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The comparison of drying and rehydration characteristics of intermittent-microwave and hot-air dried-apple slices

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Abstract

The influence of intermittent-microwave drying and hot-air drying on drying characteristics and rehydration properties of apple slices were compared. Microwave powers have crucially affected the drying rate, effective moisture diffusivity and drying time. As microwave power increased, the drying rate and effective moisture diffusivity increased while the drying time reduced. In intermittent-microwave drying, the effective moisture diffusivities were estimated between 4.47×10^{-9} and 2.54×10^{-8} $m^2\ s^{-1}$. Longer drying time, slower drying rate and less effective moisture diffusivity were obtained from hot-air drying when compared to intermittent-microwave drying. Higher temperatures provided higher drying rate and effective moisture diffusivity. Effective moisture diffusivities of hot-air dried-apple slices were calculated in the range of 3.38×10^{-10}–6.25×10^{-10} $m^2\ s^{-1}$. Moreover, Page model gave the best fitting to intermittent-microwave drying curves, while hot-air drying curves were suitably described by Parabolic Model. On the other hand, the rehydration ratio of intermittent-microwave dried-apple slices was higher than hot-air dried-apple slices. Additionally, Peleg model was defined to be the best model predicting experimental rehydration data in both drying techniques.

Keywords Apple slices · Hot-air drying · Intermittent-microwave drying · Rehydration

Abbreviations

MR	Moisture ratio
M_t	Moisture content at any of time (g g^{-1} dry matter)
M_i	Initial moisture content of samples (g g^{-1} dry matter)
M_e	Equilibrium moisture content (g g^{-1} dry matter)
DR	Drying rate (g water g^{-1} dry matter.min^{-1})
$M_{t+\Delta t}$	Moisture content at time difference
Δt	Difference of time between two measuring points
RMSE	Root mean square error
χ^2	Reduced chi-square
$MR_{pre,i}$	Predicted MR of mathematical models
$MR_{exp,i}$	Is experimental MR,
D_{eff}	The effective moisture diffusivity ($m^2\ s^{-1}$)
L	Half-thickness of initial size of sample before drying (m)
R	Universal gas constant (1.987 cal mol^{-1} K^{-1} or 8.314 J mol^{-1} K^{-1})
T	Absolute temperature,
E_a	Activation energy (kJ mol^{-1}, kcal mol^{-1} or W g^{-1})
D_0	The pre-exponential constant ($m^2\ s^{-1}$)
m	Initial sample weight (g)
P	Microwave output power
RR	Rehydration ratio
M_0	Weight of non-rehydrated sample,
M_r	Weight of rehydrated sample at any of time
M	Moisture content of sample (g water g^{-1} dry matter)
t	Drying or rehydration time (min),
k_1	Rate constant of Peleg (min g water g^{-1} dry matter)
k_2	Capacity constant of Peleg (g water g^{-1} dry matter)

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α	Is the shape of Weibull model parameter
β	Is the speed of Weibull model parameter.

Highlights Drying characteristics of apple slices were significantly affected by microwave power and temperature.

As both microwave powers and temperature increased, DR, D_{eff} increased and drying time reduced.

DR and D_{eff} of intermittent-microwave dried-apple slices were higher than hot-air dried-apple slices.

Page model described intermittent-microwave drying curves, while Parabolic model was found to be more suitable for fitting to hot-air drying curves.

Rehydration ratio of intermittent-microwave dried-apple slices were greater than hot-air dried-apple slices.

Peleg model gave the best fitting to rehydration curves of both drying techniques.

1 Introduction

Apple (*Malus domestica*) is one of the important fruits of Turkey with an annual production of 3,625,960 tones [1]. Apples are generally consumed fresh. However, apples are very perishable fruit because of high water content [2]. Chemical reactions, microbiological activity and physical alterations in pre- or post-harvest period of many plant-based foods mostly require high water content [3–5].

The drying process, an alternative process for preservation of foods, aims to reduce water activity by removing water content, extend shelf-life, provide microbiological stability and prevent undesirable physical and chemical alterations [6–10]. In addition to benefits in terms of food quality, drying provides lower packing, transportation and storage costs because of reduction in weight and volume [3]. However, a drying process that last for a long time may cause some quality losses such as degradation of vitamins, unfavorable flavor and color changes or loss of essential amino acids [9, 11].

The main mechanisms of drying are surface diffusion or liquid diffusion on pore surfaces, liquid or vapor diffusion because of moisture concentration differences and capillary movements due to surface forces in granular and porous foods. The main diffusion mechanism, which determines the drying rate, is a function of moisture content and the structure of the foods. The main mechanism may change during the process and determining the main drying mechanism is important in modeling the process [12]. Drying can be generally separated into two periods; constant rate period and one or more falling rate period [13]. Constant rate period is explained with sufficient internal moisture transfer to surface for maintaining a satured surface and thus, evaporation rate remains constant [12, 13]. At the end of the constant period, critical moisture content is reached and the falling rate period begins. The falling rate period is related to unsaturated surface since moisture transfer from interior is insufficient to support evaporation rate on surface, meaning that the rate of moisture transfer from interior is less than the evaporation rate on surface. Therefore, drying rate decreases in falling rate period [13].

Hot-air drying is the most commonly used method for removing water from foods [14]. In hot-air drying, the main mechanism is mass and heat transfer and phase transition. The costs of drying process quietly increase, as hot-air drying requires high energy and is a lengthy process [8, 15, 16]. Some alternative drying methods have been developed for energy efficiency and shortening drying time. Microwave drying, which has become a popular drying method, has many advantages in comparison to hot-air drying [17]. Microwaves could be used at different stages of drying such as pre, during and post drying [18]. In microwave application, water vapor pressure gradient between the surface and inner section of the material occurs due to volumetric heating which is induced by microwave field [19]. Thus, the moisture evaporation rate increases whereas the drying rate considerably increases. Higher microwave power provides more rapid moisture transfer from interior regions of the sample as more heat is generated due to more water vapor pressure gradient between the surface and inner section [20]. Although, microwave treatment accelerates the transfer of moisture, non-uniform distribution of temperature and moisture causes cold and hot surfaces on the food. It is stated that this issue could be eliminated with intermittent-microwave treatment [21]. Besides, microwave drying can be suggested to shorten falling rate period [22]. In addition to this, it was reported that microwave heating provides structural modification such as shrinkage reduction advantage [18].

To determine the drying kinetics of fruit and vegetables, it is noted that thin-layer drying has been used. Thin layer drying technology is a kind of mathematical modelling of drying process which enables to select the most appropriate operating conditions. Thus, drying process can be designed and optimized [23].

Drying process strongly affects final products in terms of structural and physicochemical properties [17]. Rehydration process is mainly carried out before the consumption of dried fruits and vegetables. Rehydration is the process of regaining water to the dried products. Based on water absorption during the rehydration process, the mass of product increases. The rate of rehydration decreases because of moisture content value of the product getting close to the equilibrium moisture content value, while water absorption rate is initially high [24]. Rehydration indicates the damage level of the foods caused by drying process [17, 25]. Different factors such as drying method can affect rehydration properties of dried foods [17].

Microwave drying method has been regarded as an alternative drying method in terms of rapid drying rate, energy efficiency and structural modification. In the literature, there are limited studies related to intermittent-microwave drying and comparison with hot-air drying in terms of drying characteristics and rehydration properties of apple slices. In this context, this study aims to determine and compare the drying and rehydration characteristics of apple slices dried by intermittent-microwave and hot-air drying methods.

2 Materials and methods

2.1 Sample preparation

Apple samples (var. Granny Smith) were provided from a local market in Denizli province of Turkey. To get prepared for the drying process, apple samples were cut into 5 ± 0.1 mm slice thickness after washing and peeling. The determination of initial moisture content of samples was performed in a drying oven at 105 °C till any changes occurred in sample weight. The initial moisture content of apple samples was determined as 85.4 ± 0.9%.

2.2 Drying procedure

In order to carry out hot-air drying experiments, 50 g of apple slices were weighted on a drying tray and placed in air ventilated drying oven (Nüve EN 055/120). The technical properties of the drying oven were given in Table 1. The drying experiments were conducted at three different temperatures (50, 60 and 70 °C). Air circulation was performed with a constant ventilation air velocity through the ventilation duct. Samples were weighted at intervals through digital weight measure with a 0.01 g precision (Denver Instruments, TP-3002, Germany). The drying experiments were concluded when the moisture content of samples was achieved approximately by 5% in wet basis (WB). All of the drying experiments were performed duplicated.

A domestic microwave oven (Arçelik MD 574), which has 700 W output at 2450 GHz, was used for intermittent-microwave drying experiments. The technical properties of microwave oven were presented in Table 1. Three different microwave outputs (460, 350 and 120 W) were selected for microwave drying experiments. For each drying experiments 30 g of samples were weighted on a glass plate and placed in the microwave oven. According to the intermittent on/off timing drying process, as suggested by Demiray et al. [16], Soysal et al. [26] and Beaudry et al. [27], microwave drying procedure was modified for apple drying and carried out 15 s on/10 s off. The microwave power applying for drying process was completed when the moisture content of samples was approximately 5% WB. Two replications were performed at each microwave power levels.

2.3 Mathematical modelling of drying data

Equation (1) was used for the calculation of moisture ratio (MR) of apple slices;

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{1}$$

Equilibrium moisture content (M_e) was ignored due to very small value in comparison to moisture content at any of time (M_t) and initial moisture content (M_i). Moisture content values were expressed on dry matter [14, 28].

Equation (2) was used for the determination of drying rate (DR) [14];

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{2}$$

Where $M_{t+\Delta t}$ represents moisture content at time difference and Δt is difference of time between two measuring points.

Root mean square error (RMSE) and reduced chi-square (χ^2) values were calculated by the Eqs. (3) and (4) as follows;

$$RMSE = \left[\frac{1}{N}\sum_{i=0}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=0}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N - n} \tag{4}$$

Table 1 Technical properties of drying oven and microwave oven

	Drying oven	Microwave oven
Model	NÜVE EN055/120 (Turkey)	Arçelik MD 574 (Turkey)
Chamber capacity	55 L	17 L
Inner dimensions	420 × 370 × 365	26.2 × 45.2 × 32.5 cm
Other technical properties	Constant ventilation air velocity N-Prime PID Microprocessor control system (with the accuracy of 0.1 °C)	Microwave output 700 W

MR_{pre} and MR_{exp} are predicted MR and experimental MR, respectively. N and n are numbers of observation data and constants of thin layer drying models [16, 29, 30]. MATLAB (ver. 8.6) was used for the calculation of statistical parameters and curve fitting. Higher values of R^2 and lower values of χ^2 and RMSE values indicated a better fit of the experimental data to the model [16].

2.4 The calculation of effective moisture diffusivity and activation energy of intermittent-microwave and hot-air dried-apple slices

Fick's second law, suggested by Crank [31], was used for infinite slab object with a constant of moisture diffusivity as Eq. (5).

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-(2n-1)\pi^2\frac{D_{eff}t}{4L^2}\right) \tag{5}$$

Effective moisture diffusivity (D_{eff}) was calculated with the Eq. (5);

Where L is half-thickness of initial size of sample before drying and t is drying time.

Equation (5) can be simplified to straight line for long drying time ($n = 1$) and Eq. (6) can be written as given below [16, 32];

$$\text{In}(MR) = \text{In}\left(\frac{8}{\pi^2}\right)-\left(\frac{\pi^2}{4L^2}D_{eff}t\right) \tag{6}$$

After natural logarithm of MR versus drying time (Eq. 6), the plot gives a straight line with a slope as follows Eq. (7) [16, 28];

$$\text{Slope} = -\frac{\pi^2}{4L^2}D_{eff} \tag{7}$$

Activation energy (E_a) is defined as required energy to initiate moisture diffusion from interior of food in terms of drying process [4]. The lower E_a indicates higher moisture diffusivity and DR in the drying process [33]. Arrhenius equation (Eq. 8), was used for calculation of E_a in in hot-air drying process [16];

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \tag{8}$$

Where D_0 is pre-exponential constant, R is universal gas constant and T represents absolute temperature.

Equation (8) can be rearranged as given below Eq. (9);

$$\text{In}D_{eff} = \text{In}D_0-\frac{E_a}{RT} \tag{9}$$

The slope of Eq. (9). gives E_a.

Due to non-precious measurement of temperature in microwave oven, Arrhenius equation was modified as suggested by Özbek and Dadali [34] as given below Eq. (10);

$$D_{eff} = D_0 \exp\left(\frac{-E_am}{P}\right) \tag{10}$$

Where m is initial sample weight and P represents microwave output power.

After rearranging of Eq. (10), the new equation is written as Eq. (11) below;

$$\text{In}D_{eff} = \text{In}D_0-\frac{E_am}{P} \tag{11}$$

The natural logarithm of D_{eff} versus the ratio of microwave power to sample weight gives a straight line with a slope which represents the E_a.

2.5 Rehydration experiments

Rehydration experiments were carried out at 40 °C. These experiments were performed with a water bath (WB-11 Model, Wisd Laboratory Instruments, Wertheim, Germany). Two hundred milliliter distilled water was added into a 250 mL glass container. The temperature of the water in the glass container was controlled by a digital thermometer with the accuracy of ± 0.1 °C (Thr233x-1). When the temperature of water was 40 °C, 5 g of the dried apple slices was weighted and placed in the rehydration water. Rehydration experiments were followed through for 21 h and during the experiments, samples were taken out from the rehydration water in the first 7 h. Before weighting, excess water was removed from the sample's surface by filter paper. Rehydration processes were duplicated. The rehydration ratio (RR) was calculated by using the Eq. (12) [35];

$$RR = \frac{M_r}{M_0} \tag{12}$$

M_r and M_0 are the weight of the rehydrated sample at any of time and the weight of the non-rehydrated sample, respectively.

Peleg model was described as given below Eq. (13) [24];

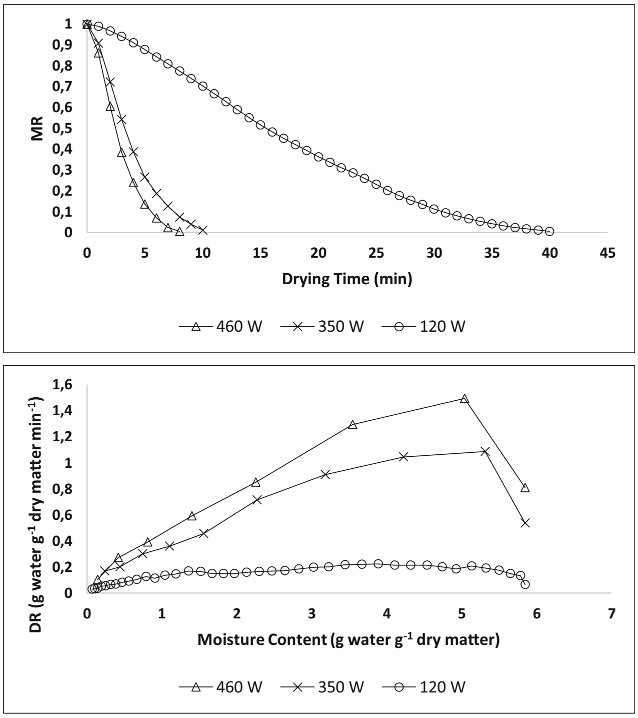

Fig. 1 Variations of MR and DR at different microwave powers

$$M = M_0 + \frac{t}{k_1 + k_2 t} \tag{13}$$

Where M is the moisture content of the sample, k_1 represents the rate constant of Peleg and k_2 is the capacity constant of Peleg.

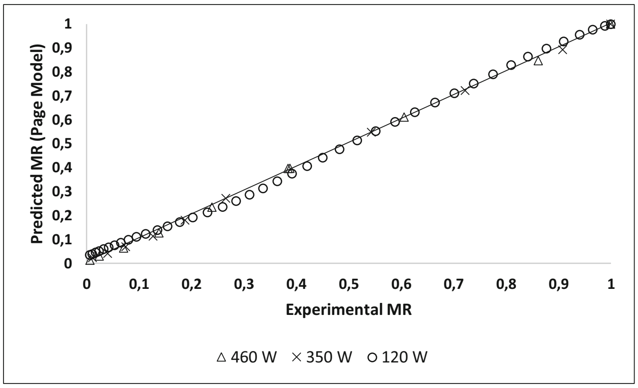

Fig. 2 Comparison of experimental MR and predicted MR (Page model) for intermittent-microwave drying

Equation (14) describes M_e as following [24];

$$M_e = M_0 + \frac{1}{k_2} \tag{14}$$

Unlike drying process, when equilibrium is reached, M_e cannot be easily calculated in rehydration process due to many alterations during gaining water. The Weibull model is described as given below Eq. (15) [24];

$$M = M_e + (M_0 - M_e)\exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{15}$$

Table 2 Model constants and statistical parameters of intermittent-microwave drying curves

Model	Microwave powers	Model constants			χ^2	RMSE	R^2
Lewis model [12]	120 W	k = 0.05326			0.001701851	0.08697	0.9307
	350 W	k = 0.24670			0.004690256	0.07219	0.9588
	460 W	k = 0.33220			0.006525389	0.07616	0.9580
Page model [12]	120 W	k = 0.00762	*n* = 1.650		7.35283E-05	0.01785	0.9972
	350 W	k = 0.11350	*n* = 1.515		8.34117E-05	0.00913	0.9994
	460 W	k = 0.16600	*n* = 1.563		0.000117383	0.00955	0.9994
Henderson and Pabis model [12]	120 W	k = 0.06153	a = 1.154		0.001099967	0.06904	0.9574
	350 W	k = 0.26910	a = 1.097		0.004108810	0.06410	0.9708
	460 W	k = 0.35720	a = 1.085		0.006665143	0.07200	0.9672
Logaritmic model [12]	120 W	k = 0.06226	a = 1.149	c = 0.0063	0.001171161	0.07032	0.9558
	350 W	k = 0.27560	a = 1.088	c = 0.0116	0.00504711	0.06698	0.9681
	460 W	k = 0.36210	a = 1.079	c = 0.0067	0.008176303	0.07383	0.9655
Wang and Singh model [12]	120 W	a = −0.0361	b = 0.0002499		0.000206862	0.02994	0.9920
	350 W	a = −0.1804	b = 0.008071		0.001258121	0.03547	0.9910
	460 W	a = −0.2414	b = 0.01449		0.001904760	0.03849	0.9906
Parabolic model [28]	120 W	a = 1.064	b = −0.04245	c = −0.0003804	8.87707E-05	0.01936	0.9967
	350 W	a = 1.049	b = −0.1990	c = 0.0095520	0.001006434	0.02991	0.9943
	460 W	a = 1.045	b = −0.2624	c = 0.0165540	0.001833302	0.03496	0.9934

Table 3 D_{eff} and E_a of intermittent-microwave and hot-air dried-apple slices

Microwave power	D_{eff} ($m^2\ s^{-1}$)	E_a ($W\ g^{-1}$)	Temperature	D_{eff} ($m^2\ s^{-1}$)	E_a ($kJ\ mol^{-1}$)
120 W	4.47×10^{-9}	6.88	50 °C	3.38×10^{-10}	28.37
350 W	1.73×10^{-8}		60 °C	4.82×10^{-10}	
460 W	2.54×10^{-8}		70 °C	6.25×10^{-10}	

α and β are the shape and speed of Weibull model parameters, respectively.

3 Results and discussion

3.1 The intermittent-microwave drying of apple slices

3.1.1 The influence of microwave power on the drying rate of apples slices

Figure 1 shows variations of MR and DR of intermittent-microwave dried-apple slices. As seen from Fig. 1, microwave powers play an important role on DR. It was observed that DR increased with the increment in microwave powers. The time required to reduce moisture content approximately by 5% (WB) was found as 40, 10 and 8 min for 120, 350 and 460 W. When microwave power raised to 120–350 W, 120–460 W and 350–460 W, reductions in drying time were 75%, 80% and 20%, respectively. The higher the microwave power, the higher the DR and the lower drying time. Higher microwave power provides more heat generation in the sample, which leads to higher evaporation rate, as stated in the introduction section. Çelen et al. [33] similarly reported more DR of microwave dried-apple slices (slice size 6 mm) at higher microwave power. Likewise, short drying time in apple slices was observed at higher microwave powers by İzli and Polat [36]. Zarein et al. [14] have stated the crucial effect of microwave power on drying time in apple slices (slice size 5 mm) and noted that the higher the microwave power, the shorter the drying time. Similar data were reported in other microwave dried-foods by Demiray et al. [16], Özbek and Dadali [34], Alibas [37] and Azimi-Nejadian and Hoseini [38]. DRs of intermittent-microwave dried-apple slices were higher in the initial phase of drying process because of the higher moisture content, which enables higher microwave absorption. Based on the decreasing moisture content, falling rate period was observed in all intermittent-microwave dried-apple slices. Similar findings were notified by Çelen et al. [33], Özbek and Dadali [34], Azimi-Nejadian and Hoseini [38] and Aghilinategh et al. [39]. As presented in Fig. 1, intermittent-microwave drying consists of three stages. The first is the warming-up stage at the beginning of drying process. After warming-up, rapid drying and falling rate stages follow the first one, respectively.

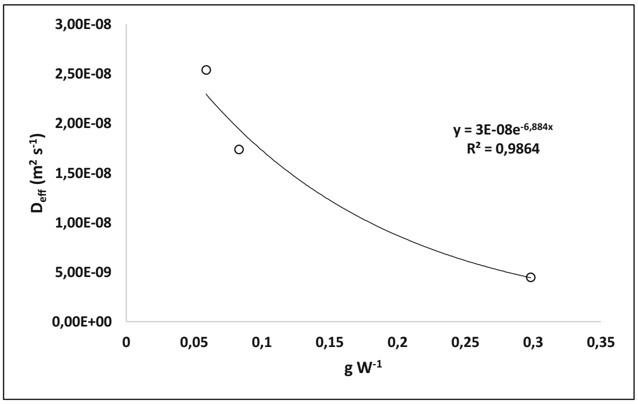

Fig. 3 The relationship between D_{eff} and sample weight for intermittent-microwave drying

3.1.2 The modelling of intermittent-microwave drying curves

As addressed in the introduction section, mathematical modelling has great importance on the designation and optimization of drying process. In this context, statistical parameters to determine the model that predicts experimental data of intermittent-microwave dried-apple slices best were presented in Table 2. As understood from Table 2, the highest R^2, the lowest RMSE and χ^2 were obtained with the Page model in all microwave powers. The Page model could adequately describe the intermittent-microwave drying behavior of apple slices. Comparison of experimental MR and predicted MR (Page model) was shown in Fig. 2. Çelen and Kahveci [40] similarly have stated that the Page model appears to be the best fit with the experimental data of microwave dried apple slices. Likewise, the Page model was found to best explain thin layer drying behavior of apple slices best as compared to the other models by Çelen et al. [33]. On the other hand, İzli and Polat [36] have reported that the Midilli et al. model was the best thin layer model to describe MR of microwave dried-apple slices. In another study, Zarein et al. [14] have observed the Midilli et al. model was best fitted to MR of microwave dried-apple slices. In the lights of these references and the result of this study, the Page and Midilli et al. models may be considered the best models in predicting MR of microwave dried-apple slices.

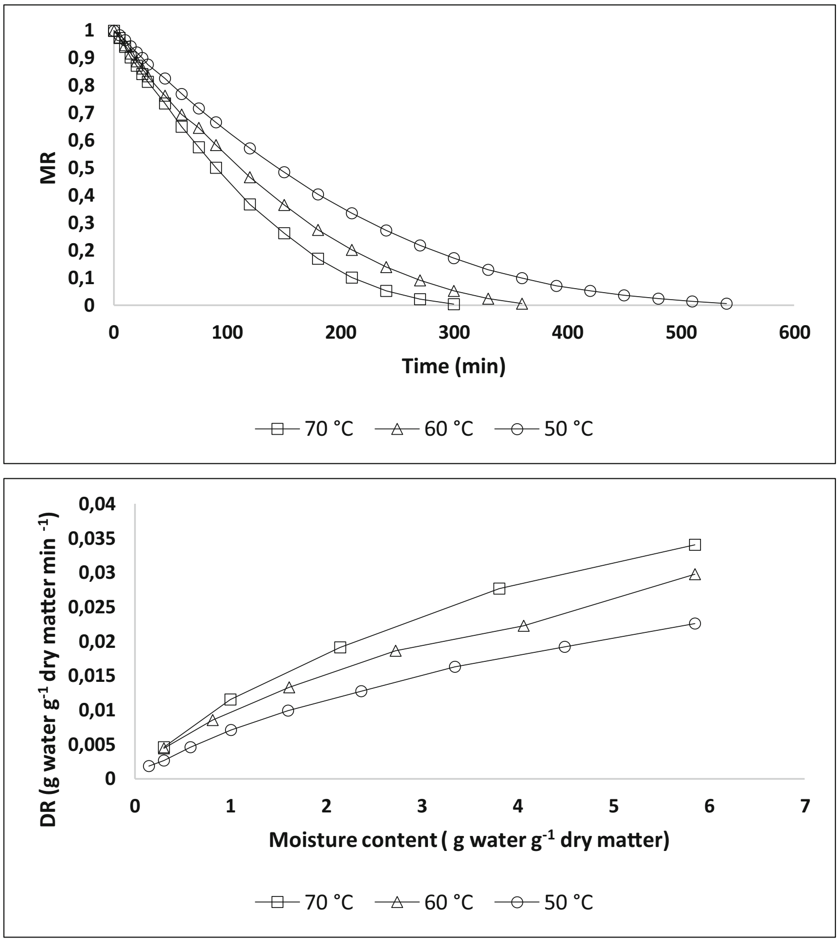

Fig. 4 Variations of MR and DR at different temperatures

Table 4 Model constants and statistical parameters of hot-air drying curves

Model	Temperature	Model constants			χ^2	RMSE	R^2
Lewis model [12]	50 °C	k = 0.005387			0.001482850	0.03776	0.9898
	60 °C	k = 0.007064			0.001901316	0.04250	0.9862
	70 °C	k = 0.008588			0.002365891	0.04727	0.9831
Page model [12]	50 °C	k = 0.001697	*n* = 1.219		0.000234735	0.01472	0.9985
	60 °C	k = 0.002381	*n* = 1.221		0.000567009	0.02259	0.9963
	70 °C	k = 0.002503	*n* = 1.263		0.000464515	0.02032	0.9971
Henderson and Pabis model [12]	50 °C	k = 0.005655	a = 1.040		0.001176178	0.03295	0.9925
	60 °C	k = 0.007417	a = 1.036		0.001702155	0.03914	0.9889
	70 °C	k = 0.009149	a = 1.046		0.001984500	0.04200	0.9875
Logaritmic model [12]	50 °C	k = 0.005729	a = 1.035	c = 0.0057	0.001342382	0.03446	0.9918
	60 °C	k = 0.007508	a = 1.031	c = 0.0059	0.001925896	0.04046	0.9881
	70 °C	k = 0.009237	a = 1.042	c = 0.0048	0.002230167	0.04311	0.9868
Wang and Singh model [12]	50 °C	a = −0.003992	b = −0.00000406		7.18342E-05	0.008143	0.9995
	60 °C	a = −0.005321	b = 0.000007167		5.05051E-05	0.006742	0.9997
	70 °C	a = −0.006512	b = −0.00001065		1.04585E-05	0.003049	0.9999
Parabolic model [28]	50 °C	a = 0.9955	b = −0.003955	c = 0.000004002	7.09618E-05	0.007923	0.9996
	60 °C	a = 0.993	b = −0.005229	c = 0.000006946	3.69600E-05	0.005605	0.9998
	70 °C	a = 1.002	b = −0.006542	c = 0.000010740	1.04006E-05	0.002944	0.9999

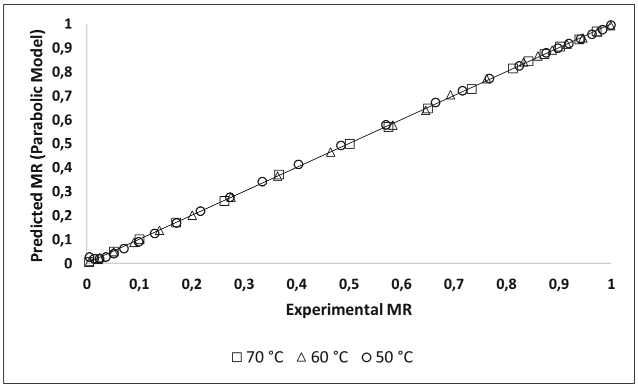

Fig. 5 Comparison of experimental MR and predicted MR (Parabolic model) for hot-air drying

3.1.3 The effective moisture diffusivity and activation energy of intermittent-microwave dried-apple slices

D_{eff} and E_a of intermittent-microwave dried-apple slices were presented in Table 3. D_{eff} of intermittent-microwave dried-apple slices was calculated in range of 4.47×10^{-9}–2.54×10^{-8} m^2 s^{-1}. D_{eff} was observed to increase with the increment of microwave power. It can be explained with more heating in water molecules in higher microwave powers which means an increase in D_{eff}. İzli and Polat [36] have observed the D_{eff} values of intermittent-microwave dried-apple slices between 8.11×10^{-9} and 1.22×10^{-8} m^2 s^{-1} depending on power on/off time. Besides, D_{eff} values increased with the increment in microwave powers from 100 to 300 W. Likewise, Aghilinategh et al. [39] have reported that D_{eff} values of intermittent-microwave dried-apple slices ranged from 1.26×10^{-8} to 2×10^{-8} m^2 s^{-1} and that D_{eff} values increased as microwave power increased from 200 to 600 W. The results of this study show similarity with those reports. Çelen et al. [33] have found higher D_{eff} values (8.51×10^{-8}–1.12×10^{-7} m^2 s^{-1}) at the microwave power ranging from 1050 to 2100 W when compared to the results of this study. In other fruits and vegetables, similar observations were recorded by Demiray et al. [16] with onion, Azimi-Nejadian and Hoseini [38] with potato slices and Kumar et al. [20] with taro slices. Besides, E_a which was calculated by plotting the natural logarithm of D_{eff} to ratio of sample weight to microwave powers (Fig. 3), was found to be 6.88 W g^{-1}. The obtained E_a was found to be higher than the E_a of microwave dried-apple slices (4.93 W g^{-1}) [39] and lower than the E_a of microwave dried-apple slices (15.15 W g^{-1}) [14], onion (7.9 W g^{-1}) [16] and mint (12.28 W g^{-1}) [34].

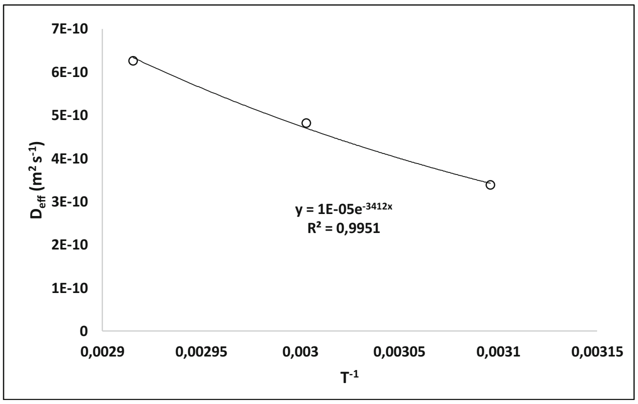

Fig. 6 The relationship between D_{eff} and temperatures hot-air drying

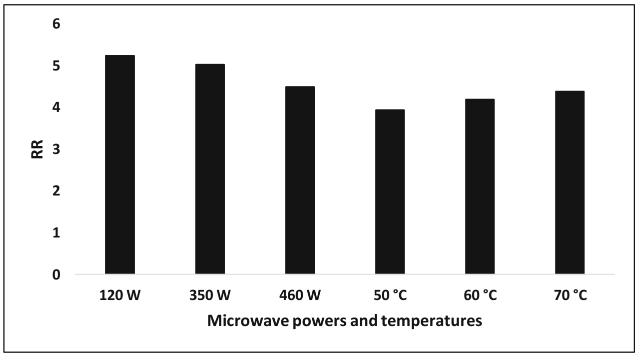

Fig. 7 RR of intermittent-microwave and hot-air dried-apple slice

3.2 The hot-air drying of apple slices

3.2.1 The influence of temperature on drying rate apple slices

The MR and DR of apple slices dried at different temperature were presented in Fig. 4. As seen from Fig. 4, it is a fact that temperature is one of the most effective parameters for drying process. As temperature increased, DR increased and drying time reduced. Seiiedlou et al. [2], Mesiami et al. [41], Beigi [42], Vega-Galvez et al. [43] Zarein et al. [44] and Sacilik and Elicin [45] have reported an increment in DR with the increasing of drying temperature regardless of slice size and air velocity. This is due to higher heat transfer rate between the food and the drying air at higher temperatures which lead to a more evaporation rate; and thus, drying time decreases [42]. Moisture content of apple slices dried at 50, 60 and 70 °C was reduced approximately by 5% (WB) for 540, 360 and 300 min, respectively. As the temperature was increased by a difference like 10 °C, from 50 to 60 °C, 50 to 70 °C and 60 to 70 °C the drying time decreased by 33.34%, 44.45% and 16.67%, correspondingly. The reduction in 50–60 °C was found higher than 60–70 °C. In the drying process, constant rate period was not observed and drying process occurred in the falling rate period. In the literature, the same results were reported for hot-air drying of apple slices by Seiiedlou et al. [2], Mesiami et al. [41], Beigi [42], Vega-Galvez et al. [43] Zarein et al. [44] and Sacilik and Elicin [45].

Table 5 Model constants and statistical parameters of rehydration models

Model	Temperature and microwave powers	k_1	k_2	β	α	χ^2	RMSE	R^2
Peleg [24]	50 °C	9.2999	0.3222			0.008129	0.079515	0.9989
	60 °C	12.073	0.2956			0.006649	0.071914	0.9980
	70 °C	9.3826	0.2816			0.007314	0.075422	0.9987
Weibull [24]	50 °C			0.018995	0.4638	0.351948	0.523199	0.9724
	60 °C			0.013692	0.4671	0.599991	0.683125	0.9984
	70 °C			0.016632	0.4655	0.537205	0.646395	0.9825
Peleg [24]	120 W	10.41	0.2206			0.032675	0.159418	0.9973
	350 W	12.65	0.2245			0.038036	0.171999	0.9956
	460 W	10.83	0.2692			0.019222	0.122272	0.9978
Weibull [24]	120 W			0.009866	0.5468	1.521097	1.087693	0.9638
	350 W			0.009304	0.4998	1.581880	1.109212	0.9756
	460 W			0.015668	0.4330	0.648954	0.710452	0.9814

3.2.2 The modelling of hot-air drying curves

Statistical parameters of models were given in Table 4. As seen from Table 4, R^2 values of all models were greater than the acceptable value (0.90). However, the lowest RMSE and χ^2 and the highest R^2 value were obtained with the Parabolic model in all drying temperatures. Parabolic model was accordingly found as the most suitable model to describe hot-air drying behavior of apple slices. The comparison of experimental MR and predicted MR (Parabolic model) was shown in Fig. 5. Meisami-Asl et al. [41], Beigi [42], Zarein et al. [44] and Meisami-Asl et al. [46] have reported that the Midilli et al. model was the most suitable model for describing the drying curves of hot- air dried-apple slices. On the other hand, Sacilik and Elicin [45] have described the experimental data of hot-air dried-apple slices with Logaritmic model. The differences may result from the selected models in different studies, apple variety, initial moisture content, drying equipment and conditions.

3.2.3 Effective moisture diffusivity and activation energy of hot-air dried-apple slices

The values of D_{eff} and E_a were listed in Table 3. The D_{eff} ranged from 3.38×10^{-10}–6.25 to 10^{-10} m^2 s^{-1}. The D_{eff} values were found to be within the range given for food materials; D_{eff} (10^{-11}–10^{-6} m^2 s^{-1}) [42]. The temperature has significantly affected D_{eff} of apple samples and considerably increased D_{eff}. The obtained D_{eff} value was similar to with the D_{eff} value of 7.03×10^{-10}–1.08×10^{-9} m^2 s^{-1} (apple slice) [42] and 2.27×10^{-10}–4.97×10^{-10} m^2 s^{-1} (apple slice) [45] and slightly lower than the D_{eff} value of 1.79×10^{-9}–4.45×10^{-9} m^2 s^{-1} (apple slice) [47] and 1.9082×10^{-9}–3.9346×10^{-9} m^2 s^{-1} (apple pomace) [48]. There is a directly proportional relationship between DR and D_{eff}. Higher temperatures provide more evaporation rate in the moisture content of the sample [16].

The Arrehenius type relation between the natural logarithm of D_{eff} and T^{-1} gives E_a (Fig. 6). E_a of apple slices was found as 28.37 kJ mol^{-1}. The E_a value was higher than the E_a value of 19.80 kJ mol^{-1} (apple slice) [42], 17.77–25.41 kJ mol^{-1} (apple slice) [49] and 24.512 kJ mol^{-1} (apple pomace) [48]. The general E_a values for foods were reported in the range of 1.27–110 kJ mol^{-1} by Aghbashlo et al. [50].

3.3 Rehydration characteristics of intermittent-microwave and hot-air dried-apples slices

RRs of intermittent-microwave and hot-air dried-apple slices were shown in Fig. 7. As understood from Fig. 7, RR of intermittent-microwave dried-apple slices was found to be greater than hot-air dried-apple slices. This can be explained with the expansion and puffing of the food by high internal pressure, which is caused by microwave drying. Depending on the reduction in structure density and the increment in intercellular gaps by this mechanism, the capacity of water absorption increases and thus, RR of microwave dried-foods can be higher than hot-air dried-foods [51, 52]. Likewise, Aghilinategh et al. [39] have reported that the RR of microwave dried-apple slices was found to be higher than that of hot-air dried-apple slices. Similarly, it was reported that microwave energy increases the rehydration capacity in microwave dried-apple slices more than hot-air dried by Askari et al. [52]. Horuz et al. [53] have reported higher rehydration rate in microwave dried-sour cherry due to microwave power. It was notified by Gaware et al. [54] that microwave dried-tomatoes showed higher RR in comparison to hot-air dried ones. Also, RR of intermittent-microwave dried-apple slices increased with the decrease in microwave powers. Permanent cellular rupture, dislocation and tissue integrity loss occur at high microwave powers; accordingly, this case leads to produce a dense structure, substantially shrunken capillaries with reduced hydrophilic attributes. The reduced hydrophilic attributes show lower rehydration capacity and prevents water re-gaining and thus, pores are left unfilled [36]. Such finding involves similarity with the reports by İzli and Polat [36], Ahmed et al. [55] and Sarimeseli [56]. On the other hand, the RR of hot-air dried-apple slices increased as drying temperature increased. RR of foods at higher temperatures improves rehydration due to the influence of temperature on cell wall and tissue. Tissue collapse and cell damage occur at higher temperatures, meaning that RR increases due to higher water absorption in the spaces created by the damaged cells [53, 57]. Likewise, higher rehydration was reported to be found at higher temperatures hot-air dried-apple slices by Aghilinategh et al. [39], Beigi [42] and Sacilik and Elicin [45]. Vega-Galvez et al. [57] similarly have stated higher RR in red bell peppers dried at higher temperatures. Likewise, Doymaz and Özdemir [58] have reported higher RR of tomatoes at higher drying temperature.

Statistical parameters of rehydration models were given in Table 5. For both drying techniques, Peleg model was agreed to be the best model predicting the rehydration behavior of dried apple slices due to the lowest RMSE and χ^2 and the highest R^2 value when compared to Weibull model. Peleg model was notified to be the most used model for determining the rehydration kinetics of several foods [17, 24].

4 Conclusions

In the current study, the drying and rehydration characteristics of intermittent-microwave and hot-air dried-apple slices were compared. According to the results of the current study;

(a) Intermittent-microwave drying has crucially affected the DR and drying time of apple slices. When compared to hot-air drying, drying time was significantly reduced.
(b) DR and drying time were also affected by microwave powers and drying temperatures. As both microwave powers and drying temperature increased, DR increased and drying time decreased. Microwave power increasing from 120 to 350 W and from 120 to 460 W were more effective than from 350 to 460 W.
(c) D_{eff} of intermittent-microwave dried-apple slices was determined in comparison to hot-air dried ones. The higher the microwave powers and drying temperatures the higher the D_{eff}. The influence of increment in temperature ranging from 50 to 60 °C and from 50 to 70 °C were greater than from 60 to 70 °C.
(d) Page model was the most suitable model predicting the drying behavior of intermittent-microwave dried-apple slices, while Parabolic model was the most appropriate model for hot-air dried-apple slices.
(e) The RR of intermittent-microwave dried-apple slices was greater than hot-air dried-apple slices.
(f) When compared to Weibull model, Peleg model was found to be a more adequate model for both intermittent-microwave drying and hot-air drying.

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