Drying Kinetics and Thermodynamic Properties of Ultrasound Pretreatment Bitter Melon Dried by Infrared

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Received 4 February 2024; Revised 15 April 2024; Accepted 4 May 2024; Published 27 May 2024

Academic Editor: Bhupendra M Ghodki

Abstract: Determination of drying characteristics of ripe and unripe bitter melon in an infrared dryer at 50, 60, and 70°C with airborne ultrasonic pretreatment with a power of 20 kW for 0, 10, and 20 minutes and a frequency of 20 kHz is the purpose of this study. At the end of drying, among the five used models that fit the moisture ratio data, the Midilli and logarithmic models were selected to properly characterize the drying behavior in the infrared dryer with ultrasonic pretreatment of ripe and unripe bitter melon samples. Moisture transfer from bitter melon samples' ripeness and early maturity was defined using Fick's diffusion equation. Then, the Arrhenius equation was utilized to determine the effective moisture diffusivity. Also, the activation energy of unripe and ripe bitter melon slices was reduced with the enhancement in the ultrasound pretreatment time. Water activity (aw) amounts of ripe and unripe bitter melon were achieved at various drying temperatures and ultrasound pretreatment. The trends of the experiment indicate a decrease in enthalpy (ΔH) and entropy (ΔS) amounts of bitter melon with enhancing temperature and ultrasonic. The Gibbs free energy (ΔG) increases with enhancing drying temperature and ultrasonic pretreatment. Specific energy consumption decreased with enhancing drying temperature and ultrasound pretreatment duration for both ripe and unripe bitter melon samples.

1. Introduction

Medicinal plants are considered one of the important genetic reserves of plants due to their high ecological flexibility in different climates. Regarding the presence of very diverse compounds in them, they have many medicinal uses [1]. Bitter melon (Momordica charantia), also known as karela, is a plant that is used for medicine originally from India and China [2].

Bitter melon is an annual monococline plant that looks like a cucumber and has several wart-like protrusions on the surface of its fruit. Despite the bitter taste of bitter melon, this fruit is considered a zucchini, and a plant whose root, stem, leaf, fruit, and seed are used for food and medicine. Bitter melon fruit is similar to other zucchinis in terms of nutrition. Bitter melon is a rich source of vitamin A and vitamin C [3, 4].

Freshly harvested fruits and vegetables usually have high water content. Water provides conditions for the reproduction of microorganisms, which leads to irreparable damage to foods. Hence, it is necessary to reduce the moisture amount and the loss of nutrients by using appropriate methods. Drying is a food preservation method utilized to decrease water activity and inhibit or reduce enzymatic reactions and microbial growth. Finally, it leads to an increase in the shelf life without the aid of additives [5].

Currently, innovative techniques are being applied to improve drying speed and maintain product quality. The infrared (IR) drying method is one of these methods. Drying with an IR system has some advantages, such as a high drying rate and heat transfer coefficient, and less specific energy consumption [6]. IR rays penetrate the sample and turn it into sensible heat which IR drying is more uniform heating [7] and may reduce the moisture gradient during heating.
and drying [8]. In order to achieve a competitive-price product, the quality and process are required to be optimized. Also, using new methods and novel techniques in agriculture has been widely developed [9–15]. Utilization of ultrasound pretreatment is one of the methods to improve the quality and reduce the drying time, simultaneously [16–18].

Acoustic cavitation is the main result of using ultrasonic waves, which suddenly generate, propagate, and collapse microbubbles in the material [19]. In general, the utilization of ultrasound could decrease water activity and modify colour. Studying the drying process provides valuable information about the mass and heat transfer between biological materials and the drying environment, which are crucial to designing equipment, identifying ideal drying conditions, and simulating dryers. According to the final moisture content, these curves are used in adjusting the drying time [20].

A study was carried out to investigate the effects of using a combination of IR and convective heat transfer on the banana’s drying characteristics. Colour changes, mathematical modeling, and drying kinetics were reported at 60, 70, and 80°C. An improvement of 31% was obtained in the novel drying process in comparison with IR drying. A reduction trend in temperature and moisture content showed a reduction in drying rate. Finally, the colour changes were achieved in the 15.18-33.61 range [21].

A deep understanding of thermodynamic properties, including enthalpy (ΔH), entropy (ΔS), and the Gibbs free energy (ΔG), provides helpful information to design drying equipment and attributes such as calculating the energy needed for the drying phenomenon, absorbed water properties, assessing the microstructure of food, and determining kinetic parameters of absorption [22]. In fact, the water molecules’ movement in foods was assessed by entropy and revealed the water-food interaction. The chemical reaction possibility during the drying and evaporation of water is obtained by computing the variations in Gibb’s free energy. According to Wanderley et al., the Gibbs free energy is a standard that shows whether water absorption occurs as a spontaneous process [23]. Therefore, evaluation of the drying behavior of ripe and unripe bitter melon in an infrared dryer; matching experimental data with models and determining the best model for ripe and unripe bitter melon; determining a_w and SCE values for dried bitter melon samples at different drying temperatures and ultrasound pretreatment and determination of bitter melon drying kinetics; and thermodynamic properties such as activation energy and effective diffusion are the purposes of the present study.

2. Materials and Methods

2.1. Materials. After planting in the greenhouse, the fruits were randomly selected considering that they were free from pest contamination and had healthy conditions. Bitter melon fruits were removed from leaves and foreign materials. Afterward, they were directly transferred to the laboratory in a speci

Bitter melon fruit was taken out from the refrigerator to reach room temperature for a minimum of 2 hours before the experiments. Distilled water was used to wash the bitter melons, and then a dehumidifier was utilized to remove surface water. Bitter melons were cut with a slicer into 3 × 3 × cm dimensions. The initial moisture content was determined by drying them in a convection oven at a temperature of 105°C ± 1°C until reaching a constant weight. Then, the average initial moisture content of bitter melons (d.b.) was calculated [24]. The initial moisture percentages of ripe and unripe bitter melon slices were achieved at 15.76 and 12.33 (d.b.), respectively.

2.2. Drying Experiment. The bitter melons were dried using an infrared dryer of medicinal plants, model GC400, made by Grok Company, Iran. The mentioned high-efficiency dryer has a humidity and temperature control system with programming capability. Four 250-watt near-infrared lamps are used in the dryer chamber. An internal sensor controlled the temperature and humidity of air within the dryer. An airborne ultrasound system model UC20, made by Zagros Company, Iran, was utilized as pretreatment. While performing noncontact wave pretreatments with a power of 20kW and a frequency of 20kHz, the temperature was controlled by two temperature sensors located within and outside the system.

To evaluate the ultrasound pretreatment effect on infrared drying, the ripe and unripe bitter melons were dried at 3 temperatures of 50°C, 60°C, and 70°C, ultrasound treatment (10 min and 20 min) with 20% power. In fact, considering the limitation in terms of the high power consumption of applying ultrasound pretreatment at 100% power and its effectiveness at 20% power level, therefore, this power level was used for pretreatments. The experiments were conducted in 3 repetitions until the samples reached 0.10 of moisture [25]. The weight changes were measured by a computer-connected scale (accuracy of 0.001g). The data recorded the values with intervals of 5 minutes. A schematic diagram of bitter melon slices’ infrared drying under ultrasonic pretreatment is presented in Figure 2.

Also, the drying equipment and the dried products are shown in Figure 3.

2.3. Mathematical Modeling. In the fitting process, five applicable models (Table 1) were fitted to moisture ratio (MR) data. According to equation (1), M denotes moisture content (%wb) at any moment, M_0 denotes the initial moisture content (%wb), and M_e denotes the equilibrium moisture content (%wb). Also, the drying rate (DR) is calculated by applying equation (2) which M_t and M_{t+dt} are the moisture content at times of t and t + dt, respectively [26].

\[
\text{MR} = \frac{M - M_e}{M_0 - M_e}, \quad (1)
\]

\[
\text{DR} = \frac{M_t - M_{t+dt}}{\Delta t}, \quad (2)
\]
A nonlinear regression analysis was utilized to determine the estimation of five models. The curve fitting toolbox in Statgraphics was utilized to estimate the moisture changes regression models for obtaining the values of the constant coefficients of these descriptive models using laboratory data related to the bitter melon drying kinetics. Then, the models describing the drying kinetics of bitter melon slices are the correlation coefficient ($R^2$), the chi-square between experimental data ($\chi^2$), and the root mean square error (RMSE). Also, the predictions of each model were compared with other models [32]. The equations of mentioned parameters are provided in equations (4), (5), and (3), respectively.

$$R^2 = 1 - \frac{\sum_i (MR_{\text{exp},i} - MR_{\text{pre},i})^2}{\sum_i (MR_{\text{pre},i} - MR_{\text{exp},i})^2}, \quad (3)$$

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

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

where $MR_{\text{exp},i}$ denotes the $i$th experimental dimensionless moisture ratio, $MR_{\text{pre},i}$ denotes the $i$th predicted dimensionless moisture ratio, $N$ denotes the number of observations, and $z$ denotes the number of constants.

2.4. Water Activity. The water activity ($a_w$) is defined as the proportion between the food’s vapor pressure when having a total balance with the air, and the distilled water’s vapor pressure. Measuring the $a_w$ is critical in drying studies since

![Figure 1: Bitter melon fruit: (a) unripe, (b), ripe, (c) unripe slices, and (d): ripe slices.](image)

![Figure 2: The schematic view of the infrared dryer and other devices utilized in the experiments.](image)
it presents beneficial information about the shelf-life of dried products [33]. The water activity of all samples after drying was obtained using an intelligent water activity meter (Aqua Lab series 3, Decagon Devices, Pullman, WA, USA) at 25 ± 1°C. The samples were analyzed in three repetitions, and the average values were calculated. About 2 gr of ground dry samples were placed in a standard measuring cup and put inside a thermostatic chamber.

2.5. Effective Diffusivity and Activation Energy. Determining the $D_{\text{eff}}$ is a key factor in modeling the drying process of foods and plants. It is a function of the material’s humidity and temperature. Fick’s second law for unsteady conditions is utilized to characterize the moisture transfer in the drying phenomenon. (1) One-dimensional assumption, (2) consistent moisture in initiate, and (3) having an internal transfer of moisture were the assumptions of applying Fick’s second law in this study. The effective moisture diffusion coefficient is achieved using the Fick equation for a blade by equations (6), (7), and (8) [24].

$$\frac{\partial \text{MR}}{\partial t} = D_{\text{eff}} \nabla^2 \text{MR}, \quad (6)$$

$$\text{MR} = \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D_{\text{eff}} t}{4L^2} \right), \quad (7)$$

$$\text{Slope} = \frac{\pi^2 D_{\text{eff}}}{4L^2}, \quad (8)$$

where $\text{MR}$ denotes the bitter melon’s moisture level (d.b), $L$ denotes the half thickness, and $D_{\text{eff}}$ denotes the effective diffusion coefficient.

$$D_{\text{eff}} = D_0 \exp \left( -\frac{E_a}{RT} + \frac{273}{15} \right), \quad (9)$$

$$\ln D_{\text{eff}} = \ln D_0 - \frac{E_a}{RT}, \quad (10)$$

$$\text{Slope} = \frac{E_a}{RT}, \quad (11)$$

where $E_a$ denotes the activation energy (kJ/mol), $D_0$ denotes the effective moisture diffusion coefficient (m$^2$/s), $T$ denotes the temperature (K), and $R$ denotes the universal gas constant (8.314 J. (mol.K)$^{-1}$).

2.6. Shrinkage. One of the most important changes that the sample faces in the drying process is the loss of moisture and the reduction of the volume of the product, which is called shrinkage. Shrinkage reduces the heat and mass transfer level and changes the transfer and thermophysical properties of food during the drying process. In this research, to obtain the shrinkage, first, the apparent volume

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<th>Table 1: The applied mathematical models for modeling.</th>
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<td>Wang and Singh</td>
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</table>

*$a$, $b$, $c$, $k$, and $n$: empirical constants and coefficients in drying models.
of the samples before and after drying was calculated by applying the solvent displacement technique (toluene) through the use of a glass pycnometer measuring using equation (12) [34].

\[
SR = \left(1 - \frac{v_d}{v_0}\right) \times 100. \tag{12}
\]

SR is the percentage of shrinkage (%), \(v_0\) is the sample’s initial apparent volume (cm\(^3\)), and \(v_d\) is the sample’s apparent volume after drying (cm\(^3\)).

2.7. Rehydration Ratio. The rehydration ratio is one of the important properties to measure the quality of food and farming dry materials. It can also be considered as an assessment of damage caused by drying processes. A slow or
An insufficient rehydration ratio is caused by internal tissue breakdown [35]. Rehydration ratios were determined by soaking the dried samples of ripe and unripe bitter melon with specific weight (2.5 g) in 300 ml of distilled water at 25 and 65 °C. Bitter melons’ rehydration ratio (RR) was calculated using equation (13).

\[ RR = \frac{W_2 - W_1}{W_1} \]  

2.8. Thermodynamics Parameters. Equations (14), (15), and (16) were utilized to compute thermodynamic properties, such as \( \Delta H \), \( \Delta S \), and \( \Delta G \), based on \( E_a \) [36].

\[ \Delta H = E_a - RT, \]  

\[ \Delta S = R \left( \ln D_0 - \ln \frac{k_b}{h_p} - \ln T_a \right), \]  

\[ \Delta G = \Delta H - T_a \Delta S, \]

where \( \Delta H \) denotes enthalpy variation (kJ/mol), \( \Delta S \) denotes entropy variation (kJ/mol K), \( \Delta G \) denotes the variation of the Gibbs free energy (kJ/mol), \( h_p \) denotes the Planck constant, and \( k_b \) denotes Boltzmann’s constant \((1.38 \times 10^{-23})/K\) and \(6.626 \times 10^{-34}/s\).

2.9. Specific Energy Consumption (SEC). In infrared drying by ultrasound pretreatment, the specific energy consumption is defined as the total energy required to evaporate one kilogram of water from bitter melon. Accordingly, reducing the drying cost is achieved through minimizing specific energy consumption. Generally, (1) the energy needed for an infrared dryer and (2) the energy needed for an ultrasound generator were used in the drying procedure. The SEC\(_{inf} \) was achieved by equation (17) [37].

\[ SEC_{inf} = \frac{\Delta W}{M_0 - M_e}, \]  

where \( \Delta W \) denotes the power consumption for drying (kW.h), \( M_0 \) and \( M_e \) denote the initial and final mass of the samples, respectively (kg). Also, the ultrasound power was achieved by equation (18) [38].

\[ UP = U I \cos \Phi, \]

where \( U \) (V) denotes applied voltage, \( I \) (A) denotes the applied current to the generator, and \( \cos \Phi \) denotes the power factor considered 0.8. The energy consumption for the ultrasound device was achieved by equation (19) [39].

\[ SEC_{ult} = \frac{UP \cdot t}{M_0 - M_e}, \]  

where \( SEC_{ult} \) is the specific energy consumption for the device (kW.h/kg), \( M_0 \) and \( M_e \) are the initial and final mass of the samples (kg), respectively. Total specific energy consumption is calculated using equation (20) [40].

\[ SEC_{Total} = SEC_{inf} + SEC_{ult}, \]

where \( SEC_{Total} \) is the total specific energy consumption in a dryer with ultrasound pretreatment (kW.h/kg).

![Figure 5: Ultrasound pretreatment effect on drying time of ripe and unripe bitter melon at temperatures 50, 60, and 70 °C.](chart.png)


3. Results and Discussion

3.1. Drying Kinetics. Figures 4 and 5 illustrate the moisture content and drying time for ripe and unripe bitter melon dried by an infrared dryer at temperatures 50, 60, and 70°C and ultrasound pretreatment, respectively. The bitter melon slices drying occurred during the deceleration period. Also, the obtained results showed an increase in the slope of the drying graphs with increasing temperature and ultrasound pretreatment.

The maximum drying time is related to the dried samples at 50°C and the control group, and the minimum time

Figure 6: Ultrasound pretreatments effect on drying rate of ripe and unripe bitter melon at temperatures 50, 60, and 70°C.
Table 2: Result of fitting and model comparison for ripe and unripe bitter melon samples.

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of drying was related to the dried samples at 70°C and ultrasound pretreatment for 20 min. Enhancing the drying temperature leads to increases in the water molecules’ movement. Also, the mass transfer rate in the drying process enhances leading to a reduction in the drying time [41].

Applying ultrasound leads to the generation of cavitation and causes a rise in the removal of moisture from the product [42]. Increasing the duration of applying ultrasound causes the creation of a large number of microchannels in the tissue, which accelerates the evaporation process in a short time [43, 44].

According to Figure 6, at the beginning of the drying process, the drying rate increased due to the sample’s higher moisture. The slope of the curve at the beginning of the process is high, but it gradually decreases over time, and the moisture content decreases at a slow rate. Actually, the drying intensity at the beginning is more significant than at the end stages. However, at the end of this stage and entering the descending rate stage, all the free water on the surface
3.2. Mathematical Modeling. The experimental data were fitted with five thin-layer drying models stated in Table 1. The benchmark for selecting the best model is the maximum $R^2$ value, the lowest RMSE, and the minimum $\chi^2$ value. Table 2 presents the statistical analysis results for the infrared drying process of ripe and unripe bitter melon using ultrasound pretreatments. The results of Table 2 show that in all the models related to infrared drying of ripe and unripe bitter melon with ultrasound pretreatment, the correlation coefficient was higher than 0.9732, so the Midilli and logarithmic models had the maximum correlation coefficient, and it has the minimum RMSE and the chi-square. Hence, this model was selected to predict the bitter melon slices’ drying behavior using infrared under different temperatures and ultrasound pretreatment. These results reveal the Midilli et al. and logarithmic model’s capability to model the drying characteristics of ripe and unripe bitter melon.
Figures 7 and 8 show the fitting of the Midilli and logarithmic models with experimental data in an infrared dryer under different drying conditions at different temperatures and ultrasound pretreatment of ripe and unripe bitter melons, respectively. These figures clearly show a great agreement between the laboratory moisture ratio and the predictions of the Midilli and logarithmic models for drying bitter melon in an IR dryer with ultrasound pretreatment. The predicted data are generally placed around straight lines at 45°C.

3.3. Water Activity. To prevent fungal growth, the water activity value of dried bitter melon should be 0.8 for short-term and 0.7 for long-term storage. The microbial growth with water activity between 0.65 and 0.75 is limited [45]. The achieved values for \( a_w \) for fresh and dried ripe and unripe bitter melon at different temperatures and ultrasound pretreatment are presented in Table 3. By enhancing drying air temperature and duration of ultrasound pretreatment, \( a_w \) values decreased for both ripe and unripe bitter melons. Additionally, all of \( a_w \) values are under 0.4. Therefore, the achieved \( a_w \) were less than the long-term storage acute amount to prevent fungal.

3.4. Effective Diffusivity and Activation Energy. Figure 9 illustrates the \( D_{\text{eff}} \) amounts of ripe and unripe bitter melon slices. The \( D_{\text{eff}} \) amounts for ripe and unripe bitter melon samples varied from \( 1.75 \times 10^{-8} \) to \( 3.98 \times 10^{-8} \) and \( 1.37 \times 10^{-8} \) to \( 2.84 \times 10^{-8} \), respectively. The amounts of the \( D_{\text{eff}} \) have been similarly reported by other researchers in the range of \( 10^{-12} \) to \( 10^{-7} \text{ m}^2/\text{s} \) for other agricultural products [46]. The temperature and ultrasound have a considerable effect on the \( D_{\text{eff}} \). The \( D_{\text{eff}} \) enhanced as the temperature and ultrasound pretreatment enhanced due to the water’s rapid flow at high temperatures of both ripe and unripe bitter melons. Also, the effect of temperature and humidity on ripe bitter melon samples was higher than on unripe bitter melon samples.

To calculate the activation energy (\( E_a \)) utilizing the Arrhenius equation (equation (9)), the plot of \( \ln D_{\text{eff}} \) against \( 1/T \) was drawn, and the \( E_a \) was computed using the achieved graph slope. The \( E_a \) indicates the amount of required energy to remove water (drying). The \( E_a \) range for foods varies from 12.7 to 110 kJ/mol [47]. The amount of \( E_a \) in the temperatures of 50 to 70°C with pretreatment of 0 to 20 min ultrasound for drying the thin layer of ripe and unripe bitter melon was calculated as 36.74 to 41.43 kJ/mol and 37.49 to 42.91 kJ/mol, respectively (Figure 10). Therefore, by increasing the ultrasound pretreatment time of the thin layer of bitter melon during the IR drying, the \( E_a \) decreased. Because, with the increase in the ultrasound pretreatment time, the moisture permeability increases, and the energy needed to begin the internal parts penetration will be less [48].

3.5. Shrinkage. Shrinkage of food during drying affects the quality of the dried product. If shrinkage is controlled during the drying process, the quality of the dried product may be improved [49]. Percent of shrinkage for ripe and unripe bitter melon slices dried with an infrared dryer pretreated with ultrasound is shown in Figure 11. Shrinkage of bitter melon slices for both ripe and unripe fruits has a direct relationship and increases with increasing drying temperature, but it has an inverse relationship with ultrasound pretreatment, that is, with increasing ultrasound pretreatment duration, the amount of shrinkage increases, so that the highest percentage of shrinkage is related to the samples The control dried at 70°C was observed for both ripe and unripe bitter melon samples. The lowest percentage of shrinkage was also observed for ripe and unripe bitter melon samples pretreated for 20 minutes and dried at 50°C.

3.6. Rehydration Ratio (RR). The rehydration ratio is a qualitative parameter that indicates the ability of food and agricultural materials to return to their original shape after drying and the extent of cellular damage during drying. Changes in the rehydration ratio of ripe and unripe bitter melon slices after the drying process with ultrasonic pretreatment and infrared dryer were measured. Figure 12 shows the average values related to the effect of drying temperature, ultrasonic pretreatment duration, and temperature of distilled water for immersing the dried samples of ripe and unripe bitter melon slices. The highest rehydration ratio values in both ripe and unripe bitter melon samples were obtained for the samples exposed to ultrasound pretreatment for 20 minutes, dried at 70°C, and soaked in distilled water at 65°C, and the values obtained were, respectively, 6.76 and 5.39 for ripe and unripe bitter melons. At higher temperatures, the matrix structure was better preserved in bitter melon slices in both ripe and unripe samples [50]. The lowest amount of rehydration ratio for ripe and unripe bitter melons, respectively, was 50°C.
melon slices was related to control samples dried at 50 °C and distilled water at 25 °C. The lowest rehydration ratio values for ripe and unripe bitter melons were 5.17 and 3.42, respectively. This behavior can be explained by damage to the cell structure as well as less diffusion of water on the surface of the product at lower temperatures. Similar results were reported by [51] for drying potato slices. Finally, the rehydration ratio increased with increasing distilled water temperature from 25 °C to 65 °C. In other words, according to Figure 11, the rehydration ratio at 65 °C was higher than at 25 °C. The rehydration ratio is improved at high temperatures due to the effect of temperature on the cell wall and tissue [52].

3.7. Thermodynamics Properties. Table 4 presents the values of thermodynamic functions (enthalpy, entropy, and Gibbs free energy) for different conditions of bitter melon drying. For both ripe and unripe samples, entropy and enthalpy reduced with enhancing ultrasound pretreatment time and drying temperature, while the Gibbs free energy increased linearly with enhancing ultrasound pretreatment time and
drying temperature (Table 4). The higher value of enthalpy means a high requirement of energy for separating product water. Also, entropy reveals random movement or disorder degree of water molecules [53, 54]. Considering the concept of entropy, it could be concluded that this thermodynamic property reveals behavior similar to enthalpy in that the entropy amount reduces with the increase in temperature and thickness [55]. When a substance’s entropy is negative, it could be related to product structure and chemical variations [56]. The feasibility and range of a chemical are achieved by the variation in the Gibbs free energy. Positive values of the Gibbs free energy is a representative for requirement of additional energy, while negative value indicates that the process does not need additional energy.

3.8. Energy Evaluations. Figure 13 presents the values of SEC for ripe and unripe bitter melons. As expected, the lowest amount of SEC was obtained at a temperature of 70°C and ultrasound pretreatment for 20 min. As the drying temperature increased, the SEC decreased. Increasing the temperature leads to penetrations in the samples and helps to transfer the inner part moisture of the slices and decrease the drying SEC of the product [57]. The decrease in SEC depends on
ultrasound pretreatment. Finally, the SEC value was higher for unripe bitter melon samples compared to ripe samples in similar treatments and temperatures.

4. Conclusions

In the present study, the ripe and unripe bitter melon’s drying process with an infrared dryer at different drying temperatures and different ultrasound pretreatment times was studied. The results showed the drying time reduces significantly with increasing the drying temperature and ultrasound pretreatment time. The maximum drying rate belonged to the drying temperature of 70°C and the ultrasound time of 20 min. Among the five used models that fit the moisture ratio data, the Midilli and logarithmic models were achieved to properly describe the drying behavior in the infrared dryer with ultrasonic pretreatment of ripe and unripe bitter melon samples. Water activity values decreased with enhancing drying temperature and ultrasound pretreatment duration for both ripe and unripe bitter melon samples, and their values were from 0.292 to 0.307 and 0.313 to 0.332, respectively.

The ultrasonic pretreatment and drying temperature strongly affect the moisture effective diffusion coefficient, and its amount for ripe and unripe bitter melon is within the range of $1.75 \times 10^{-8}$ to $3.98 \times 10^{-8}$ m²/s and $1.37 \times 10^{-8}$ to $2.84 \times 10^{-8}$ m²/s, respectively, followed the Arrhenius relationship. The activation energy values considering ultrasound pretreatment at various temperatures were obtained for ripe bitter melon in the range of 36.74 to 41.43 kJ/mol and for unripe bitter melon in the range of 37.48 to 42.91 kJ/mol.

The trends of the experiment indicate a decrease in enthalpy and entropy values of ripe and unripe bitter melon

### Table 4: Thermodynamic property values of ripe and unripe bitter melon at different temperatures in ultrasound-pretreatment infrared drying.

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Control</th>
<th>Unripe U10 min</th>
<th>U20 min</th>
<th>Ripe Control</th>
<th>U10 min</th>
<th>U20 min</th>
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<tbody>
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<tr>
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**Figure 13: Specific energy consumption in drying of ripe and unripe bitter melon in ultrasound-pretreatment infrared drying.**

ultrasound pretreatment. Finally, the SEC value was higher for unripe bitter melon samples compared to ripe samples in similar treatments and temperatures.

4. Conclusions

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The trends of the experiment indicate a decrease in enthalpy and entropy values of ripe and unripe bitter melon
samples by enhancing the temperature and ultrasonic. Moreover, the $\Delta G$ enhances with enhancing drying temperature and duration of ultrasonic pretreatment. Specific energy consumption decreased with enhancing drying temperature and pretreatment duration for both ripe and unripe bitter melon samples. The specific energy consumption for ripe and unripe bitter melon was in the range of 188.89-284.69 kW h/kg and 224.14-303.57 kW h/kg, respectively. The results obtained from this study show a reduction in energy consumption and less drying time.

**Nomenclature**

$M$: Moisture content (kg/kg dry matter, d.b.)  
$M_d$: Balance humidity  
$M_t$: Moisture in time  
$M_i$: Initial moisture  
MR: Moisture content  
d$t + t$: Moisture content  
$T$: Temperature  
$M_{t+\Delta t}$: Moisture in $t + \Delta t$  
d,b: Dry bases  
DR: Drying ratio  
t: Time (s)  
$\Delta t$: Difference between two-time scales  
$R^2$: Correlation coefficient  
RMS: Root mean square error  
$N$: Number of observations  
pre: Predicted  
exp: Experimental  
$Z$: Constant coefficient numbers  
a:$: Water activity  
$\chi^2$: Chi-square  
$\Pi$: Pi number  
UP: Ultrasonic power.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author (Ali Hassanpour) upon request.

**Additional Points**

**Novelty Impact Statement.** Decreasing moisture by mass and heat transfer is necessary for keeping medicinal plants and food in good quality conditions and reducing losses. The demands to combine different drying technologies with non-destructive methods have been developed to minimize quality loss and enhance efficiency. Due to the sensitivity of bitter melon components to heat, it is very important to dry it properly. This research evaluates drying conditions and provides a model for infrared drying of bitter melon with ultrasound, and the results reveal that bitter melon drying can be conducted with high-quality commercial infrared dryers.

**Conflicts of Interest**

The authors declare that there is no conflict of interest regarding the publication of this article.

**Acknowledgments**

This work was supported by Urmia University.

**References**


