, 2010).

Effective Moisture Diffusivity

Considering roundness of almond kernels and assuming distribution of initial moisture to be uniform, second law of Fick in diffusion with sphere geometry was used to calculate the effective moisture diffusivity. Fick's Equation for computing effective moisture diffusivity of almond kernels is as follows:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{D_{eff}n^2\pi^2t}{r_0^2}\right)$$

$$(4)$$

Where, MR is the moisture ratio, M is the moisture content at any time (g$_{warter}$/g$_{drysolid}$), M_e is the equilibrium moisture content of the sample (g$_{warter}$/g$_{drysolid}$), M_0 is the initial moisture content (g $_{water}$ g^{-1} $_{dry\ solid}$), and n= 1, 2, 3,… is the number of terms taken into attention. D_{eff} is the effective moisture diffusivity (m^2 s^{-1}) and r_0 is the radius of almond kernel (m).

Drying of almond kernels was performed in a long drying time. Therefore, according to Doymaz (2007), the first term of Equation (2) was enough for consideration in the calculations. The relationship was simplified as follows:

$$MR = \left(\frac{6}{\pi^2}\right)\exp\left(-\frac{\pi^2 D_{eff}t}{r_0^2}\right) \qquad (5)$$

After linearization, Equation (4) was achieved as follows (Tunde-Akintunde and Ogunlakin, 2011):

$$Ln(MR) = Ln\left(\frac{6}{\pi^2}\right) + \left(-\frac{\pi^2 D_{eff}t}{r_0^2}\right) \qquad (6)$$

The effective moisture diffusivity was calculated from the slope of the linear segment (K_1):

$$K_1 = \left(\frac{D_{eff}\pi^2}{r_g^2}\right) \qquad (7)$$

Where, r_g is the geometric mean radius.

Energy Consumption

Energy consumed in the infrared-vacuum dryer is the sum of energy consumed by the

vacuum pump and IR lamp used for warming the dryer chamber with the dried material. Energy consumption by vacuum pump can be computed using Equation (8) (Motevali *et al*., 2011). The vacuum pump in this dryer is 380W at 220V coated electric.

$$E_1 = L \times t \qquad (8)$$

Where, E_1 is the energy consumed by the pump (kWh), L is the nominal pump power (kW), and t is the total turning time of the pump (h). During the test on absolute pressure of 2 kPa, the pump was always on to provide the desired pressure and for other pressures to become on and off.

Rate of energy expenditure by the infrared lamps was constant at any given time and was obtained using Equation (7) (Motevali *et al*., 2011). The infrared lamp in this dryer was 100W at 220V coated electric.

$$E_2 = K \times t \qquad (9)$$

Where, E_2 represents the power consumption by the Infrared lamp (kWh), K is the nominal lamp power (kW), and t is the total operating time of lamp during drying of almond kernels (h).

Energy consumption of microwave was calculated using Equation (10) (Motevali *et al*., 2011).

$$E_3 = P_{MW} \times t \qquad (10)$$

Where, E_3 is the energy consumption of microwave (kWh), P_{MW} is the microwave power (kW), and t is the drying time (h) in microwave.

Total energy consumption (E_t) in infrared-vacuum with microwave pre-treatment drying is equal to:

$$E_t = E_1 + E_2 + E_3 \qquad (11)$$

Color

Almond kernels color coordinates (L* a* b*) before and after drying were measured using a flatbed scanner to measure the color, and the graphics software Photoshop to analyze the color. Color values of the pixels on the food surface was obtained by the term of ''measure'' using flatbed scanner. Manipulation of those color values to obtain color distribution, averages, and so on, was performed by the term of ''analyze'' using Photoshop. Similar to this method has been reported for the color of pizza (Yam and Papadakis, 2004).

$L*$ $a*$ $b*$ color space has conceptual uniformity property. The color space includes $L*$, $a*$ and $b*$. $L*$ layer indicates lightness that has a range of 0 to 100. Layers of $a*$ and $b*$ are in the range of -120 to 120. Positive values of $a*$ and $b*$ layers, respectively, represent red and yellow colors and negative values of $a*$ and $b*$ layers indicate green and blue colors. The total color difference ΔE was then determined using the following equation:

$$\Delta E = \sqrt{(L_0* - L_t*)^2 + (a_0* - a_t*)^2 + (b_0* - b_t*)^2}$$
$$(12)$$

Where, ΔE is the total color change, $\Delta L*$ is the lightness difference between before and after drying of almond kernels, $\Delta a*$ is the intensity of the red color, and $\Delta b*$ is the intensity of the yellow color.

Thirty samples in each test were scanned before and after drying and the obtained data were transferred to laptop core i5 with USB port. Then color mean values of *Lab* for thirty samples were computed by Adobe Photoshop CS6 software .

Response Surface Methodology (RSM)

A quadratic Central Composite Design (CCD) of three numerical factors (inlet air temperature, vacuum pressure, and microwave power) with three levels and five repetitions at the center point was used in this study. Table 1 shows the range of parameters. The first step in RSM is to find a suitable approximation for the true functional relationship between response and the set of independent variables. After determination of the targets and importance of the parameters that allow the results to be close, targets were also determined by

Table 1. Experimental domain of cCentral Composite Design (CCD).

Input parameters	Levels		
	-1	0	1
Inlet air temperature (°C)	45	60	75
Microwave power (W)	270	450	630
Vacuum pressure (kPa)	20	40	60

design expert software treatments using RSM. The software used to determine the suitability of recommended treatments based on desirability index. The Design Expert (version 7) software (Stat-Ease, Inc.,Minneapolis, MN) was used to obtain the response surfaces and the contours.

Genetic Algorithms (GA)

A GA program was developed in order to optimize the almond kernels drying process using RSM. The RSM model was unified with an effective GA to find the optimum point. In the present study, Genetic Algorithm for Optimization Toolbox (GAOT) in MATLAB environment was used to search for the optimal conditions of

drying of almond kernels in infrared-vacuum dryer with microwave pretreatment. To select the chromosomes, Roulette Wheel method was used. The crossover operator randomly selected two individuals as parents and exchanged part of their construction to form new individuals. For each selected pair, a two cut-point crossover operation was used to produce an offspring with the crossover probability. The mutation operator randomly selects one individual from the parent population and changes its internal representation and puts it in the child population.

RESULTS AND DISCUSSION

Optimization with RSM

The effects of three process variables i.e. inlet air temperature (X_1), microwave power (X_2), and vacuum pressure (X_3) were studied while conducting the experiments. The four responses of interest were shrinkage, effective moisture diffusivity, energy consumption, and total color change. The results of 20 runs using CCD design are presented in Table 2 which

Table 2. Results of experiments using CCD design.

Experiment	X_1 (Inlet air temperature) (°C)	X_2 (Microwave power) (W)	X_3 (Vacuum pressure) (kPa)	S_b (%)	D_{eff} (m² s⁻¹)	EC (kWh)	ΔE
1	1	0	0	13.63	4.25×10^{-9}	0.11	6.74
2	0	0	0	10.96	1.80×10^{-9}	0.19	6.07
3	1	-1	1	13.40	1.98×10^{-9}	0.15	5.86
4	0	0	0	10.85	1.95×10^{-9}	0.19	5.95
5	-1	-1	1	7.94	8.03×10^{-10}	0.15	3.91
6	-1	-1	-1	7.78	1.22×10^{-9}	0.26	2.61
7	1	1	1	14.14	5.17×10^{-9}	0.07	8.85
8	-1	1	-1	8.33	1.57×10^{-9}	0.21	7.07
9	0	0	0	10.98	1.90×10^{-9}	0.20	5.06
10	1	0	-1	10.81	2.51×10^{-9}	0.19	5.95
11	-1	1	1	8.66	9.55×10^{-10}	0.17	7.18
12	1	1	-1	14.06	5.33×10^{-9}	0.10	8.12
13	0	0	0	11.07	1.82×10^{-9}	0.19	7.55
14	-1	0	0	8.23	1.14×10^{-9}	0.22	5.88
15	1	-1	-1	13.26	3.11×10^{-9}	0.16	5.54
16	0	0	0	11.02	2.51×10^{-9}	0.19	6.85
17	0	0	0	10.94	2.64×10^{-9}	0.20	5.95
18	0	-1	0	10.52	1.52×10^{-9}	0.22	4.45
19	0	1	0	11.42	2.48×10^{-9}	0.15	7.68
20	1	0	1	11.17	1.30×10^{-9}	0.17	6.46

includes the design, observed responses and the predicted values. Results showed that there was a close agreement between experimental and predicted values. In addition, it was observed that the shrinkage ranged from 7.78% to 14.14%. The maximum shrinkage (14.14%) was found under the experimental conditions of X_1= 75°C, X_2= 630W, and X_3= 60 kPa. A wide range of effective moisture diffusivity was also observed (8.03×10^{-10}– 5.33×10^{-9} m^2 s^{-1}) and the maximum point (5.33×10^{-9} m^2 s^{-1}) was noticed in conditions of X_1= 75°C, X_2= 630W, and X_3= 20 kPa. The energy consumption ranged from 0.07 to 0.26 kWh. The highest energy consumption (0.26 kWh) value was found in conditions of X_1= 45°C, X_2= 270W and X_3= 20 kPa. The total color change ranged from 2.61% to 8.85%. The maximum total color change (8.85%) was found under the experimental conditions of X_1= 75°C, X_2= 630W and X_3= 60 kPa. These conditions seemed to vary depending on the required response. Therefore, an optimum process should be investigated in order to obtain the minimum value of shrinkage, energy consumption, and total color change and the maximum value of effective moisture diffusivity.

Tables 3-6 present the results of fitting quadratic models to the data. The results of Analysis Of Variance (ANOVA) indicated that the contribution of quadratic model was significant. The fitted quadratic model for shrinkage, effective moisture diffusivity, energy consumption, and total color change in coded variables is given in Equations (11), (12), (13) and (14), respectively. The significance of each coefficient was determined using the F-test and p-value as shown in Tables 3-6. The corresponding variables would be more significant if the absolute F-value becomes greater and the p-value becomes smaller (Atkinson and Doney, 2002).

Shrinkage

Variables with the largest effect on shrinkage were linear term of inlet air temperature (X_1) ($p<0.0001$) followed by linear term of microwave power (X_2) ($P< 0.0001$). Linear term of vacuum pressure (X_3) showed the significant effect on shrinkage ($P< 0.005$) (Table 3). However, the interaction terms (X_{12}, X_{13} and X_{23}) and quadratic terms (X_{11}, X_{22} and X_{33}) were found insignificant ($P> 0.05$). The results shown in Table 3 suggested that the change of inlet air temperature, microwave power, and vacuum pressure had significant effects on the shrinkage, however, there is no significant ($P> 0.05$) interaction effect of these parameters on the shrinkage. The coefficient of determination (R^2) of the predicted models in this response was 0.9991. This would give a good fit to the mathematical model in Equation (13).

$$S_b = -1.67 + 0.21T + 1.19 \times 10^{-3} P_{MW} + 6.42$$
$$\times 10^{-3} P_V + 1.19 \times 10^{-5} T P_{MW} - 1.12 \times 10^{-4} T P_V$$
$$+ 4.10 \times 10^{-6} P_{MW} P_V - 1.90 \times 10^{-4} T^2 - 1.80 \times$$
$$10^{-8} P_{MW}^2 + 4.74 \times 10^{-5} P_V^2$$

$$R^2 = 0.9991 \tag{13}$$

Where, T is the air temperature (°C), P_{MW} is the microwave power (W), and P_V is the vacuum pressure (kPa).

Three-dimensional (3-D) plots for shrinkage as a function of inlet air temperature and microwave power at different vacuum pressure conditions are presented in Figure 2-a. Increase in the inlet air temperature demonstrated an increase in the shrinkage (Figure 2-a). The effect of inlet air temperature also displayed linear increase at a range of 45–75°C. Increase in microwave power and vacuum pressure gave a slight increase in shrinkage value. The contours indicated that drying of almond kernels at low air temperature (45°C), low microwave power (270W) and low vacuum pressure (20 kPa) was necessary for minimum shrinkage value (7.78%). The results indicated that the shrinkage increased with increasing air temperature, microwave power, and a vacuum pressure but the effect of air temperature was more than the other parameters. Drying rate (velocity of water loss from the solid matrix), is the basic
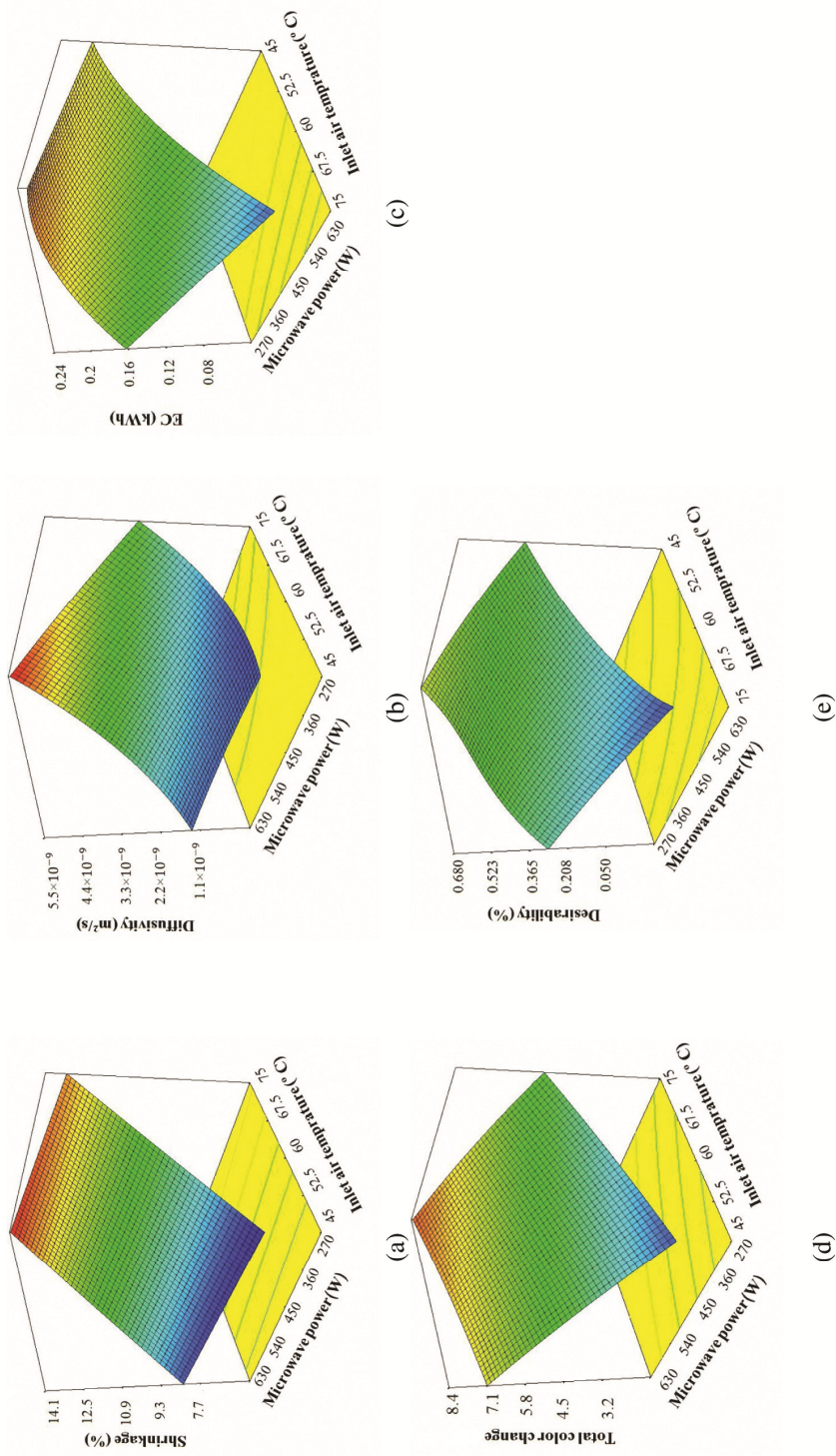
Figure 2. Effect of inlet air temperature and microwave power on (a) shrinkage, (b) effective moisture diffusivity, (c) energy consumption, (d) total color change, and (d) response variables.

Table 3. Results of fitting quadratic models to the data for shrinkage.

Source	Sum of squares	DF	Mean square	F-value	P-Value
Shrinkage					
Model	77.37	9	8.596122	1185.68	< 0.0001
(X_1) T^a	75.86	1	75.85703	10463.11	< 0.0001
(X_2) P$_{MW}$ ^{b}	1.37	1	1.367718	188.6521	< 0.0001
(X_3) P$_V$ ^{c}	0.12	1	0.115172	15.88597	0.0026
X_{12}	8.28×10^{-3}	1	0.008281	1.142198	0.3103
X_{13}	8.96×10^{-3}	1	0.008963	1.236317	0.2922
X_{23}	1.74×10^{-3}	1	0.001742	0.240281	0.6346
X_1^2	5.05×10^{-3}	1	0.005052	0.696833	0.4233
X_2^2	9.38×10^{-7}	1	9.38×10^{-7}	0.000129	0.9911
X_3^2	9.88×10^{-4}	1	0.000988	0.136274	0.7197
Residual	0.072	10	0.00725		
Cor Total	77.4376	19			

^{a} air temperature (°C), ^{b} microwave power (kW), ^{c} vacuum pressure (W), X, A, B and C are substitution parameters, DF is degree of freedom.

Table 4. Results of fitting quadratic models to the data for effective moisture diffusivity (EMD).

Source	Sum of squares	DF	Mean square	F-value	P-Value
EMD					
Model	3.05×10^{-17}	9	3.05×10^{-17}	28.77	< 0.0001
(X_1) T	2.00×10^{-17}	1	2.00×10^{-17}	170.25	< 0.0001
(X_2) P$_{MW}$	4.71×10^{-18}	1	4.71×10^{-18}	39.97	< 0.0001
(X_3) P$_V$	1.24×10^{-18}	1	1.24×10^{-18}	10.51	0.0088
X_{12}	3.00×10^{-18}	1	3.00×10^{-18}	25.47	0.0005
X_{13}	8.53×10^{-21}	1	8.53×10^{-21}	0.072	0.7933
X_{23}	7.47×10^{-20}	1	7.47×10^{-20}	0.63	0.4443
X_1^2	1.13×10^{-18}	1	1.13×10^{-18}	9.59	0.0113
X_2^2	1.07×10^{-20}	1	1.07×10^{-20}	0.091	0.7693
X_3^2	6.49×10^{-20}	1	6.49×10^{-20}	0.55	0.4749
Residual	1.18×10^{-18}	10	1.18×10^{-18}		
Cor Total	3.17×10^{-17}	19			

Table 5. Results of fitting quadratic models to the data for energy consumption.

Source	Sum of squares	DF	Mean square	F-value	P-Value
Energy consumption					
Model	0.037	9	4.11×10^{-3}	19.09	< 0.0001
(X_1) T	0.018	1	0.018	84.49	< 0.0001
(X_2) P$_{MW}$	5.68×10^{-3}	1	5.68×10^{-3}	26.4	0.0004
(X_3) P$_V$	4.30×10^{-3}	1	4.30×10^{-3}	20.01	0.0012
X_{12}	1.86×10^{-3}	1	1.86×10^{-3}	8.67	0.0147
X_{13}	1.68×10^{-3}	1	1.68×10^{-3}	7.79	0.0191
X_{23}	2.44×10^{-4}	1	2.44×10^{-4}	1.14	0.3115
X_1^2	1.86×10^{-3}	1	1.86×10^{-3}	8.63	0.0148
X_2^2	7.66×10^{-9}	1	7.66×10^{-9}	3.56×10^{-5}	0.9954
X_3^2	1.92×10^{-4}	1	1.92×10^{-4}	0.89	0.3671
Residual	2.15×10^{-3}	10	2.15×10^{-4}		
Cor Total	0.039	19			

Table 6. Results of fitting quadratic models to the data for total color change.

Source	Sum of squares	DF	Mean square	F-value	P-Value
Total color change					
Model	36.1561	9	4.017344	9.057833	0.0010
(A) T	7.164524	1	7.164524	16.15372	0.0024
(B) P$_{MW}$	27.35574	1	27.35574	61.67849	< 0.0001
(C) P$_V$	0.878327	1	0.878327	1.980348	0.1897
AB	0.580557	1	0.580557	1.308972	0.2792
AC	0.016664	1	0.016664	0.037571	0.8502
BC	0.07412	1	0.07412	0.167118	0.6913
A^2	0.019361	1	0.019361	0.043654	0.8387
B^2	0.065337	1	0.065337	0.147315	0.7091
C^2	0.000985	1	0.000985	0.002222	0.9633
Residual	4.435216	10	0.443522		
Cor Total	40.59132	19			

parameter for the determination of shrinkage. A cellular structure behaves according to the velocity of water loss from the cell. Air temperature is the main factor in drying rate value (Hatamipour and Mowla, 2002). The decrease in apparent volume of solid due to higher air temperature is similar to the volume of water loss during the process, which may mean that the rate of water loss is responsible for the decrease in solid volume (Frias *et al.*, 2010).

It can be seen that the volume shrinkage became more severe at higher vacuum chamber pressures. This phenomenon could be explained as follows: when water was removed from the material during drying, a pressure unbalance was generated between the interior of the dried material and the external environment that induced the contracting stresses which led to drying shrinkage (Wu *et al.*, 2007). Shrinkage increased with increasing microwave power, probably due to the reason that entering higher microwave power causes faster mass transfer in almond kernels, accordingly, the product becomes more shrinked. Usually, continuous microwave volumetric heating increases internal pressure and reduces shrinkage due to the puffing effect. However, in this study, microwave heating was applied alternately as a pretreatment at the very beginning of the process of drying when the amount of water was relatively high. Fast water transfer can be considered as a factor responsible for structural changes which enhance shrinkage. Probably, the increase in microwave power would decrease the shrinkage, if microwave drying was applied as a final step of drying.

Effective Moisture Diffusivity (EMD)

Variables with the largest impact on EMD were the linear term of inlet air temperature (X_1) (P< 0.0001) and the linear term of microwave power (X_2) (P< 0.0001). Linear term of vacuum pressure (X_3) (P< 0.05) and the interaction term between inlet air temperature and microwave power (X_{12})

(p<0.05) also showed significant effects on EMD (Table 4). Interaction term between inlet air temperature and vacuum pressure (X_{13}), interaction term between microwave power and vacuum pressure (X_{23}) and the quadratic terms (X_{11}, X_{22} and X_{33}) were not significant (P> 0.05). The coefficient of determination (R^2) of the predicted models in this response was 0.9628, suggesting a good fit to the mathematical model [Equation (14)].

$$D_{eff} = 1.10 \times 10^{-8} - 3.45 \times 10^{-10} T - 9.14 \times 10^{-12} P_{MW} + 7.58 \times 10^{-12} P_V + 2.27 \times 10^{-13} TP_{MW} - 1.09 \times 10^{-13} TP_V + 2.68 \times 10^{-14} P_{MW} P_V + 2.85 \times 10^{-12} T^2 - 1.92 \times 10^{-15} P_{MW}^2 - 3.84 \times 10^{-13} P_V^2$$
$$R^2 = 0.9628 \tag{14}$$

EMD values as a function of inlet air temperature and microwave power at different vacuum pressure conditions are presented in Figure 2-b. Results indicated that increase in the inlet air temperature demonstrated an exponential increase in the *EMD* (Figure 2-b). Increase in microwave power and decrease in vacuum pressure gave a slight degree of increase in *EMD*. It was also observed that increase in inlet air temperature and microwave power, caused an increase in the *EMD*. Maximum value of *EMD* (5.33×10^{-9} m^2 s^{-1}) for almond kernel drying was achieved at air temperature of 75°C, vacuum pressure of 20 kPa and

microwave power of 630 W. Air temperature had greater effect on *EMD* values of almond kernels. It is explicit that *EMD* value increased as the air temperature increased. Applying higher

value of microwave power caused higher temperature level in almond kernel. Higher microwave power similar to the air temperature led to higher heat transfer rate to the kernels. As a result, mass transfer, especially in the constant period, was extremely high. A similar effect of air temperature on moisture diffusivity during drying has already been found in berberis fruit (Aghbashlo *et al.,* 2008), Asian white

radish (Lee and Kim, 2009) and sweet potato (Doymaz, 2011).

Energy Consumption

The variable with the significant effect on energy consumption was the linear term of inlet air temperature (X_1) (P< 0.0001). In terms of energy consumption, it can be observed that linear term of inlet air temperature (X_1) (P< 0.0001), linear term of microwave power (X_2) (P< 0.01), linear term of vacuum pressure (X_3) (P< 0.01), interaction term between inlet air temperature, and microwave power (X_{12}) (P< 0.05), interaction term between inlet air temperature and vacuum pressure (X_{13}) (P< 0.05), and quadratic term of inlet air temperature (X_{11}) (P< 0.05) had significant effects on energy consumption. Interaction term between microwave power and vacuum pressure (X_{23}) and quadratic terms of microwave power (X_{22}) and quadratic term of vacuum pressure (X_{33}) were not significant (P> 0.05) (Table 5). The coefficient of determination (R^2) of the predicted models in energy consumption was 0.9450, which is a good fit to the mathematical model [Equation (15)].

Energy consumption as a function of inlet air temperature and microwave power at different vacuum pressure conditions are shown in Figure 2-c. Increase in inlet air temperature demonstrated an exponential

$$EC = 5.57 \times 10^{-3} + 0.01T + 1.44 \times 10^{-4} P_{MW}$$
$$-2.95 \times 10^{-3} P_V - 5.65 \times 10^{-6} TP_{MW} + 4.82 \times$$
$$10^{-5} TP_V + 1.53 \times 10^{-6} P_{MW} P_V - 1.15 \times 10^{-4} T^2$$
$$+1.63 \times 10^{-9} P_{MW}^2 - 2.09 \times 10^{-5} P_V^2$$
$$R^2 = 0.9450 \qquad (15)$$

decrease in energy consumption (Figure 2-c). It was also observed that increase in inlet air temperature, vacuum pressure, and microwave power decreases energy consumption. Optimum energy consumption (0.07 kWh) was developed at air temperature of 75°C, vacuum pressure of 60 kPa and microwave power of 630 W. With

decreasing air temperature, total energy consumption increased because the turning on of the infrared lamp and pump related to total drying time was increased. Similar results were reported in some previous studies (Aghbashlo *et al.,* 2008; Motevali *et al.*, 2011; Tunde-Akintunde and Ogunlakin, 2011).

Total Color Change

The variable with the largest effect on total color change was the linear term of microwave power (X_2) (P< 0.0001). Linear term of inlet air temperature (X_1) (P< 0.005) and linear term of microwave power (X_2) showed significant effect on total color change (Table 6). However, linear term of vacuum pressure (X_3), the interaction terms $(X_{12}, X_{13}$ and $X_{23})$ and quadratic terms $(X_{11}, X_{22}$ and $X_{33})$ were found insignificant (P> 0.05). These results indicated that the change of inlet air temperature and microwave power had significant effects on total color change. The coefficient of determination (R^2) of the predicted models in this response was 0.8907. This would give a good fit to the mathematic model in Equation (16).

$$\Delta E = -5.12 + 0.06T + 0.02 P_{MW} + 0.04 P_V$$
$$-9.98 \times 10^{-5} TP_{MW} - 1.52 \times 10^{-4} TP_V - 2.67$$
$$\times 10^{-5} P_{MW} P_V + 3.73 \times 10^{-4} T^2 - 4.76 \times 10^{-6} P_{MW}^2$$
$$-4.73 \times 10^{-5} P_V^2$$
$$R^2 = 0.8907$$

Total color change as a function of inlet air temperature and microwave power at different vacuum pressures is shown in Figure 2-d. Increase in microwave power demonstrated an increase in total color change (Figure 2-d). Increase in air temperature gave a slight increase in total color change. Increase in vacuum pressure, increased total color change. The optimum condition for minimum total color change (2.61) occurred at air temperature of 45°C, vacuum pressure of 20 kPa and microwave power of 270 W. It is evident that drying at

higher temperatures and microwave powers yielded greater total color change than drying at lower temperatures and microwave powers. This is because enzymatic browning reactions were accelerated by temperature and microwave power. Total color change increased with an increase of vacuum pressure. It can be explained by the fact that less oxygen was present in the drying chamber under low pressure. This led to less enzymatic browning reaction which is the main cause of the color changes of the dried almond kernels (Artnaseaw *et al.,* 2010).

Based on the above-mentioned findings, an optimization study was performed to evaluate the optimal operating conditions for the shrinkage, *EMD*, energy consumption as well as total color change. Several combinations were found to optimize these responses taking into consideration the desirability and feasibility of the experiment. These are given in Table 7. The optimal conditions for desired shrinkage, *EMD*, energy consumption and total color change corresponded to inlet air temperature of 45 °C, vacuum pressure of 34.04 kPa and microwave power of 270W with 68% desirability (Figure 2-e). At this optimum condition, shrinkage of 7.80%, *EMD* of 1.29×10^{-9} m^2 s^{-1}, energy consumption of 0.23 kWh, and total color change of 3.26% were achieved.

Optimization with GA

The fitness functions [Equations (13-16)] used to evaluate the fitness values of each individual extrudate property was the second-order polynomial regression equation obtained using RSM. Random populations of 30 chromosomes were generated. Selection of good chromosomes was based on fitness values at a crossover probability of 0.95 and mutation rate of 0.15. The search was stopped after 2000 iterations and the corresponding results were displayed. Optimum point for drying almond in vacuum-infrared dryer with microwave pretreatment and GA method attention to minimum value of shrinkage, energy consumption and total color change and maximum value of *EMD* was achieved at air temperature of 45°C, vacuum pressure of 34.05 kPa, and microwave power of 270 W. With respect to the obtained results with RSM method, the GA approach was found to be a useful tool to find the global optimum point for drying almond in vacuum-infrared dryer with microwave pre-treatment.

CONCLUSIONS

In this study, almond kernels drying process in infrared-vacuum dryer with

Table 7. Number of combinations of variables that could give levels of responses with high desirability.

Number	Air temperature (°C)	P_V (kPa)	P_{MW} (W)	S_b (%)	D_{eff} (m^2/s)	EC (kWh)	ΔE	Desirability
1	45	34.04	270	7.80	1.28×10^{-9}	0.23	3.26	0.68
2	45	34.33	270	7.80	1.28×10^{-9}	0.23	3.27	0.68
3	45	33.44	270	7.80	1.29×10^{-9}	0.23	3.25	0.68
4	45	33.2	270	7.79	1.30×10^{-9}	0.23	3.24	0.68
5	45	32.39	270	7.79	1.31×10^{-9}	0.23	3.22	0.679
6	45	33.65	270.87	7.80	1.29×10^{-9}	0.23	3.26	0.679
7	45	38.23	270	7.82	1.21×10^{-9}	0.22	3.35	0.677
8	45	32.53	276.19	7.80	1.31×10^{-9}	0.23	3.30	0.676
9	45	39.37	270	7.83	1.19×10^{-9}	0.22	3.38	0.676
10	45	27.21	270.06	7.76	1.38×10^{-9}	0.24	3.10	0.673

microwave pretreatment were performed at the drying air temperatures of 45, 60, and 75°C, microwave powers of 270, 450, and 630 W and vacuum pressures of 20, 40, and 60 kPa. RSM and GA successfully indicated the relationship between the input and output parameters. Optimum point for drying of almond kernels in infrared-vacuum dryer with microwave pretreatment using RSM method with regard to minimum value of shrinkage, energy consumption, and total color change and maximum value of effective moisture diffusivity were achieved at air temperature of 45°C, vacuum pressure of 34.04 kPa, and microwave power of 270W with 68% desirability. Furthermore, optimum condition with genetic algorithm was obtained at air temperature of 45°C, vacuum pressure of 34.05 kPa, and microwave power of 270W.

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بهینه‌سازی فرآیند خشک‌کردن مغزبادام در شرایط خلائی مادون قرمز با پیش‌تیمار میکروویو با استفاده از روش بهینه‌سازی سطح پاسخ و الگوریتم ژنتیک

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چکیده

هدف از این مطالعه، بهینه‌سازی فرآیند خشک‌کردن مغزبادام در خشک‌کن خلائی مادون قرمز با پیش‌تیمار میکروویو با استفاده از روش بهینه‌سازی سطح پاسخ و الگوریتم ژنتیک است. دانه‌های مغزبادام به صورت لایه نازک با درجه حرارت هوای ۴۵، ۶۰ و ۷۵ درجه سلسیوس، با فشارهای خلاء ۲۰، ۴۰ و ۶۰ کیلوپاسکال و توان‌های میکروویو ۲۷۰، ۴۵۰ و ۶۳۰ وات خشک شدند. برای تعریف آزمایش‌ها، تحلیل آماری و مدل‌های رگرسیونی از نرم‌افزار دیزاین اکسپرت ورژن هفت استفاده شد. نتایج نشان داد که شرایط بهینه برای خشک‌کردن مغزبادام در خشک‌کن خلائی مادون قرمز با پیش‌تیمار میکروویو در نرم‌افزار دیزاین اکسپرت با توجه به کمترین مقدار چروکیدگی، انرژی مصرفی و تغییرات کلی رنگ و بیشترین مقدار برای ضریب پخش رطوبت موثر می‌تواند در درجه حرارت هوای ۴۵ درجه سلسیوس، فشار خلاء ۳۴/۰۴ کیلوپاسکال و توان میکروویو ۲۷۰ وات با شاخص مطلوبیت ۶۸٪ پیشنهاد شود. همچنین نقطه بهینه بدست آمده توسط الگوریتم ژنتیک می‌تواند در درجه حرارت هوای ۴۵ درجه سلسیوس، فشار خلاء ۳۴/۰۵ کیلوپاسکال و توان میکروویو ۲۷۰ وات باشد.