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Research Article

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Posted Date: January 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-138330/v1>

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Version of Record: A version of this preprint was published at Scientific Reports on April 28th, 2021. See the published version at <https://doi.org/10.1038/s41598-021-88270-z>.

Estimation of Moisture Ratio and Specific Energy Consumption for Apple Slices Drying by Convective and Microwave Methods using Neural Network Modeling

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Abstract: Two different drying methods were applied for dehydration of apple, i.e., convection drying (CD) and microwave drying (MD). The process of convection drying through divergent temperatures; 50, 60 and 70 °C at 1.0 m/s air velocity and three different levels of microwave power (90, 180, and 360 W) were studied. In the analysis of the performance of our approach on moisture ratio of apple slices, artificial neural networks (ANNs) was used to provide with a background for further discussion and evaluation. In order to evaluate the models mentioned in the literature, the Midilli et al. model was proper for dehydrating of apple slices in both MD and CD. The microwave drying technology enhanced the drying rate when compared with convective drying significantly. Effective diffusivity of moisture in CD drying (1.95×10^{-7} - 4.09×10^{-7} m²/s) was found to be lower than that observed in MD (2.94×10^{-7} - 8.21×10^{-7} m²/s). The Ea values of convective drying and microwave drying were 122.28- 125 kJ/mol and 14.01- 15.03 W/g respectively. The MD had the lowest SEC as compared to CD drying methods. According to ANN results, the best values for predication of MR in CD and MD were 0.9993 and 0.9990, respectively.

Keywords: Apple; Energy consumption; Drying; Modeling; Artificial neural network;

Nomenclature

MC	Moisture content ($\text{g}_{\text{water}}/\text{g}_{\text{dry matter}}$)	D_0	Constant number
W_x	Initial weight of sample (g)	P	Output power of microwave (W)
W	Amount of evaporated moisture (g)	$E_{a(m)}$	Energy of activation in MD method (W/g)
W_y	Dry matter content of sample (g)	m	Weight of raw sample (g)
M_t	MC at any time ($\text{kg}_{\text{water}}/\text{kg}_{\text{dry matter}}$)	SEC_{mic}	Specific energy consumption in MD method
M_e	Equilibrium MC	P_{mic}	Microwave output power (W)
M_0	Initial MC ($\text{kg}_{\text{water}}/\text{kg}_{\text{dry matter}}$)	t_1	Drying time (s)
R^2	Coefficient of determination	m_w	Mass of evaporated water (kg)
$RMSE$	Root mean square error	SEC_{con}	Specific energy consumption in CD method
χ^2	Chi square	C_{pv}	Vapor specific heat capacity ($1004.16 \text{ J}/(\text{kg}^\circ\text{C})$)
$MR_{exp,i}$	Experimental value	C_{pa}	Air specific heat capacity ($1828.8 \text{ J}/(\text{kg}^\circ\text{C})$)
$MR_{pre,i}$	Predicted value	Q	Inlet air to drying chamber (m^3/min)
N	Number of observations	t_2	Total drying time (min)
Z	Constants	h_a	Absolute air humidity ($\text{kg}_{\text{vapor}}/\text{kg}_{\text{dry air}}$)
D_{eff}	Effective moisture diffusivity (m^2/s)	T_{in}	Inlet air to drying chamber temperature ($^\circ\text{C}$)
M	Material MC ($\text{kg}_{\text{water}}/\text{kg}_{\text{dry matter}}$)	T_{am}	Ambient air temperature ($^\circ\text{C}$)
L	Half of the slab thickness (m)	m_v	Mass of removal water (kg)
i	Positive integer	V_h	Specific air volume (m^3/kg)
t	Drying time (s)	ΔE	Total color differences
$E_{a(c)}$	Energy of activation in CD method (kJ/mol)	ΔL^*	Lightness difference
R_g	Universal gas constant ($8.3143 \text{ kJ}/\text{mol}$)	Δa^*	Intensity of the color red
T_a	Absolute air temperature (K)	Δb^*	Intensity of the color yellow
U_n	Normalized value		
U_R	Actual value		
$U_{\max}$	Maximum of the actual value		
$U_{\min}$	Minimum of the actual value		

1. Introduction

Apple (*Malus domestica* Borkh.) is one of the oldest fruits known to mankind and has grown to nourish it. It is one of the most important horticultural products in the world, and countries such as China, the United States, Turkey, Poland, India, the Russian Federation and Iran are considered as major apple producers. Apples, like many other fruits, have a high water content (80–85% on w.b.). Apple is rich in vitamins, minerals and fiber and is usually consumed raw, but it is used in many foods (especially desserts) and beverages^{1,2,3}. Drying, in addition to being a way to increase the shelf life of foods, is known as a way to increase the value added of food products. Removing water from a product under controlled conditions reduces the moisture content of the food to a certain extent, which lessens the activity of enzymes, the rate of undesirable chemical changes and microbial growth. Also, the decrease in moisture is accompanied by a reduction in volume and weight, which is one of the important factors for transportation and maintenance⁴. Throughout the decades, hot air drying method has been one of the most long-established technologies in the food industries. The process of hot air drying includes both the heat and mass transfer while the water is provided by the agricultural products through diffusion. However the total energy of this diffusion goes hand in hand with air temperature, time and air velocity⁵. One of the methods that has been given a lot of attention during the last decade is drying using microwave radiation. Microwave beams are electromagnetic beams with a long wavelength of 2450 MHz. During the passing of these waves from the tissue of matter, polar molecules, such as water and salts, vibrate, and this vibration causes the microwave energy to be converted into heat. Unlike other methods of drying, in which heat should penetrate from the surface to depth, in this method heat is produced in the tissue of the food itself and it is prevented from damaging the superficial parts of the food^{6,7}. Different methods are used to reduce the moisture content of fruits and vegetables. Izli and Isik⁸ used microwave, convective, and microwave-convective dryers to dry tomatoes. They showed that microwave-convective dryers require less time to dry tomatoes. Seremet et al.⁹ investigated effect of different drying methods (Hot air convection and hot air convection- microwave dryer) on weight loss and rehydration of sliced pumpkin. Drying of sorbus fruits by convective (50°C and 70°C at air velocity of 0.3 m/s) and microwave (90, 160 and 350 W) were studied in order to determine the drying behaviors. The results showed that the temperature of 50 °C and the microwave power of 90 W had the slightest variations in color. Also, the lowest specific energy consumption were 0.69 kWh/kg and 37.07 kWh/kg respectively at 70°C and 350 W¹⁰. The correlation of the unpredictable input and output process parameters interconnection follows the stimulated computing approach named Artificial Neural Network (ANN)¹¹. ANNs are capable of modeling nonlinear and complex systems with a large number of input and output data. The ability to predict a neural network is completely dependent on its structure (type of activation function, number of layers and number of hidden layer neurons)^{12,13}. In recent years, methods based on ANNs have been

used to predict the moisture content of many food and agriculture products during the drying process, including green peas, tomatoes, corn and pomegranate seeds¹⁴⁻¹⁷. In this research, the neural network modeling method was used to estimate the moisture ratio of apple slices during drying in microwave and hot air dryer. The results of this model are compared with the results of mathematical modeling to determine its effectiveness. Also, moisture diffusion coefficient, activation energy, specific energy consumption and color changes were also determined for apple slices.

2. Material and methods

2.1. Sample preparation

Apple was supplied from one of apple orchards of Ardabil city, Iran, in September 2016. Generally, apple samples of uniform sizes were selected. The apple fruit were cleaned and stored in a refrigerator at $4\pm1^{\circ}\text{C}$. The premature and spoiled apple was separated manually. The initial MC of apple slices was measured by oven drying method. Apple slices to the nearest 40 g (4 mm thickness and 36 mm diameter) in triplicate samples were dehydrated at $70\pm1^{\circ}\text{C}$ for 24 h¹⁸. Apple fruit with average initial MC of 45% (d.b.) was selected for drying material.

2.2. Experimental procedure

2.2.1. Convective dryer

Convective drying (CD) was conducted by using laboratory drying oven (BF55E; FG Co., Iran). The velocity of the air approaching to the apple samples was measured by an anemometer (Lutron AM-4202; Electronic Enterprise Co., Taipei, Taiwan) with ± 0.1 m/s accuracy and the average air velocity was 1.2 ± 0.02 m/s. Electrical heating unit of this dryer equipped with PT100 thermometer sensor and PID controller with $\pm 0.1^{\circ}\text{C}$ accuracy. Average humidity and air temperature of ambient air during convection dryer were 30% and 26°C , respectively.

2.2.2. Microwave dryer

A fully programmable microwave oven (Panasonic NN-CD997S Microwave Oven) with maximum output of 1000 W was utilized for this study. The microwave oven has the capability of operating at different microwave output powers, 90, 180, 270, 360, 450, 540, 630, 720, 900 and 1000 W. The microwave drying area is 462 mm, 242 mm and 412 mm inner size and includes a 380 mm diameter rotary glass plate at the oven base. The microwave output power and processing time was set fully by using digital control panel of microwave oven.

2.3. Experimental setup

2.3.1. Determination of moisture ratio

Drying curves may be represented in different ways; MC (wet and dry base) versus time, drying rate versus time, or drying rate versus MC. The MC of apple was calculated by using Equation 1¹⁹; Equation 2 was used for calculating the moisture ratio of apple slices²⁰:

$$MC = \frac{((W_x - W) - W_y)}{W_y} \quad (1)$$

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \quad (2)$$

It should be noted that due to the insignificant value of M_e in comparison with M_t and M_0 , it can be saved, Therefore Equation 2 can be simplified to Equation 3²¹:

$$MR = \frac{M_t}{M_0} \quad (3)$$

2.3.2. Mathematical modelling of drying curves

The models listed in Table 1 were used for mathematical modeling drying kinetics of apple slice in MD and CD. To compare the data to each model, curve expert was used for curve fitting. This software has linear and nonlinear regression models and various interpolation methods. In order to select the suitable drying kinetics descriptor, the statistical parameters of R^2 , $RMSE$ and χ^2 were used. Finally, the drying model with maximum R^2 and minimum $RMSE$ and χ^2 was selected as the appropriate model for describing drying kinetics. The mentioned statistical parameters are defined by the following equations^{22,23}:

$$R^2 = 1 - \frac{\sum_{i=1}^N [MR_{exp,i} - MR_{pre,i}]^2}{\sum_{k=1}^N \left[\frac{\sum_{i=1}^n MR_{pre,i}}{N} - MR_{pre,i} \right]^2} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (5)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{\frac{1}{2}} \quad (6)$$

Exponential equation form of Equation 2 can be used as follows²⁴:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \exp(-kt^n) \quad (7)$$

Table 1. Mathematical empirical drying models given by various authors for the drying curves

Models	Equation	References
Midilli <i>et al.</i>	$MR = a \exp(-kt^n) + bt$	25
Page	$MR = \exp(-kt^n)$	26
Logistic	$MR = a / (1 + b \exp(kt))$	27
Two-term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	28
Logarithmic	$MR = a \exp(-kt) + c$	29

2.3.3. Effective moisture diffusivity

Mass transfer during food drying is a complex process involving various mechanisms such as molecular penetration, movement in capillary tubes, and liquid penetration in the porous materials, penetration of vapor in air pores and hydrodynamic flow, or surface propagation. Moisture penetration is one of the most important factors controlling the drying process. When different mechanisms are effective in transmitting, it is difficult to examine each mechanism and measure the mass transfer rate in each one. Hence, in such processes, the description of effective diffusion is used and its concept is described by the Fik's second law as follows³⁰:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (8)$$

Calculation of effective diffusion coefficient using the Fik's second law is a tool for describing the drying process and possible mechanisms for the transfer of moisture within food products. The analytical solution of Fik's law is as follows³¹:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left(-\frac{(2i+1)^2 \pi^2}{4L^2} D_{eff} t\right) \quad (9)$$

Where i is a positive integer that is equal to 1 for long drying time. Therefore, Equation 9 can be written in simpler form as Equation 10:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (10)$$

The coefficient K_1 is calculated by plotting the curve $\ln(MR)$ versus time, in accordance with Equation 11 as follows³²:

$$K_1 = \left(\frac{D_{eff} \pi^2}{4L^2}\right) \quad (11)$$

2.3.4. Activation energy

Dependence of the diffusion coefficient with temperature is shown using the Arrhenius equation (Equation 12). Activation energy of the convective dryer ($E_{a(c)}$) was determined by plotting the effective moisture diffusion coefficient curve versus absolute air temperature reversal³³.

$$D_{eff} = D_0 \exp\left(\frac{E_{a(c)}}{R_g T_a}\right) \quad (12)$$

The linear form of Equation 12 can be obtained by applying the logarithms as:

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_{a(c)}}{R_g} \cdot \frac{1}{T_a}\right) \quad (13)$$

K_2 can be obtained by plotting $\ln(D_{eff})$ versus $\frac{1}{T_a}$:

$$K_2 = \frac{E_{a(c)}}{R_g} \quad (14)$$

Linear regression analyses were used to fit the equation to the experimental data to obtain correlation coefficient (R^2).

The activation energy for microwave dryer ($E_{a(m)}$ (W/g)) was calculated by using a correlation between effective moisture diffusivity and ($\frac{m}{P}$) is taken into account³⁴.

$$D_{eff} = D_0 \exp\left(-\frac{E_{a(m)}m}{P}\right) \quad (15)$$

$E_{a(m)}$ may be accomplished using one of several methods as follows:

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_{a(m)}}{P} \cdot m\right) \quad (16)$$

Following plotting of $\ln(D_{eff})$ versus $(1/P)$, K_3 is calculated for the microwave as follows:

$$K_3 = \frac{E_{a(m)}}{P} \quad (17)$$

2.3.5. Specific energy consumption

The specific energy consumed during the drying process, which is the amount of energy used to evaporate one kilogram of water from the product, was obtained using Equation 18 under microwave drying method³⁵:

$$SEC_{mic} = 60 \frac{P_{mic} t_1}{m_w} \quad (18)$$

Specific energy consumption (SEC_{con}) of apple slice in CD approach was measured through the Equation 19 as follows^{36,37}:

$$SEC_{con} = (C_{pa} + C_{pv}h_a)Qt_2 \frac{(T_{in} - T_{am})}{m_v V_h} \quad (19)$$

2.3.6. Color

Three color schemes, including RGB, CMYK and Lab, are used to determine the color of food. The Lab model is often used for food color research studies. L demonstrates brightness in the range 0-100, and two colored components (-120 - +120) including a (greenness to redness) and b (blueness to yellowness). The color parameters of apple slice were measured using digital portable colorimeter (CR-10-PLUS, Konica Minolta Co, Japan), appropriate test method based on CIELAB. Total color changes (ΔE) was calculated using Equation 20. All color changes were obtained with averaging in six replicates samples^{38,39}:

$$\Delta E = [(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2]^{0.5} \quad (20)$$

2.3.7. ANN

ANN was used for modeling the drying process of apple slice in microwave and hot air dryer to predict MR by using Matlab software. In this research, the Levenberg-Marquard optimization method was used to learn the network. The inputs for ANN model are drying time, and drying chamber inlet air temperature, and the output is MC variations of apple slice. Figure 1 shows ANN inputs and output structure with two hidden layers.

Figure 1. Four-layer ANN inputs and output structure used in this study

2.3.7.1. Convective dryer

Apple slice drying experiments were done at 50, 60 and 70°C set temperature. The two input parameters had applied in the experiments with convective dryer. The moisture ratio (MR) values were derived. Networks with two neurons in the input layer (air temperature and drying time) and one

neuron in the output layer (MR) were designed. In this part, the total data of, moisture ratio (163 data) for artificial neural networks were used. In the first group, 70% (115 data) were taken for training phase and in the second group 30% (48 data) for testing, chosen randomly from the set of 163 data.

2.3.7.2. Microwave dryer

Applying the two inputs in all experiments, the moisture ratio values obtained for different conditions. Networks with two neurons in input layer (microwave power and drying time) and one neuron in output layer (MR) were designed. About 70% (49 data) of the all experimental data (70 data) were separated for network training to find suitable structure. Prior to training the neural network, input data normalized to it. The purpose of normalizing is to convert data between zero and one. Therefore, the following equation was used for normalization⁴⁰:

$$U_n = \frac{U_R - U_{\min}}{U_{\max} - U_{\min}} \quad (21)$$

In order to evaluate the accuracy and performance of the developed models of artificial neural networks, the statistical criteria of the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE) were used. The mentioned statistical parameters calculated using the following equations⁴¹:

$$MSE = \frac{1}{mq} \sum_{p=1}^m \sum_{i=1}^q (S_{ip} - T_{ip})^2 \quad (22)$$

$$R^2 = 1 - \frac{\sum_{k=1}^m [S_k - T_k]}{\sum_{k=1}^m \left[S_k - \frac{\sum_{k=1}^n S_k}{n} \right]} \quad (23)$$

$$MAE = \frac{100}{n} \sum_{k=1}^m \left| \frac{S_k - T_k}{T_k} \right| \quad (24)$$

3. Results and discussion

3.1. Drying characteristics (Convective and microwave drying kinetics)

Changes in moisture ratio of apple slice with drying time at different air temperatures 50, 60, and 70°C and air velocity 1 m/s were presented in Figure 2a. The drying experiments of apple slices continued until the moisture content of the samples reached about 0.18 (d.b.) in both drying methods. As can be seen in Figure 2a, increase of air temperature from 50 to 70 °C causes a decrease on final product drying time, which is consistent with the results of Beigi⁴² and Kaleta et al.⁴³. In the process of convective drying, increasing air temperature from 50 to 70 °C resulted to increase in mass transfer, reduce process time and energy consumption⁴⁴. Drying time for apple slice in air velocity 1 m/s, were 200, 150 and 100 min at 50, 60 and 70°C, respectively. Kara and Doymaz⁴⁴ reported that the drying times of apple pomace at air velocity 1 m/s for four air temperatures 50, 60, 70 and 80°C. An

increment in air temperature caused also a decrease in drying time at apple pomace. Beigi⁴² reported that air temperature had a shorter effect on drying time in Hot air drying of apple slices at 1.5 m/s air velocity 50, 60 and 70°C. Effect of air temperature (50, 65, 80 and 90°C), three levels of drying product thickness (3,5, and 7 mm), engine load levels (25, 50, 75, and 100%), and air velocity (1 m/s) on moisture ratio of apple slices in combined heat and power (CHP) dryer have been investigated by Samadi et al.⁴⁵. With increasing of air temperature in the tested range, the amount of moisture removed from apple slices increased.

Changes in MR of apple slice with drying time in microwave dryer at different microwave power (90, 180 and 360 W) were shown in Figure 2b. As shown in Figure 2b, it can be seen that the rate of water loss in MD method was higher than CD, due to the electromagnetic heating effect of microwave in drying food products⁴⁶. Also, with higher microwave power, more heat generated within the sample created a larger vapor pressure difference between the center and the product surface. Thus accelerated the interior moisture migration and increased surface water evaporation⁴⁷.

Figure 2. Moisture ratio versus drying time for apple slice under different drying: a) air temperature ((♦) 50 °C, (●) 60 °C, (▲) 70 °C); b) microwave powers ((♦) 90 W, (●) 180 W, (▲) 360 W)

The times of the drying process in MD were 50, 80 and 130 min at 360, 180 and 90 W, respectively. The results showed that with increasing microwave power, the drying time had a downward trend. Similar results were obtained for drying crops in a microwave dryer such as pomegranate arils⁴⁸, mushroom, tomatoes⁸ and broccoli stalk slice⁴⁹.

In order to mathematical modeling of apple slice drying kinetics in the convective dryer, five commonly mathematical models for thin layer products were used (Table 1). For all convective drying experiments (50, 60 and 70°C air temperature and 1 air velocity), determination coefficient (R^2), root mean square error ($RMSE$), and reduced Chi square (χ^2) values ranged between 0.9932–0.9999, 0.0172–0.0845 and 0.0003–0.0468, respectively. From Table 2, Midilli et al. model had the highest R^2 (0.9994– 0.9999) and the lowest $RMSE$ (0.0194– 0.0274) and χ^2 (0.0004– 0.0041) values. Therefore, the Midilli et al. drying model was achieved as appropriate one for describing drying behaviors of apple slices. Chayjan et al.⁵⁰ tested five empirical models (Midilli et al., Demir et al.,

Logistics, Logarithmic and Wang and Singh) in their research for continuous band drying of eggplant slices and claimed that all models described well drying kinetics at studied air temperatures, air velocities and infrared power. Midili et al. model was chosen as the best model for describing the moisture ratio of the sour cherry. Torki-Harchegani et al.⁵¹ examined the kinetics of drying lemon slices in convective dryer at 50, 60 and 75°C air temperature. Their results showed that the drying temperature had a significant effect on the drying time and drying rate. Among the models used, the Midilli et al. model was proposed as the best model for prediction moisture content of lemon slices.

Table 2. The statistical comparison for prediction drying of apple slices in convective dryer

Model	R^2			χ^2			$RMSE$		
	50 °C	60 °C	70 °C	50 °C	60 °C	70 °C	50 °C	60 °C	70 °C
Midili et al.	0.9999	0.9998	0.9998	0.0003	0.0009	0.0010	0.0172	0.0211	0.0221
Page	0.9998	0.9998	0.9996	0.0007	0.0011	0.0014	0.0282	0.0681	0.0741
Logistics	0.9993	0.9991	0.9989	0.0039	0.0059	0.0103	0.0268	0.0302	0.0398
Two-term	0.9966	0.9941	0.9932	0.0222	0.0401	0.0468	0.0629	0.0886	0.0845
Logarithmic	0.9998	0.9994	0.9990	0.0018	0.0028	0.0031	0.0224	0.0240	0.0251

The results of the fitting of apple slices drying data in microwave method with different mathematical models were presented in Table 3. For all microwave drying experiments, R^2 , $RMSE$ and χ^2 values ranged between 0.9966–0.9999; 0.0188–0.0421 and 0.0005–0.0291. Midili et al. model had the highest R^2 (0.9999) and the lowest $RMSE$ (0.0188) and χ^2 (0.0005) values. Therefore, Midili et al. model was proposed as the best model for drying apple slice in MD. Darvishi et al.⁵² dried white mulberry in microwave drying at 100, 200, 300, 400 and 500 W power levels and applied the experimental data to five thin layer models where Lewis, Henderson and Pabis, Page, Wang and Singh, and Midilli et al. models, the Page model gives the highest R^2 (0.999) and lower $RMSE$ (0.009) and χ^2 (0.00009) values. Ganesapillai, Murugan & Singh⁵³ used 100, 180, 300, 450, 600 and 900 W power levels for dehydration of Ginger rhizomes and to determine the drying characteristics of sample, Henderson, Page, Logarithmic, Wang and Singh, Diffusion, Verma, Two-term exponential, Midilli models tested. Diffusion model gave the best results (maximum values R^2 = 0.99958, minimum values $RMSE$ (0.00429) and χ^2 (0.00019).

Table 3. The statistical comparison for prediction drying of apple slices in microwave dryer

Model	R^2			χ^2			$RMSE$		
	90 W	180 W	360 W	90 W	180 W	360 W	90 W	180 W	360 W
Midili et al.	0.9999	0.9996	0.9994	0.0005	0.0021	0.0027	0.0188	0.0249	0.0251
Page	0.9994	0.9991	0.9995	0.0057	0.0084	0.0148	0.0279	0.0313	0.0410
Logistics	0.9981	0.9967	0.9967	0.0077	0.0194	0.0272	0.0304	0.0501	0.0596
Two-term	0.9976	0.9974	0.9968	0.0116	0.0243	0.0324	0.0359	0.0564	0.0618
Logarithmic	0.9968	0.9979	0.9966	0.0018	0.0051	0.0291	0.0231	0.0268	0.0421

3.2. Effective moisture diffusivity

Effective moisture diffusivity values (D_{eff}) of apple slice at different dryer calculated by Equation (10). The Reported D_{eff} values were within the general range of 10^{-8} to $\times 10^{-12}$ m²/s for agricultural product and food materials²⁷. In convective drying, minimum D_{eff} value (1.95×10^{-7} m²/s) belonged to pretreated apple slice of at air temperature 40°C, and maximum value (4.09×10^{-7} m²/s) belonged to apple slice at air temperature 70°C. Obtained values were demonstrated in Figure 3a. The results indicated direct correlation between D_{eff} and temperature. Increasing the air temperature was accompanied by an increase in D_{eff} and a reduction in the drying time. Beigi⁴² estimated as 7.03×10^{-10} to 1.08×10^{-9} m²/s for apple in convective dryer at 50°C and 70°C, 1.5 m/s air velocity. The values of D_{eff} are comparable with the reported values of 1.73×10^{-10} to 4.40×10^{-10} m²/s for apple pomace at 50 to 80°C and air velocity of 2 ± 0.1 m/s in convective dryer⁴⁴, 6.97×10^{-11} to 2.38×10^{-10} m²/s for quince slices drying in convective dryer⁵⁴ and 3.27×10^{-9} to 1.23×10^{-8} m²/s consideration for broccoli slices with air temperatures of 45–70°C and air velocities of 2 m/s in convective dryer⁵⁵.

The values of D_{eff} for microwave dryer are presented in Figure 3b. In microwave drying, minimum value (2.94×10^{-7} m²/s) belonged to apple slice which had a microwave power level of 90 W; maximum value (8.21×10^{-7} m²/s) belonged to apple slice that had a microwave power level of 360 W. According to the results the values of D_{eff} in MD were higher than CD. Also, the microwave power and lower air velocity can accelerate the water molecules present in the apple slice to evaporate faster, thus providing a faster decrease of the apple slice MC and the corresponding higher value of effective moisture diffusivity³⁷.

Figure 3. Effective moisture diffusivity (D_{eff}) for drying of apple slice in different:

a) air temperature, b) microwave power

Similar results for the amount of D_{eff} in microwave dryers are provided by other authors for fruits and vegetables. For example: effective moisture diffusivity values for ginger rhizomes was obtained

ranged from 20.24×10^{-12} to 9.8×10^{-11} m²/s at 100 – 900 W⁵³, D_{eff} values for bamboo shoot slices increased from 4.15×10^{-10} to 22.83×10^{-10} m²/s at different power levels ranging from 140 to 350 W in microwave dryer⁵⁶ and effective diffusivity of mulberry increased with increasing microwave power. It varied from 1.06×10^{-8} to 3.45×10^{-8} m²/s at five microwave powers of 100, 200, 300, 400 and 500 W⁵⁷.

3.3. Activation energy

During the drying process, the highest values of activation energy for CD and MD methods were obtained 125 kJ/mol and 15.03 W/g, respectively (Table 4). The air temperature and microwave power were important factors influencing the effective moisture diffusivity and activation energy. By increasing the temperature and microwave power, the activation energy was reduced as the result of mass transfer and more moisture loss of apple slice. The obtained results are in line with the stated values for hot air drying of cherry tomato (31.99 and 36.21 kJ/mol for the raw and blanched cherry tomatoes⁵, and microwave drying of kiwi slices (17.96–21.38 W/g)⁵⁷.

Table 4. The estimated activation energy in convective and microwave dryer

Air temperature (°C)	50	60	70
Ea (kJ/mol)	125	124.44	122.28
Microwave power (W)	90	180	360
Ea (W/g)	15.03	14.50	14.01

3.4. Specific energy consumption (convection and microwave)

Figure 4a shows the specific energy consumption of drying process of apple slice in convection dryer. In this study, the specific energy consumption was obtained in the range of 122.77 to 174.67 MJ/kg. According to the results, the highest and lowest energy values were consumed in the process of drying apple slices at 50 and 70°C, respectively. As shown in Figure 4a, the increase in the air temperature of the dryer chamber from 50 to 70°C continuously reduces energy consumption. In spite of lowering the specific heat of the air at higher temperatures, because of the significant reduction in the process time at these temperatures, the increase in the air temperature of the dryer chamber decreases the amount of energy consumed by the process. The values of *SEC* are comparable with the reported values of 74.73 MJ/kg mentioned for fluidized bed drying of rough rice⁵⁸, average specific energy consumption for potato in convection dryer was obtained 3.491 MJ/kg⁵⁹.

As shown in Figure 4b, during the drying process of apple slices in microwave dryer, the specific energy consumption at 90 and 360 W microwave power were obtained 80.05 and 52.03 (MJ/kg), respectively. In other words, the ratio of highest to lowest value of specific energy consumption was 1.53. According to the results, with the increase in microwave power, the specific energy consumption dropped significantly. The reduction in specific energy consumption at higher microwave power in MD method is due to the effect of its volumetric heating, which reduces the drying time³⁷. Advantages such as shorter drying times and lower energy consumption were the key drivers for the further

development of the microwave drying technique. The minimum value of *SEC* for drying of sunflower seeds were obtained to be 5.81 MJ/kg at microwave power 300 W³⁵ and the maximum and minimum values of energy consumption in microwave drying for tomato were obtained to be 350 and 8.4 Wh, respectively at range 90- 600 W⁶⁰.

Figure 4. Variations of specific energy consumption for drying process of apple slice in different: a) air temperature, b) microwave power

3.5. Color for (convection and microwave)

Color is one of the most important qualitative properties of fresh, processed food and its marketing. As shown in Figure 5a, color variations (ΔE) at different temperatures of 50, 60 and 70°C are shown in convective dryer. The most and the least amount of color variations (ΔE) occurred at temperatures of 70 and 50°C, respectively. According to the results, with the increase in air temperature of the dryer, the amount of color changes (ΔE) increased due to the decrease in moisture content in apple slice and the shrinkage process⁶¹. During the drying process, oxidation occurs and as a result of this oxidation, the intensity of the color decreases. The color change (ΔE) of pomegranates arils (6.80- 14.16 N) at hot air dryer were reported by Horuz and Maskan⁴⁸. The minimum color change (9.316) was obtained at air velocity of 2 m/s, air temperature (60°C) and belt linear speed of 2.5 mm/s, while the maximum color change was 18.24 MJ/kg observed at 1.5 m/s air velocity, air temperature 40°C and belt linear speed (mm/s) of 10.5 mm/s, for terebinth³⁶.

As shown in Figure 5b, color changes in microwave dryer increased by increasing microwave power from 90 to 180 W. The microwave power and process time are the effective factors influencing the color change in the microwave dryer. Due to the heat, the chlorophyll green pigments may turn into pheophytin, which has a brownish color. The change in the color of the pigments can be due to the effect of heat on heat-sensitive compounds such as carbohydrates, proteins and vitamins, which also causes color change during the drying process⁶².

a)

b)

Figure 5. Color change values of apple slices in different a) air temperature, b) microwave power

3.6. ANN

3.6.1. Convective dryer

Table 5 presents the best results for combining CFBF and FFBF networks with different topologies and activation functions to predict the moisture ratio of apple slices in CD method. According to Table 5, we can get the best performance of the FFBF network, which with the topology 2-10-10-1, along with the TAN, TAN and PUR threshold function and LMA (Levenberg-Marquardt algorithm) for training neural network, has the best result through the three-layer and four-layer topologies. The selected topology created the highest level of correlation (0.9993 for train and 0.9994 for test) and the lowest values of MAE and MSE achieved were 0.0047 for train, 0.0041 for test and 0.00044 respectively, for output variables. Tavakolipour et al.⁶³, the moisture ratio of zucchini were predicted by using artificial neural networks at convective dryer. According to the results, the coefficient of determination 0.998 and the RMSE value (0.0335) for the moisture ratio was obtained.

Table 5. The best values of evaluation criteria for FFBF and CFBF networks in different conditions of the number of layers and threshold functions for MR in convective dryer

Network	Training algorithm	Threshold function	Number of layers and neurons	MSE	Train		Test	
					R^2	MAE	R^2	MAE
FFBP	LM	TAN-TAN-PUR	2-10-10-1	0.00044	0.9993	0.0047	0.9994	0.0041
FFBP	BR	TAN-LOG-PUR	2-15-10-1	0.00099	0.9988	0.0089	0.9990	0.0076
CFBP	LM	TAN-TAN-PUR	2-12-1	0.00084	0.9991	0.0064	0.9992	0.0057
CFBP	BR	TAN-TAN-TAN	2-8-8-1	0.00102	0.9988	0.0093	0.9989	0.0082

3.6.2. Microwave dryer

Table 6 presents the best networks with the highest R^2 values and the lowest MAE and MSE values for prediction MR of apple slices in microwave dryer. The cascade forward back propagation (CFBP) structure, TAN- TAN- TAN threshold function, LM algorithm with 2-15-10-1 topology structure had

the lowest MSE (0.00059), MAE (0.0045 for test and 0.0053 for train) values and the highest R^2 (0.9993 for test and 0.9991 train) values (Table 6).

Table 6. The best values of evaluation criteria for FFBF and CFBF networks in different conditions of the number of layers and threshold functions for MR in microwave dryer

Network	Training algorithm	Threshold function	Number of layers and neurons	MSE	Train		Test	
					R^2	MAE	R^2	MAE
FFBP	LM	TAN-PUR-LOG	2-5-5-1	0.00080	0.9988	0.0075	0.9989	0.0070
FFBP	BR	TAN-LOG-TAN	2-10-1	0.00064	0.9990	0.0059	0.9992	0.0051
CFBP	LM	TAN-TAN-TAN	2-15-10-1	0.00059	0.9991	0.0053	0.9993	0.0045
CFBP	BR	TAN-TAN-PUR	2-8-8-1	0.00095	0.9984	0.0094	0.9986	0.0088

4. Conclusion

The effects of CD and MD at different air temperatures (50, 60 and 70°C), and microwave powers (90, 180, and 360 W) on the drying characteristics of apple slice were evaluated in this study. The drying time of apple slice was the highest in MD drying as compared to another one. Midili et al. model was the most suitable model for prediction of apple MR. This model had the highest correlation coefficients (R^2) and lowest chi-square (χ^2) and root mean square error ($RMSE$) values. So, it can be able to describe the thin layer drying characteristics of samples at two dryers. The maximum D_{eff} value of 8.21×10^{-7} m²/s was obtained under the MD with power of 360 W. The minimum SEC value (52.03 MJ/kg) was obtained from microwave drying. The obtained R^2 values using ANN for predication of MR at two different dryers (data test) were equal to 0.9993 and 0.9990 in CD and MD, respectively.

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Author contributions

Methodology, V.RS., R.A. and M.K. Formal analysis, V.RS., M.K. and M.S. Investigation, V.RS., R.A. and M.K. Experiment conduction, V.RS., R.A. and M.K. Statistical Analysis, V.RS., R.A., M.K. and W.T. Writing original draft preparation, V.RS., R.A., M.K. and M.S. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Figures

Figure 1

Four-layer ANN inputs and output structure used in this study

Figure 2

"See the Supplemental Files section for the complete figure caption".

Figure 3

Effective moisture diffusivity (D_{eff}) for drying of apple slice in different: a) air temperature, b) microwave power

Figure 4

Variations of specific energy consumption for drying process of apple slice in different: a) air temperature, b) microwave power

Figure 5

Color change values of apple slices in different a) air temperature, b) microwave power

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