Research Article

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Determination of drying kinetics, specific energy consumption, shrinkage, and colour properties of pomegranate arils submitted to microwave and convective drying

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Abstract: In this study, the drying kinetics, effective moisture diffusivity (D_{eff}), specific energy consumption (SEC), colour, and shrinkage (S_b) of pomegranate arils were compared when dried by convective (CV) drying and microwave (MW) drying. The experiments were performed at air temperature of 50, 60, and 70°C and air velocity of 1 m/s for CV drying and 270, 450, and 630 W for MW drying. The results showed that increasing air temperature and MW power increased the D_{eff}. The calculations demonstrated that the maximum D_{eff} for pomegranate arils was obtained for MW drying (630 W). Maximum SEC for pomegranate arils in the CV dryer was 145.12 kWh/kg, whereas in the MW dryer was 35.42 kWh/kg. In MW dryer, the lowest values of colour change and shrinkage were 6.77 and 50.5%, respectively. Comprehensive comparison of the different drying methods (MW and CV) revealed that MW drying had best drying performance for pomegranate arils, considering the drying time, effective moisture diffusion, SEC, colour, and shrinkage.

Keywords: colour, energy, convective drying, microwave drying, pomegranate, shrinkage

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1 Introduction

Pomegranate (*Punica granatum* L.) is one of the most important fruits in the subtropical regions, which is cultivated for its nutritional and therapeutic value (Galaz et al. 2017). Drying process, in addition to being a way to increase the shelf life of foods, is known as a way to increase the added value of food products. Under controlled conditions, removing water from a food product reduces its moisture content (MC) to a certain extent, which diminishes the activity of enzymes, the rate of undesirable chemical changes and microbial growth. In addition, the decrease in moisture is accompanied by a reduction in volume and weight, which is one of the important factors for transportation and storage (Sakare et al. 2020).

Throughout the decades, convective (CV) drying has been one of the most long-established technologies in the food industries. This includes both the heat and mass transfer while the water is extracted from the agricultural products through diffusion and evaporation (Castro et al. 2018).

One of the methods that has been given a lot of attention during the last decade is the use of microwave (MW) radiation in the drying process. MW beams are electromagnetic beams with a long wavelength (2.45 GHz). When these waves pass through the tissues, polar molecules, such as water and salts, vibrate, and this vibration causes the MW energy to be converted into heat. Other mechanisms are also involved, such as transportation of ions, which contribute to the generation of heat inside the sample. Unlike other drying methods, in which heat should penetrate from the surface to depth, in this method heat is produced in the tissue of the food itself, and, therefore, it causes minimal damage to the surface of the food (Kumar et al. 2020; Rattanadecho and Makul 2016). Among the advantages of MW drying are the fast volumetric heating and consequent fast drying rate and short drying time; enhanced quality of the product; reduced energy consumption that allows saving energy; and lower operating costs. Nevertheless, some disadvantages were also identified for the MW drying, such as high equipment investment on an industrial scale; potential quality loos, particularly in what concerns aroma, texture and other sensory characteristics; or the fact that specific sample size and shape may be needed to make the drying process effective (Orsat et al. 2006).

Different methods are used to reduce the MC of fruits and vegetables. Cuccurullo et al. (2019) used MW, CV, and MW–CV dryers to dry apple. They showed that MW–CV dryers led to lower drying rates when compared with the other methods investigated. Jebri et al. (2019) investigated the effect of different drying methods (MW and CV) on weight loss and rehydration of *Salvia officinalis* L. leaves. Drying of garlic puree by CV (50, 60, and 70°C) and MW drying (180, 360, and 540 W) was studied by İlter et al. (2018) to determine the drying behaviour. The results showed that the temperature of 70°C and the MW power of 540 W had the lowest variations in colour. In addition, the highest effective moisture diffusivity (D_{eff}) was 3.7×10^{-10} and 285×10^{-10} m^2/s at 70°C and 540 W, respectively.

As dried pomegranate arils are produced for consumption as an alternative to the fresh form, because of the higher preservation capacity and concentrated flavour and aroma, the interest for the drying kinetics of the arils is very relevant from the industrial point of view to optimize drying conditions and energy saving. There is still a lack of knowledge about this topic, as seen by the scientific literature published. Although there have been a few recent studies about the drying kinetics of pomegranate peel (Galaz et al. 2017; Kaderides et al. 2019; Mphahlele et al. 2019), only one study evaluated the drying kinetics of the arils (Kingsly and Singh 2007), and this was performed more than a decade ago and focused only on the CV drying, and just testing a few thin layer models, without evaluating relevant aspects other than the plain kinetic equations, such as for example diffusivity or specific energy consumption (SEC) analysis. Therefore, this study aims to bring new knowledge into the drying of pomegranate arils by comparing the drying of the product by two different methods: CV thin layer and MW drying. Furthermore, besides the estimation of the parameters of the drying equations, other technological aspects were also investigated, namely D_{eff}, activation energy, and SEC. Finally, the product's qualitative properties colour and shrinkage were evaluated for the arils dried using CV (in the range from 50 to 70°C) and MW drying (in the range from 270 to 630 W).

2 Materials and methods

2.1 Sample preparation

Pomegranate was supplied by one of the pomegranate orchards of Sardasht city, Iran, in October 2019. Generally, pomegranate aril samples of uniform size were selected. The pomegranate arils were cleaned and stored in a refrigerator at 4 ± 1°C. The premature and spoiled pomegranate fruits were separated manually. The initial MC of pomegranate was measured by oven drying method. A sample batch of pomegranate arils in triplicate essays were dehydrated at 70 ± 1°C for 24 h (Alaei and Chayjan 2015). Pomegranate arils with average initial MC of 70.25 ± 0.50% (wet basis), corresponding to 2.36 g/g dry solids, were selected for drying experiments. About 40 g of pomegranate arils was used for each of the drying experiments. The weight of the samples was measured by a digital balance, and recorded in time intervals of 10 min. The drying experiments of pomegranate arils continued until the MC of the samples reached about 0.1 (dry basis) in both drying methods.

2.2 Drying apparatus

2.2.1 CV dryer

CV drying was conducted using a laboratory drying oven (BF55E; FG Co., Iran). The inside air velocity close to the pomegranate samples was measured by an anemometer (Lutron AM-4202; Electronic Enterprise Co., Taipei, Taiwan), and the average air velocity was 1.00 ± 0.02 m/s. The electrical heating unit of this dryer is equipped with a PT100 thermometer sensor and a PID controller with ±0.1°C accuracy. The air temperature and relative humidity (RH) have been measured for the laboratory ambient. Therefore, during the experiments of CV drying, air temperature of ambient has been recorded as 26°C using a thermometer with type K (NiCr–Ni) thermocouple sensor and accuracy of ±0.1°C (Lutron TM-903, made in Taiwan) as well as air RH of ambient has been obtained 30% by a hygrometer with accuracy of ±3% RH (Lutron TM-903, made in Taiwan). Therefore, on average, during the CV dryings, average ambient air humidity and temperature were 30% and 26°C, respectively.

2.2.2 MW dryer

A fully programmable MW oven (Panasonic NN-CD997S Microwave Oven) with maximum output of 1,000 W was used in the experiments. The MW oven has the capability of operating at different MW output powers: 90, 180, 270, 360, 450, 540, 630, 720, 900, and 1,000 W. The area of the MW oven is 462 × 242 × 412 mm inner size and includes a 380 mm diameter rotary glass plate at the oven base. The MW output power and processing time were set fully using the oven digital control panel. The experiments of MW drying were carried out individually, and there was no control for measuring humidity inside the MW chamber during drying process because a local MW was used for the experiments. The power levels were the input parameters for MW drying process. The measurement of weight was done manually in the specific intervals during the drying experiments.

2.3 Experimental setup

2.3.1 Determination of MC and moisture ratio

Drying curves may be represented in different ways: MC at wet or dry basis versus time (t), drying rate versus time, or drying rate versus MC. The MC considered in the present study was the dry basis MC (M). Both M and moisture ratio (MR) of pomegranate arils were calculated using equations (1) and (2), respectively (Jebri et al. 2019):

$$M = \frac{((m_0 - m_v) - m_{dm})}{m_{dm}}, \quad (1)$$

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

where m_0, m_v, and m_{dm} are the initial mass, the mass of vapour (evaporated moisture), and the dry matter, respectively (g). In addition, M_0, M_t, and M_e represent the dry basis MC at time zero, time t, and equilibrium, respectively (kg water/kg dry matter).

It should be noted that, according to Süfer and Palazoğlu (2019), because usually the value of M_e is very low compared with M_t and M_0, then it can be considered not relevant for the calculation of the MR, and in that case equation (2) can be simplified to equation (3), which was used in the present work for the determination of the MR values:

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

2.3.2 Mathematical modelling of drying curves

To analyse the data for the drying curves obtained in the experimental essays, appropriate fitting equations were used. The models listed in Table 1 were used for the mathematical modelling of drying kinetics of pomegranate arils in CV and MW dryers. The CurveExpert software (version 1.4) was used to fit the equations in Table 1.

To select the suitable drying kinetics descriptor, the statistical parameters of coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2) were used. In this way, the drying model with maximum R^2 and minimum RMSE and χ^2 was selected as the most appropriate model for describing drying kinetics. The mentioned statistical parameters are defined by the following equations (Alaei and Chayjan 2015):

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

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

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

Table 1: Empirical mathematical models for drying kinetics

Models	Equation	References
Page	$MR = \exp(-kt^n)$	Ashtiani et al. (2018)
Aghbashlo	$MR = \exp\left(-\left(\frac{at}{1+bt}\right)\right)$	Kayran and Doymaz (2017)
Wang and Singh	$MR = 1 + at + bt^2$	Agbede et al. (2020)
Logarithmic	$MR = a\exp(-kt) + c$	Jebri et al. (2019)
Two-term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	İlter et al. (2018)

In these equations, $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted values of moisture ratio for a number of observations N, and z represents the number of model parameters.

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 vapour 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 transmission processes, it is difficult to examine each mechanism and measure the mass transfer rate in each one. In such processes, the description of effective diffusion is described by the Fick's second law as follows (Agbede et al. 2020):

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \nabla^2 M, \tag{7}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), M is the dry basis material MC (kg water/kg dry matter), and t is the time (s).

Calculation of D_{eff} using the Fick's second law is a tool for describing the drying process and possible mechanisms for the transfer of moisture within food products. Assuming that the pomegranate arils resembled a spherical geometry, considering a uniform distribution of the initial moisture, assuming a symmetric mass transfer in turn of the centre of the arils, assuming that the surface resistance to the mass transfer of the water from the aril to the surrounding air was negligible, and that the diffusion coefficient could be approximated to a constant value throughout the process, then the analytical solution of Fick's law can be represented by the following equation (Süfer and Palazoğlu 2019):

$$\text{MR} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n^2 \frac{D_{\text{eff}}\, t}{r_p^2}\right), \tag{8}$$

where M_t, M_o, and M_e corresponding to the moisture at any time, initial, and equilibrium (kg water/kg dry matter), and where n is a positive integer that can be considered equal to 1 for long drying time. Therefore, equation (8) can be written in a simpler form as:

$$\text{MR} = \left(\frac{6}{\pi^2}\right) \exp\left(-\frac{\pi^2 D_{\text{eff}}\, t}{r_e{}^2}\right). \tag{9}$$

By plotting the curve ln(MR) versus time, in accordance with equation (9), the slope (K_1) allows calculating the effective diffusivity as follows (Alaei and Chayjan 2015):

$$K_1 = \left(\frac{D_{\text{eff}} \pi^2}{r_p^2}\right), \tag{10}$$

where r_p is the dimension (m), in this case corresponding to the sample radius, given the spherical shape assumed.

2.3.4 Activation energy

The dependence of the diffusion coefficient with temperature follows an Arrhenius type model as shown in equation (11). Activation energy of the CV dryer ($E_{a(c)}$) was determined by plotting the D_{eff} curve versus absolute air temperature (T_a) reversal (Jebri et al. 2019).

$$D_{\text{eff}} = D_0 \exp\left(\frac{E_{a(c)}}{R_g T_a}\right), \tag{11}$$

where D_0 is a constant and R_g is the universal gas constant (8.3143 kJ/mol).

The linear form of equation (11) can be obtained by applying the logarithms as:

$$\ln(D_{\text{eff}}) = \ln(D_0) - \left(\frac{E_{a(c)}}{R_g} \cdot \frac{1}{T_a}\right), \tag{12}$$

and the slope (K_2) can be obtained by plotting $\ln(D_{\text{eff}})$ versus $\frac{1}{T_a}$, thus allowing to calculate the activation energy for the CV, $E_{a(c)}$ expressed in kJ/mol:

$$K_2 = \frac{E_{a(c)}}{R_g}. \tag{13}$$

Linear regression analysis was used to fit the equation to the experimental data to obtain coefficient of determination (R^2), considering a level of significance of 5% ($p < 0.05$).

Similar to what was done to obtain the activation energy of the CV dryer, also the activation energy for MW dryer ($E_{a(m)}$ expressed in W/g) was calculated using an Arrhenius type function that relates D_{eff} and the ration of mass to MW power (m/P (g/W)) (Agbede et al. 2020):

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_{a(m)} m}{P}\right). \tag{14}$$

Therefore, $E_{a(m)}$ may be obtained by the logarithmic form of equation (14):

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

By plotting $\ln(D_{\text{eff}})$ versus $(1/P)$, the slope (K_3) is calculated for the MW and allows calculation the activation energy for the MW:

$$K_3 = \frac{E_{\text{a(m)}}}{P}. \quad (16)$$

2.3.5 Specific energy consumption

The specific energy consumed during the drying process, which is the amount of energy used to evaporate 1 kg of water from the product, was obtained using equation (17) under MW drying method (Taghinezhad et al. 2020):

$$\text{SEC}_{\text{mic}} = \frac{P_{\text{mic}} t_1}{m_{\text{w}}}. \quad (17)$$

In this equation, SEC_{mic} is the specific energy consumption for MW, P_{mic} is the MW power (W), t_1 is the drying time (s), and m_{w} is the mass of evaporated water (kg).

SEC_{con} of pomegranate arils in CV drying approach was measured through equation (18) as follows (Kaveh et al. 2020):

$$\text{SEC}_{\text{con}} = (C_{\text{pa}} + C_{\text{pv}} h_{\text{a}}) Q t_2 \frac{(T_{\text{in}} - T_{\text{am}})}{m_{\text{v}} V_{\text{h}}}. \quad (18)$$

In the above equation, C_{pa} and C_{pv} are the air- and vapour-specific heat capacities (1,828.8 and 1,004.16 J/(kg°C), respectively), h_{a} is the absolute air humidity (kg vapour/kg dry air), Q is the inlet air to drying chamber (m^3/min), t_2 is total drying time (min), T_{am} and T_{in} are the temperatures of ambient and inlet air to drying chamber, m_{v} is the mass of water removed (kg), and V_{h} is the specific air volume (m^3/kg).

2.3.6 Colour

The *Lab* model is often used in food colour research studies, where L represents brightness, in the range 0–100 (black to white), and two coloured components: a (greenness to redness) and b (blueness to yellowness), both in the range from −120 to +120. After each experiment, the colour parameters of whole mass of different pomegranate arils samples used for that drying process were measured in three replications using digital portable colorimeter (HP-200, China) in an imaging box with a black background and standard illuminant.

Total colour changes (ΔE) was calculated using equation (19). All colour changes were obtained with averaging in three replicates samples (İlter et al. 2018):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2}, \quad (19)$$

where ΔL^*, Δb^*, and Δa^* are the differences in lightness, parameter b, and parameter a, respectively.

2.3.7 Shrinkage

To calculate the degree of shrinkage, the pomegranate arils' volume was measured before and after the drying process through the toluene displacement method using a pycnometer (Dehghannya et al. 2019). Based on the measuring of primary and secondary volumes of material, shrinkage of pomegranate arils (S_{b}) was determined using the following equation (Ashtiani et al. 2018):

$$S_{\text{b}} = \frac{(\theta_{\text{o}} - \theta_{\text{f}})}{\theta_{\text{o}}} \times 100, \quad (20)$$

where θ_0 and θ_{f} are the initial and final volumes (cm^3).

2.3.8 Statistical analysis

The results obtained for the different properties of the dried pomegranate arils were submitted to a statistical analysis, by comparing the mean values in ANOVA with *post hoc* test of Tukey. The results were expressed as mean values ± standard deviation. For this, a level of significance of 5% was considered ($p < 0.05$) and software SPSS version 26 was used.

Ethical approval: The conducted research is not related to either human or animal use.

3 Results and discussion

3.1 Drying characteristics

Variation in dry basis MC (M) of pomegranate arils with drying time at different air temperatures 50, 60, and 70°C and air velocity 1 m/s is shown in Figure 1. The curves for variation in the MC on dry basis versus time showed how the moisture varied within the sample. Typical CV drying curves would reveal some characteristic drying stages, namely the initial stage, when the sample mass is being

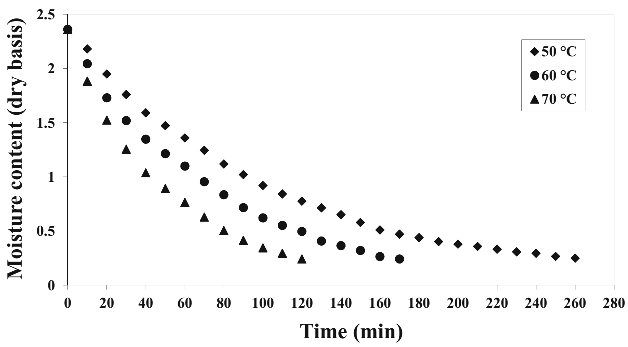

Figure 1: Experimental drying curves for convective drying of pomegranate arils under different air temperatures, in the form of dry basis moisture content versus drying time.

heated to reach equilibrium with the drying air, the following stage corresponds to maximum and constant drying rate, and during this phase the material surface is kept wet because the rate of transfer from the inner sample to the surface equals the rate of evaporation of the water from the surface, and then a period of decreasing drying rate, when the surface starts do dry. In the case of drying of pomegranate arils under the experimented conditions, the initial phase was not observed, which means that the heating of the sample was very fast. Moreover, the constant rate period was very short, and the curves show mostly the falling rate period for all temperatures tested.

As expected, the increment in the drying air temperature caused a decrease in drying time of pomegranate, which is in line with the results of Agbede et al. (2020) and Cuccurullo et al. (2019). In the process of CV drying, increasing the drying air temperature from 50 to 70°C lead to the increase in mass transfer ratio and a reduction in the drying process time and energy consumption. Drying time for pomegranate arils were 260, 170, and 120 min at 50, 60, and 70°C, respectively. The results are in accordance with Süfer and Palazoglu (2019) that, for pomegranate arils, reported the drying times of 660, 240, and 150 min at air velocity 1 m/s for three drying air temperatures 55, 65, and 75°C, respectively. Contrarily, Briki et al. (2019) reported that air temperature had a small effect on drying time in CV drying of pomegranate arils in the temperature range similar to that of the present work, 50–70°C.

The mathematical modelling of pomegranate arils' drying kinetics in the CV dryer was done using five common mathematical models for thin layer products (Table 1). For all CV drying experiments (50, 60, and 70°C air temperature and 1 m/s air velocity), the calculated values of regression coefficient (R^2), RMSE, and reduced χ^2 ranged between 0.9935 and 0.9999, 0.0159 and 0.0754, and 0.0002 and 0.0339, respectively, as shown in Table 2. These results indicated that the Page Model had the highest values of R^2 (0.9997–0.9999), and the lowest RMSE (0.0159–0.0754) and χ^2 (0.0003–0.0011). Therefore, the Page model was selected as the most appropriate to describe the drying behaviours of pomegranate arils. Jebri et al. (2019) tested five empirical models (Newton, Page, Henderson and Pabis, Logarithmic, and Two-term) in their research for CV drying of *Salvia officinalis* L. and claimed that all models described well the drying kinetics at the tested air temperatures and air velocities. İlter et al. (2018) examined the kinetics of drying garlic puree in CV and MW. Among the models used, the Logarithmic model in both CV and MW dryers was the best model for prediction of the MC of garlic puree.

Figure 2 shows the variation in pomegranate arils' MC (dry basis) with drying time in MW dryer at different MW powers (270, 450, and 630 W). It can be observed that the rate of water loss in MW method was higher than CV because of the electromagnetic heating effect of MW in drying food products. In addition, with higher MW power, more heat generated within the sample creates a larger vapour pressure difference between the centre and the product's surface, thus accelerating the interior moisture migration and increasing surface water

Table 2: Statistical parameters characterizing the modelling of pomegranate arils' drying in CV 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
Page	0.9999	0.9997	0.9997	0.0002	0.0010	0.0011	0.0159	0.0175	0.0181
Aghbashlo	0.9996	0.9995	0.9996	0.0014	0.0017	0.0015	0.0201	0.0221	0.0207
Wang and Singh	0.9975	0.9968	0.9959	0.0064	0.0105	0.0177	0.0425	0.0469	0.0533
Logarithmic	0.9977	0.9965	0.9988	0.0071	0.0126	0.0055	0.0409	0.0511	0.0354
Two-term	0.9935	0.9947	0.9960	0.0339	0.0259	0.0754	0.0224	0.0611	0.0525

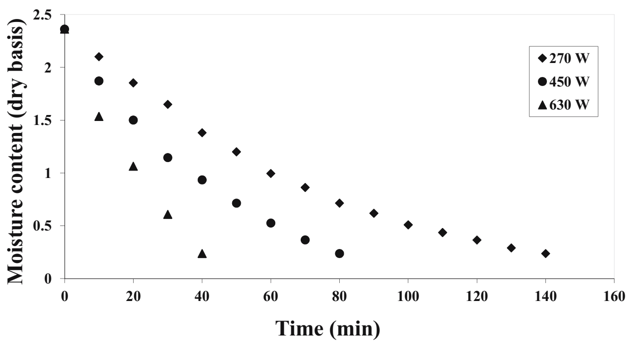

Figure 2: Experimental drying curves for microwave drying of pomegranate arils under different microwave powers, in the form of dry basis moisture content versus drying time.

evaporation (Dai et al. 2019). In MW, the duration of the drying processes was 40, 80, and 140 min at 630, 450, and 270 W, respectively. As expected, the results showed that increasing MW power tends to decrease the drying time. Similar trends were obtained by other researchers for drying fruit in MW dryers, such as for quince slices (Taghinezhad et al. 2020), kiwi slices (Darvishi et al. 2016), and apple slices (Horuz et al. 2018).

Table 3 presents the results of the fitting with mathematical models to data of pomegranate arils drying by MW method. For all MW drying experiments, values of R^2, RMSE, and χ^2 ranged between 0.9929 and 0.9999; 0.0193 and 0.0831, and 0.0004 and 0.0369, respectively. Page model presented the highest value of R^2 (0.9999) and the lowest RMSE (0.0193) and χ^2 (0.0004) values.

Darvishi et al. (2014) dried white mulberry in MW drying at 100, 200, 300, 400, and 500 W power levels and applied to the experimental data of five thin layer models: Lewis, Henderson and Pabis, Page, Wang and Singh, and Midilli et al. Their results showed that the Page model presented the highest value of R^2 (0.999), and lower RMSE (0.009) and χ^2 (0.00009) values.

Table 4 presents the values obtained for all parameters in the models listed in Table 1, obtained by fitting the experimental data for both types of drying CV and MW. These parameters allowed making predictions of the drying curves, and therefore Figure 3 shows these curves predicted with model Page together with the experimental points. The selection of the model Page to highlight this fitting was because based on the previous discussion of the results, the Page model was the one with best fitting performance for both dryings, CV and MW. The results in Figure 3 confirm the good agreement between the experimental and predicted curves for the three temperatures in the case of CV and three powers in the case of MW.

3.2 Effective moisture diffusivity

The D_{eff} values of pomegranate arils at different drying temperatures were calculated by equation (10). Taghinezhad et al. (2020) reported that, for agricultural and food products, D_{eff} values were in general in the range of 10^{-8} to 10^{-12} m^2/s. In the present experiments of CV drying, the minimum D_{eff} value (4.11×10^{-10} m^2/s) corresponded to the drying at 50°C, and the maximum value (9.35×10^{-10} m^2/s) was obtained for the pomegranate arils' drying at air temperature of 70°C, as shown in Figure 4. These results confirm a direct relation between D_{eff} and temperature, by which increasing the air temperature leads to an increase in D_{eff} and a reduction in the drying time.

The values of D_{eff} obtained in the present work are in accordance with the values reported by Briki et al. (2019) (2.56×10^{-10} to 4.75×10^{-10} m^2/s) for pomegranate arils at 50–70°C in CV dryer. In addition, for drying pomegranate arils in CV dryer at 55–75°C, Süfer and Palazoglu (2019) estimated D_{eff} values from 3.56×10^{-11} to 1.93×10^{-10} m^2/s.

The values of D_{eff} for MW dryer are shown in Figure 5. In this case, the minimum value of D_{eff} (3.14×10^{-9} m^2/s) corresponded to the drying of pomegranate arils at MW

Table 3: Statistical parameters characterizing the modelling of pomegranate arils' drying in MW dryer

Model	R^2			χ^2			RMSE		
	270 W	450 W	630 W	270 W	450 W	630 W	270 W	450 W	630 W
Page	0.9999	0.9997	0.9995	0.0004	0.0009	0.0018	0.0193	0.0224	0.0241
Aghbashlo	0.9997	0.9992	0.9993	0.0011	0.0032	0.0027	0.0239	0.0283	0.0268
Wang and Singh	0.9966	0.9970	0.9949	0.0132	0.0147	0.0262	0.0488	0.0452	0.0696
Logarithmic	0.9982	0.9974	0.9967	0.0098	0.0121	0.0158	0.0349	0.0444	0.0499
Two-term	0.9929	0.9951	0.9938	0.0369	0.0229	0.0311	0.0831	0.0672	0.0761

Table 4: Model parameters for equations in Table 1 obtained for experimental fitting of the data for CV and MW drying of pomegranate arils

Model parameters	Convective drying			Microwave drying		
	50°C	60°C	70°C	270 W	450 W	630 W
Page						
k	1.950×10^{-4}	3.165×10^{-4}	6.358×10^{-4}	6.451×10^{-5}	1.885×10^{-4}	2.103×10^{-4}
n	9.737×10^{-1}	9.589×10^{-1}	9.189×10^{-1}	1.158	1.099	1.176
Aghbashlo						
a	1.607×10^{-4}	2.304×10^{-4}	3.608×10^{-4}	2.039×10^{-4}	3.567×10^{-4}	5.893×10^{-4}
b	4.999×10^{-6}	5.886×10^{-6}	2.530×10^{-5}	-3.249×10^{-5}	-4.470×10^{-5}	-1.391×10^{-4}
Wang and Singh						
a	-1.281×10^{-4}	-1.843×10^{-4}	-2.718×10^{-4}	-1.950×10^{-4}	-3.285×10^{-4}	-5.728×10^{-4}
b	4.709×10^{-9}	9.776×10^{-9}	2.121×10^{-8}	1.060×10^{-8}	3.010×10^{-8}	8.418×10^{-8}
Logarithmic						
a	9.770×10^{-1}	9.856×10^{-1}	9.531×10^{-1}	1.138	1.135	1.331
k	1.646×10^{-4}	2.171×10^{-4}	3.485×10^{-4}	1.991×10^{-4}	3.204×10^{-4}	4.540×10^{-4}
c	2.681×10^{-2}	-3.530×10^{-3}	3.248×10^{-2}	-1.221×10^{-1}	-1.390×10^{-1}	-3.387×10^{-1}
Two-term						
a	9.770×10^{-1}	3.918×10^{-2}	8.455×10^{-2}	5.203×10^{-1}	5.003×10^{-1}	5.037×10^{-1}
k_0	1.646×10^{-4}	2.296×10^{-3}	1.819×10^{-3}	2.519×10^{-4}	4.154×10^{-4}	7.615×10^{-4}
b	2.681×10^{-2}	9.621×10^{-1}	9.162×10^{-1}	5.181×10^{-1}	5.147×10^{-1}	5.092×10^{-1}
K_1	3.270×10^{-14}	2.140×10^{-4}	3.009×10^{-4}	2.519×10^{-4}	4.155×10^{-4}	7.615×10^{-4}

power level of 270 W, and the maximum value (8.55×10^{-9} m^2/s) was for the power level of 630 W. According to the results obtained in the present tested conditions, the values of D_{eff} in MW were higher than those obtained in CV experiments.

The MWs accelerate the vibration of water molecules present in the pomegranate arils, and their faster evaporation, thus providing a faster decrease in the pomegranate arils' MC and the corresponding higher value of D_{eff} (Dai et al. 2019). Similar results for D_{eff} values are reported by other authors for drying fruits and vegetables in MW dryers. For example, Minaei et al. (2012) reported D_{eff} values in the range of 6.77×10^{-10} to 52.5×10^{-10} m^2/s, 3.43×10^{-10} to 29.19×10^{-10}, and 4×10^{-10} to 32×10^{-10} m^2/s, for pomegranate arils in vacuum, MW, and infrared dryers, respectively. Taghinezhad et al. (2020), for the drying of sliced quince, reported that D_{eff} values increased from 7.73×10^{-10} to 22.83×10^{-9} m^2/s at different MW power levels, ranging from 100 to 300 W, in MW dryer. Darvishi et al. (2014) for dried mulberry referred that D_{eff} increased from 1.06×10^{-8} to 3.45×10^{-8} m^2/s with the increase in MW power from 100 to 500 W.

3.3 Activation energy

During drying, the highest values of activation energy (E_a) obtained for CV and MW methods were 63.11 kJ/mol and 14.13 W/g, respectively (Table 5). The air temperature and MW power were important factors influencing the D_{eff} and also the activation energy. It is confirmed that increasing the temperature and MW power reduces the E_a, as a result of higher mass transfer and moisture loss of pomegranate arils.

The obtained results are in line with those reported by Jebri et al. (2019), according to which the values of E_a for CV and MW drying of *Salvia officinalis* leaves were 1.054 kJ/mol and 4.85 W/g, respectively. İlter et al. (2018), in their study about drying of garlic puree, obtained E_a values of 20.90 kJ/mol and 21.96 W/g, in CV and in MW dryers, respectively.

3.4 Specific energy consumption

Figure 6 shows the values of SEC for three drying temperatures of pomegranate aril in CV dryer. In this study, the SEC obtained was in the range of 79.44–145.12 kWh/kg. The highest and lowest SEC values were consumed at drying temperatures of 50 and 70°C, respectively. From Figure 6, it is also observed that SEC reduces with the increase in the drying air temperature.

Even though the specific heat of the air is lower at higher temperatures, the increase in the air temperature of the drying chamber decreases the amount of energy consumed by the process because of the substantial reduction in the process duration at these temperatures

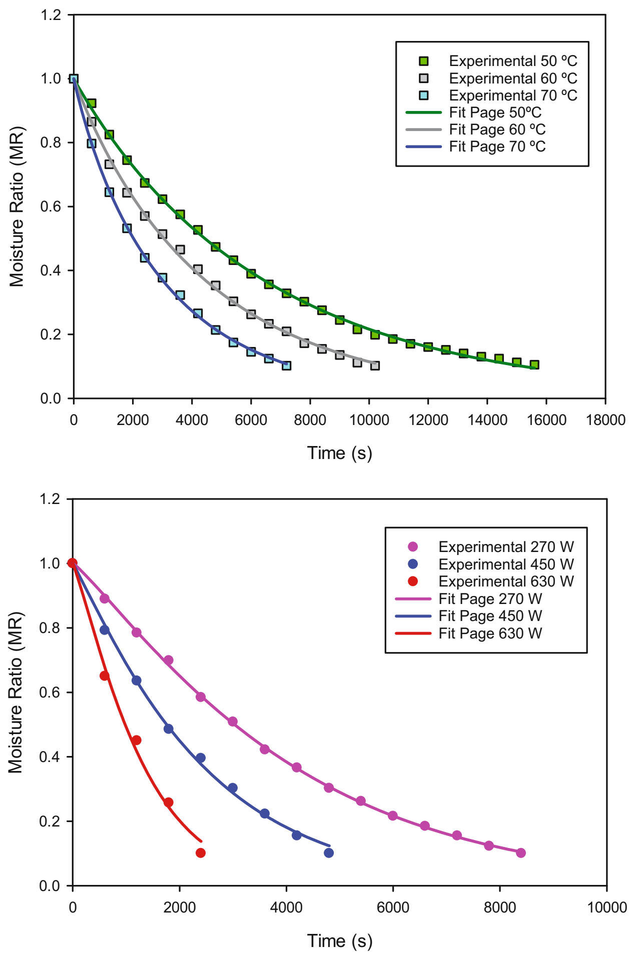

Figure 3: Experimental curves for moisture ratio versus time and fitting with model Page for convective drying (top) and for microwave drying (bottom) of pomegranate arils.

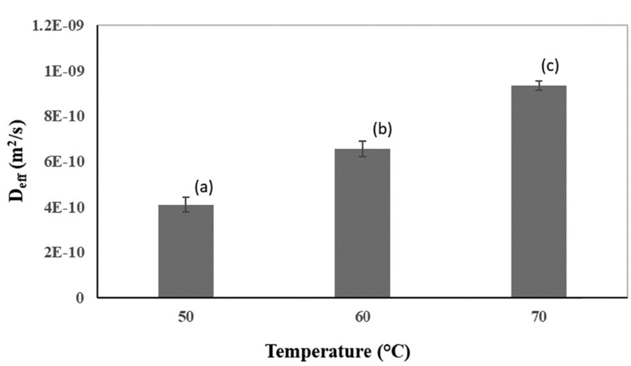

Figure 4: Variation in D_{eff} for the drying of pomegranate arils at different CV temperatures. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

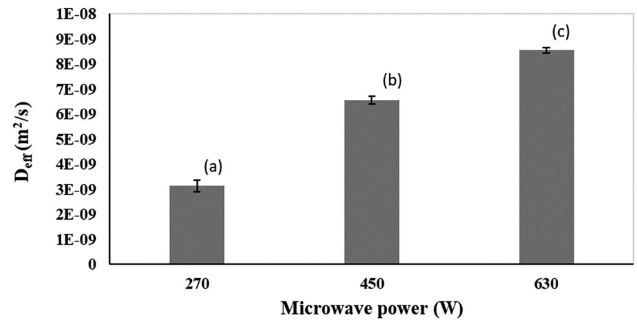

Figure 5: Variation in D_{eff} for the drying of pomegranate arils at different MW powers. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

Table 5: Estimated activation energy in CV and MW dryers

Convective dryer		Microwave dryer	
Air temperature (°C)	E_a (kJ/mol)	Microwave power (W)	E_a (W/g)
50	63.11	270	14.13
60	52.52	450	13.50
70	37.28	630	13.09

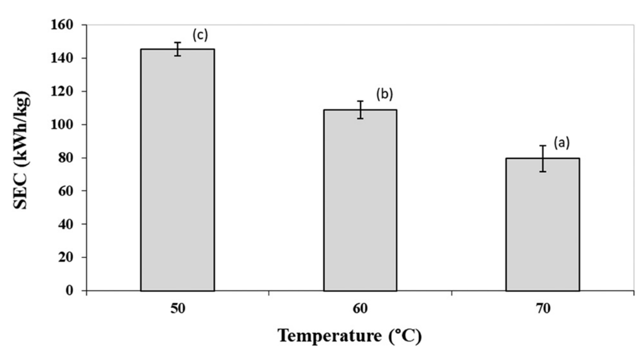

Figure 6: Values of SEC in CV for different drying air temperatures. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

(Kaveh et al. 2020). The values of SEC are considerably higher than the reported value of 21.57 kWh/kg for CV drying of dog-rose at 40°C and 1 m/s (Motevali and Koloor 2017), but lower that 184.29 kWh/kg reported for the drying of *Pistacia atlantica* in CV dryer with hot air at 40°C and an air velocity of 1.5 m/s (Kaveh et al. 2020).

As shown in Figure 7, during the drying process of pomegranate arils in MW dryer, the SEC at 270 and 630 W were obtained as 35.42 and 13.19 (kWh/kg), respectively. In this case, the ratio between the highest and lowest

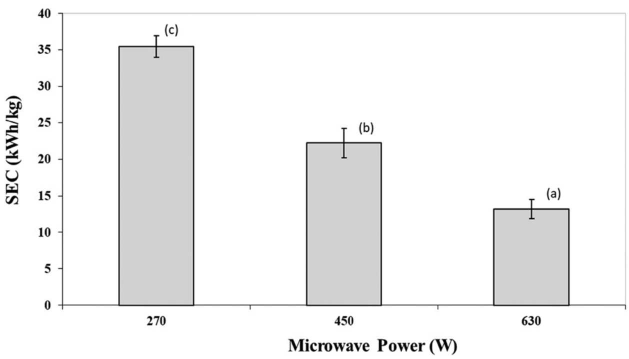

Figure 7: Values of SEC in MW for different microwave powers. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

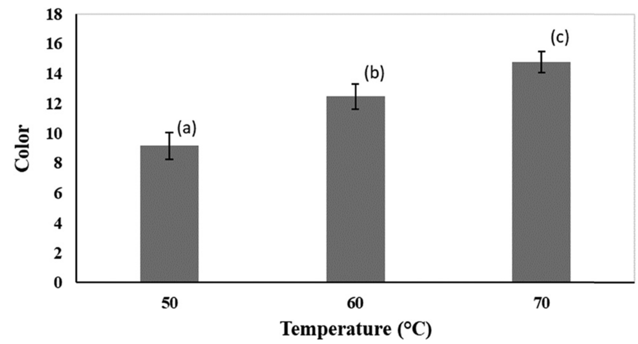

Figure 8: Colour change of dried pomegranate arils in CV dryer. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

values of SEC is 2.68. According to the results, with the increase in MW power, a significant decrease in SEC is observed, almost three times less.

The reduction in SEC at higher MW power is because of the effect of its volumetric heating, which reduces the drying time (Taghinezhad et al. 2020). Advantages such as shorter drying times and lower SEC were the key drivers for the further development of the MW drying technique (Motevali and Koloor 2017). In the drying of cherry tomatoes, Kipcak and Doymaz (2020) reported that the minimum obtained value of SEC was 0.0420 kWh at MW power 360 W. In addition, Çelen (2019), in MW drying of trabzon persimmon, report that the maximum and minimum values of SEC obtained were 0.05 and 0.1 kWh, at the range of MW power 120–600 W. Although these values are not directly comparable with ours, they also allow calculating the ration between highest and lowest values of SEC, which is for the MW drying of trabzon persimmon equal to 2, which is relatively similar to the value we obtained of 2.68.

3.5 Colour

Colour is one of the most important marketing qualitative properties of fresh or processed food products. Figure 8 shows the colour variations (ΔE) of dried pomegranate arils, in relation to the unprocessed product, for the CV drying at different temperatures (50, 60, and 70°C). For the dried pomegranate arils, the highest and the lowest values of colour variation were 14.78 and 9.15, corresponding to the temperatures of 70 and 50°C, respectively. It is observed that the increase in drying air temperature induced an increase in the colour change. During the drying process, oxidation occurs and, as a result of this oxidation, the intensity of the colour decreases. The colour changes (16.70–18.61) of pomegranate arils at near infrared (NIR)-vacuum dryer were reported by Alaei and Chayjan (2015). For dried pomegranate arils in CV dryer, Süfer and Palazoglu (2019) reported the minimum colour change of 6.17 for air drying temperature of 55°C, whereas the maximum colour change of 8.03 was observed for 70°C.

As shown in Figure 9, colour changes in MW dryer increased from 6.77 to 13.11 with the increase in MW power from 270 to 630 W. In the MW drying process, the MW power and process duration are the relevant factors that influence the sample colour change. The change in the colour of the pigments can be because of the effect of heat on heat-sensitive compounds such as carbohydrates, proteins, and vitamins, which also causes colour change during the drying process (Xu et al. 2020). According to Horuz and Maskan (2015), the maximum

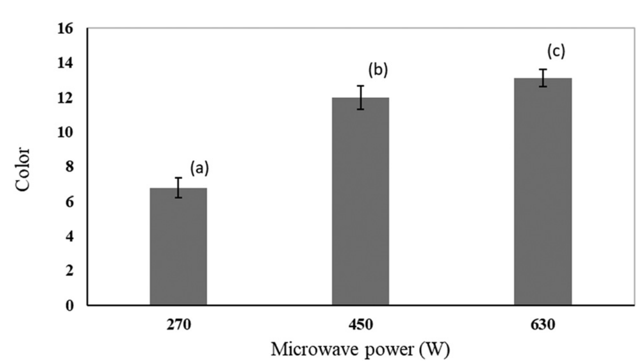

Figure 9: Colour change of dried pomegranate arils in MW dryer. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

and minimum values of 3.87 and 27.93 were obtained for colour change of pomegranate arils in MW drying for powers varying in the range of 210–490 W.

3.6 Shrinkage

The values of pomegranate arils shrinkage for CV and MW dryers are reported in Figures 10 and 11, respectively. As can be observed in Figure 10, from the experiments in CV dryer, the shrinkage ranged from 54.35 to 76.8%, for the drying temperatures of 70 and 50°C respectively.

In the MW drying approach, as shown in Figure 11, the highest shrinkage (70.21%) was obtained at the MW power of 270 W, and the lowest value (50.5%) occurred for MW power of 630 W.

The results obtained from both drying techniques indicate that increasing the drying air temperature or MW power led to faster processes and consequently to lower shrinkage rates. This may be explained by the shrinkage rate dependence from sample MC, so increasing drying air temperature or MW power causes higher rate of water evaporation. Yemmireddy et al. (2013) reported that drying at lower temperatures promoted relatively more shrinkage as compared with higher temperatures, which was explained by the fact that at longer drying times the samples have more time to allow the structure rearrangements and shrinking. During the drying process, the intercellular water moves regularly and air replaces it, and this leads to tensions in the structure of the cells. As a result, the texture would not be able to keep its structural network, the external structure of the cell collapses, and shrinkage takes place (Ashtiani et al. 2018). These changes were more evident for the samples submitted to CV drying as compared with MW drying.

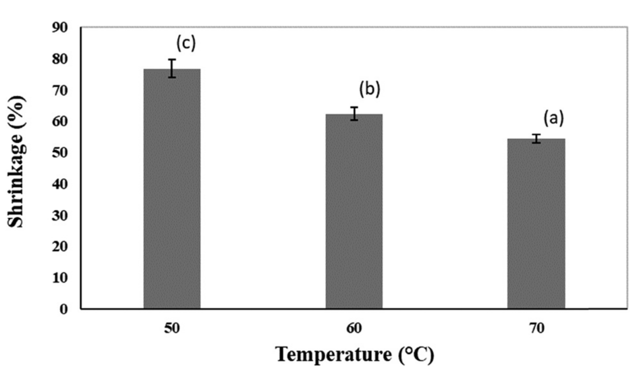

Figure 10: Shrinkage of dried pomegranate arils in CV dryer. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

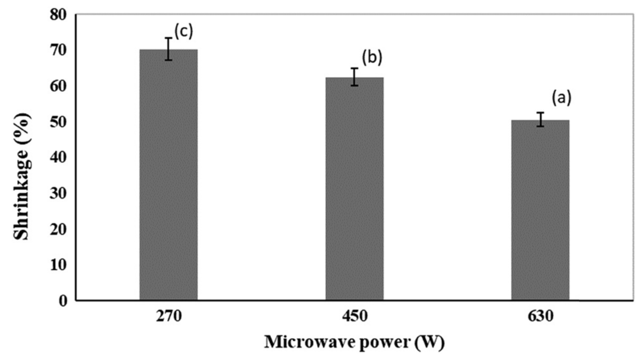

Figure 11: Shrinkage of dried pomegranate arils in MW dryer. The bars represent mean values and the corresponding standard deviations. Bars with the same letter are not significantly different according to ANOVA and Tukey test ($p < 0.05$).

Our results are in accordance with those reported by Horuz and Maskan (2015) in their work on drying pomegranates, according to which the maximum shrinkage rates were 78.57% for a drying temperature of 50°C (in a tested range from 50 to 70°C) and 65.45% for a MW power of 210 W (in a tested range from 270 to 630 W). However, contradicting results were obtained by Süfer and Palazoglu, (2019) in their study on CV drying of pomegranate arils, according to which the highest shrinkage rate (79.74%) was achieved for a higher drying temperature (75°C), and the lowest (72.88%) for a temperature of 55°C.

4 Conclusions

In this study, the effects of CV drying at three air temperatures (50, 60, and 70°C) and MW drying at three MW powers (270, 450, and 630 W) on the drying characteristics of pomegranate arils were evaluated. The duration of the process for pomegranate arils' drying by MW was shorter if compared to CV drying. The results showed that the Page model was the most suitable for prediction of pomegranate arils' MR. This model presented the highest coefficients of determination (R^2) and the lowest χ^2 and RMSE values. Therefore, this model is appropriated to describe the drying characteristics of pomegranate arils dried by both drying methodologies. The maximum D_{eff} value of 8.55×10^{-9} m^2/s was obtained for the MW method and at a MW power of 630 W. The minimum SEC value (13.19 kWh/kg) was obtained also for MW drying method, but for 270 W. The colour changes were higher as the temperature or power increased, respectively, for CV or MW drying techniques. Finally, shrinkage was found more intense for longer drying processes, i.e., for lower temperature and lower power, respectively, for CV and MW methods.

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Author contribution: MK and IG: conceptualization; MK, IG, and RG: data curation; MK, IG, and SG: formal analysis; RG and JCG: funding acquisition; MK and IG: methodology; MK and IG: resources; MK, IG, and SG: writing – original draft; RG and JCG: writing – review and editing.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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