

Intermittent Microwave-Vacuum Drying Effects on Pears

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In the present study, the effects of intermittent microwave-vacuum drying on the “Deveci” pear in terms of the drying kinetics, mineral content, protein content, rehydration ratio, color, energy, specific energy and microstructure were investigated. According to the drying treatments, increased microwave power (100 and 200 W) and vacuum (200 and 400 mmHg) applications provided higher drying rates and protein content. Dried pear samples had a higher mineral content than fresh samples because of the increasing dry matter content. At the higher vacuum level experiments, the energy consumption reduced and the rehydration ratio increased. Moreover, the higher microwave power caused a decrease of the L^* (lightness) value. However, a regular pore size and pore distribution in all drying experiments were observed in the microstructures of microwave-vacuum-dried samples.

INTRODUCTION

The pear (*Pyrus communis* L.) belongs to the *Rosaceae* family [Antal *et al.*, 2017]. It is a fruit native to temperate zones and is cultivated in Europe [Guiné *et al.*, 2007]. According to the Food and Agriculture Organization data [FAO, 2018], the worldwide pear production in 2014 was estimated at approximately 25.8 million tons. Fully mature pears play an important role in the human diet and nutrition as sources of dietary fiber, vitamins C and B₆, and minerals such as magnesium and potassium [Lutovska *et al.*, 2016]. They are eaten in both the natural and processed forms as purees, jams, and dried pears [Santos, *et al.*, 2014]. In fact, dried pears are widely used in bakery products, gravies, and compotes [Doymaz & İsmail, 2012].

Drying is a complex biological and chemical reaction whose mechanism is not yet entirely understood [Ferreira *et al.*, 2008]. However, it is widespread industrial preservation method used to decrease water content of agricultural products to minimize chemical, biochemical, and microbiological deterioration [Doymaz & İsmail, 2012], as well as to prolong the shelf life of the fruit, and avoid spoilage and contamination during storage. Using an appropriate drying procedure also minimizes storage and transportation costs [Doymaz, 2013]. Therefore, drying methods have been garnering increased attention, and detailed studies have been conducted on the effects of different [Lüle & Koyuncu, 2015] or hybrid

drying [Huang *et al.*, 2015] methods on food quality. In recent years, drying with a microwave vacuum has been used as a hybrid method for top-quality dried products [Cui *et al.*, 2003]. The advantage of the microwave-vacuum process is drying acceleration under low temperature by an increased pressure gradient between layers [Therdthai & Zhou, 2009]. If the microwave being used is not applied properly, poor-quality products may be manufactured due to irregular drying depending on product characteristics, shape, and size [Han *et al.*, 2010; Kuş, 2016]. Thus far, intermittent microwave application during drying has been an effective methodology to avoid improper heating and improve product quality and energy efficiency within the product during microwave off times [Zhang *et al.*, 2017].

There are ample literature data on the drying of pears using various drying methods, such as osmotic pre-treated convective air drying [González-Martínez *et al.*, 2006], solar drying [Guiné *et al.*, 2007], sun drying [Ferreira *et al.*, 2008], hot air drying [Doymaz & İsmail, 2012], ultrasound-assisted infrared drying [Dujmić *et al.*, 2013], solar stove of greenhouse type drying [Guiné *et al.*, 2013], convective drying [Lutovska *et al.*, 2016; Santos *et al.*, 2014], osmo-vacuum drying [Amiripour *et al.*, 2015], forced air convection drying [Dotto *et al.*, 2017], microwave drying [Kuş, 2016], intermittent convective drying [Silva *et al.*, 2014], and infrared and freeze drying [Antal *et al.*, 2017]. To the best of our knowledge, no study has been reported on the intermittent microwave-vacuum drying effect on pear slices. The pear cultivar “Deveci” is one of the best winter-type pear cultivars in Turkey, originating from Anatolia, that has recently gained popularity because

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of the high fruit quality, production and storage capacity [Ozturk & Ozturk, 2014]. Therefore, this study was aimed to investigate the drying kinetics of “Deveci” pear slices and drying effects on the mineral content, protein content, rehydration ratio, color, energy specific energy and microstructure analyses when using intermittent microwave-vacuum drying conditions.

MATERIALS AND METHODS

Drying experiments

Wholly matured and healthy fruits of “Deveci” pears were selected for this study and were stored before drying at $4 \pm 0.5^\circ\text{C}$ for a day. The initial moisture content of fresh samples was determined by oven drying (ED115; Binder, Tuttingen, Germany) at 105°C [Celen & Kahveci, 2013] and was found to be 5.67 (g water/g dry matter). The samples were dried until the final moisture content of 0.1 (g water/g dry matter). The samples were horizontal sliced into 5 ± 0.04 -mm thickness using a food slicer (Nicer Dicer, China).

The drying experiments were carried out in a custom-modified intermittent microwave-vacuum dryer with a power output of 900 W and a microwave frequency of 2450 MHz. It consists of a microwave oven (NE1846; Panasonic, Japan), vacuum pump (VRT404; Bacca, Taiwan), voltage variac (DVT2.5; Devotrans, Turkey), pulse controller (MCB9; Entes, Turkey), and glass container (Figure 1). Before starting the drying experiments, the glass container with the dimensions of 200 (diameter) \times 92 (height) mm with the pear to be dried was positioned inside the microwave cavity, and the pressure inside the container was managed by a pressure regulator valve connected to a 0.18-kW vacuum pump and was monitored using a vacuum gauge. Once the vacuum level was reached, the microwave oven was run, and various output power levels and the pulse ratio were adjusted using a voltage variac and pulse controller, respectively [Kumar & Shrivastava, 2017; Zaki *et al.*, 2007]. The weight of the sample (80 g) was determined by the digital balance (Radwag, Radom, Poland) and was recorded at 10-min intervals after turning off the microwave-vacuum dryer [Zaki *et al.*, 2007]. The experimental conditions of drying included: microwave power of 100 and 200 W, vacuum pressure of 200 and 400 mmHg, and pulse ratio of 3 and 4. The pulse ratio (PR) for each run was computed as $\text{PR} = (t_{\text{on}} + t_{\text{off}})/t_{\text{on}}$, where t_{on} is the magnetron power “on” time and t_{off} is the mag-

netron power “off” time [Gunasekaran & Yang, 2007]. During the study, 20 s of t_{on} and 40 s of t_{off} represented PR=3, and 15 s of t_{on} and 45 s of t_{off} represented PR=4.

Determining mineral contents

The total contents of some elements were determined by using dry samples after microwave treatment of the 0.20–0.50 g samples with 4 mL HNO_3 and 3 mL H_2O_2 in a microwave oven (MWS 2 DAP 60K, Berghof, Germany). Contents of Na, K, and Ca were determined by the flame emission method using a flame photometer (6361, Eppendorf Elex, Germany), whereas these of P, Mg, Fe, Cu, Zn, and Mn was determined in the extracts using inductively coupled plasma optical emission spectroscopy (ICP OES) and expressed in mg/kg (Optima 2100 DV, Perkin Elmer, United States).

Determining protein contents

The Kjeldahl method was used to determine the protein content in pear samples. The conventional factor 6.25 was used to obtain the protein content of fruits [AOAC, 1960]. Digestion/distillation unit (K-437/K-350, Buchi, Switzerland) was used for nitrogen determination.

Rehydration ratio

Dried pear samples were rehydrated by immersion in a distilled water bath at a controlled temperature of 25°C . The weight of dehydrated pear samples used in each experiment was 5 ± 0.02 g. Rehydration of dried pears was stopped after three hours. Next, the samples were drained with a tissue paper to remove excess water from the surface. The data were quantified in terms of the rehydration ratio (RR) using the following formula [Zielinska *et al.*, 2016]:

$$\text{RR} = \frac{\text{Mass of the rehydrated sample}}{\text{Mass of the dried sample}} \quad (1)$$

Color measurements

The color of the pear sample was measured before and after drying using a colorimeter (Hunter Lab, MSEZ-4500L, USA) at four different points on the pear’s sample for all experiments. The color values were indicated as L^* (whiteness/darkness), a^* (redness/greenness), and b^* (yellowness/blueness). Additionally, L_0^* , a_0^* and b_0^* represented the color parameters of the fresh samples. The following formulas were used to calculate Chroma C (Eq. 2), hue angle α (Eq. 3), and total color difference ΔE (Eq. 4), [Izli, 2017]:

$$C = \sqrt{(a^2 + b^2)} \quad (2)$$

$$\alpha = \tan^{-1}\left(\frac{b}{a}\right) \quad (3)$$

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (4)$$

Energy and specific energy consumption

The energy consumption values of the intermittent microwave-vacuum drying processes were measured using a power meter (EU TS-836A; Floureon, China). The drying devices

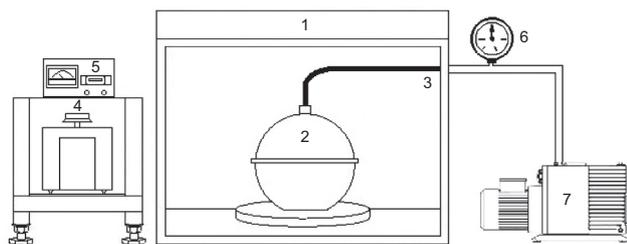


FIGURE 1. Schematic diagram of the laboratory apparatus: (1) dryer, (2) glass container, (3) teflon hose, (4) variac, (5) pulse controller, (6) vacuum gauge, and (7) vacuum pump.

(i.e., the microwave oven and vacuum pump) were connected to the power meter that was on the electric grid. During the drying conditions, the energy consumption values were recorded by the power meter in kWh [Orikasa *et al.*, 2018]. The energy required to evaporate a unit mass of water from the sample (specific energy consumption, SEC) was calculated for each drying experiment. It was defined in terms of the MJ/kg of water removed and was used as process parameters of optimization [Kumar & Shrivastava, 2017].

$$SEC \text{ (MJ/kg)} = \frac{t_{on} M(1-m_f) \times 10^{-6}}{M_i (m_i - m_f)} \quad (5)$$

where: t_{on} is the total power on time (s), M is microwave input power (W), M_i is the initial mass of the sample (kg), m_i is the initial moisture content (g water/g dry matter), and m_f is the final moisture content (g water/g dry matter).

Microstructure analysis

The effect of different drying conditions on the microstructure of pear samples was observed using a scanning electron microscope (EVO 40, Carl Zeiss, Oberkochen, Germany). Particles extracted from the dried samples were vertically cut into 1-mm-thick slices and coated with gold-palladium. All samples were examined under high vacuum (20 kV) (SCD-005, Baltec, Wetzlar, Germany), and then their microphotographs were taken [Tian *et al.*, 2015].

Statistical analysis

The study was performed using randomized plots factorial design of experimental type. All experiments were done in triplicate. The data were subjected to the analysis of variance (ANOVA) using JMP software (Version 7.0; SAS Institute Inc., Cary, NC, USA). The least significant difference (LSD) test was used to compare the means at the 5% significance level ($P < 0.05$).

RESULTS AND DISCUSSION

Drying kinetics

The drying rates of the “Deveci” pear dried by the intermittent microwave-vacuum methodology are shown in Figure 2. A higher microwave power and vacuum application provided higher drying rates. The shortest drying time of pears (150 min) was noted at process conditions “200 W - 400 mmHg - PR=3”, and the longest one (460 min) at “100 W - 200 mmHg - PR=4”. These results indicate that it was possible to decrease the drying time by 310 min. A higher microwave power with more microwave energy made the pears have a higher temperature and increased the evaporation rate. With a rapid increase in the mass transfer rate of the pear, the drying time was reduced. The drying rates of the pear dried by constant microwave power and a pulse ratio under a vacuum of 400 mmHg were higher than those dried under 200 mmHg because a higher vacuum resulted in a lower boiling point of water and a higher evaporation rate. Several authors reported the total times for the drying of the pear to be 525, 480, 360 and 255 min in a convective

dryer at 50, 57, 64 and 71°C, respectively [Doymaz, 2013]; as well as 20, 19, 16, 14 and 1260 min in an infrared dryer at 40, 50, 60, 70°C and in a freeze dryer (−47°C condenser temperature and 85–95 Pa absolute pressure), respectively [Antal *et al.*, 2017]. On the other hand, the results were in good agreement with those reported by Cheenkachorn *et al.* [2012] who used a microwave-vacuum method to dry papaya cubes. Their drying times at a vacuum pressure of 400 mmHg, were 72.6, 115.5, 38.2, and 84 min at “400 W - PR=2”, “400 W - PR=3”, “800 W - PR=2”, and “800 W - PR=3”, respectively. Additionally, the drying time decreased with vacuum pressure increase.

Mineral content

The mineral contents of intermittent microwave-vacuum dried “Deveci” pears are shown in Table 1. The “Deveci” pears were found a significant source of K, whereas their Mn contents were low. The mineral contents of pears exposed to different drying treatments were higher than those of fresh fruits because of the increased dry matter ratio. The highest K levels determined at “100 W - 200 mmHg - PR=4”, “100 W - 400 mmHg - PR=3”, and “200 W - 400 mmHg - PR=4” did not differ significantly ($P > 0.05$). On the other hand, the high-

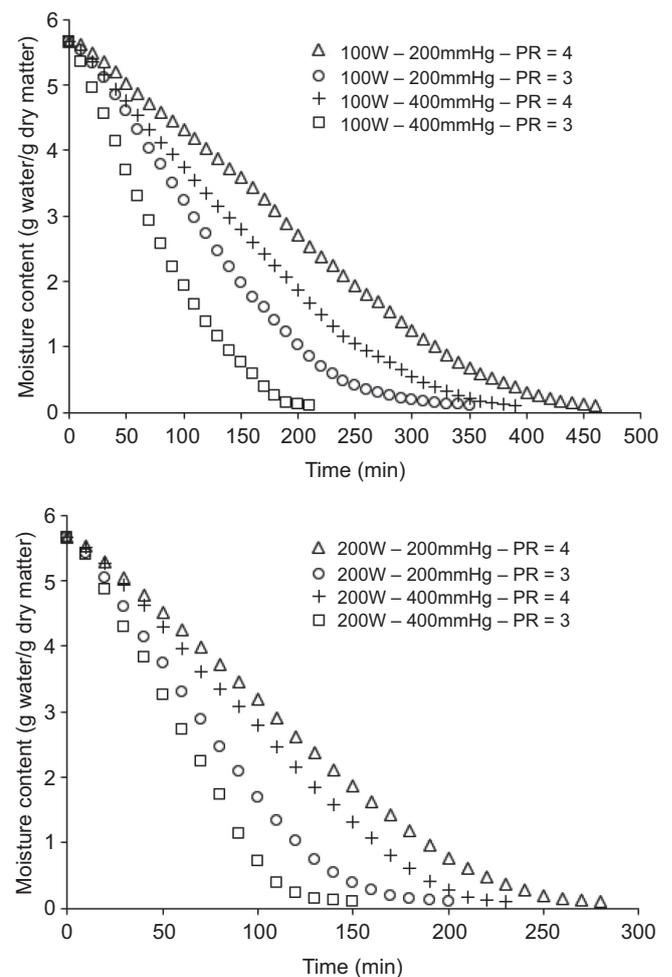


FIGURE 2. The moisture content of the “Deveci” pear vs. time under different drying conditions of pulses (PR=3 and 4), microwave powers (100 and 200 W), and vacuum levels (200 and 400 mmHg).

TABLE 1. Mineral contents of “Deveci” pears (mg/kg) fresh and dried under different conditions of pulses (PR=3 and 4), microwave powers (100 and 200 W), and vacuum levels (200 and 400 mmHg).

Minerals	Fresh	100 W 200 mmHg PR=4	100 W 200 mmHg PR=3	100 W 400 mmHg PR=4	100 W 400 mmHg PR=3	200 W 200 mmHg PR=4	200 W 200 mmHg PR=3	200 W 400 mmHg PR=4	200 W 400 mmHg PR=3
P	464±6 ^d	1446±27 ^a	1049±144 ^{bc}	1206±33 ^{abc}	1300±92 ^{ab}	1206±291 ^{abc}	1159±76 ^{bc}	979±26 ^c	1238±6 ^{abc}
K	353±136 ^c	6470±114 ^{ab}	3521±662 ^d	3424±167 ^d	7533±1107 ^a	3445±588 ^d	4383±472 ^{cd}	6987±551 ^a	5523±13 ^{bc}
Ca	64.8±0.8 ^f	291±25 ^{cd}	258±40 ^{de}	364±25 ^{ab}	292±34 ^{cd}	279±14 ^{de}	224±34 ^e	423±7 ^a	343±25 ^{bc}
Mg	47.1±1.5 ^d	284±11 ^b	228±4 ^c	290±16 ^b	378±20 ^a	223±16 ^c	235±6 ^c	376±48 ^a	338±4 ^a
Na	246±2 ^c	733±56 ^a	536±52 ^d	629±5 ^{bc}	640±30 ^{ab}	621±73 ^{bcd}	629±17 ^{bc}	579±49 ^{cd}	685±0.4 ^{ab}
Fe	3.97±1.00 ^c	8.84±0.88 ^{ab}	6.71±1.30 ^{bc}	8.19±0.54 ^{ab}	10.96±2.37 ^a	6.82±2.26 ^{bc}	6.58±0.34 ^{bc}	8.71±1.43 ^{ab}	8.41±0.75 ^{ab}
Cu	2.89±0.03 ^d	7.29±0.24 ^b	5.53±0.92 ^c	7.39±0.44 ^b	8.87±0.52 ^a	7.46±1.36 ^{ab}	6.98±0.37 ^{bc}	6.82±0.55 ^{bc}	7.69±0.41 ^{ab}
Zn	2.35±0.07 ^c	5.20±0.01 ^{ab}	3.93±0.51 ^b	4.82±0.22 ^{ab}	5.58±0.08 ^a	5.38±1.21 ^a	4.03±0.73 ^b	5.14±0.75 ^{ab}	5.12±0.43 ^{ab}
Mn	0.56±0.02 ^f	0.94±0.04 ^{ef}	1.34±0.01 ^{de}	3.47±0.01 ^a	2.06±0.12 ^c	1.83±0.13 ^c	1.66±0.01 ^{cd}	2.74±0.55 ^b	1.89±0.01 ^c

^{a-g} means with different letters in the same row differ significantly ($P < 0.05$).

est Mn level was found at “100 W - 400 mmHg - PR=4”. There were significant differences between drying experiments in terms of contents of all minerals compared with the fresh samples ($P < 0.05$). Al Juhaimi *et al.* [2016] reported the mineral contents of three pear varieties (“Santa Maria”, “Deveci” and “Ankara”). The P, K, Ca, Mg, Fe, and Mn contents of fresh “Deveci” pears were found to be 164.3, 1255.4, 42, 101.5, 19.7, and 1.5 mg/kg, respectively. On the other hand, contents of Na, Cu, and Zn were closer to those of the presented study. The differences between the studies can be attributed to the growth conditions of “Deveci” pears which were picked in the province of Bursa and Konya. After drying 5-mm slices of “Deveci” pears for 15, 20, and 25 h at 70°C, the K content increased to 5298, 7245.6, and 7649.1 mg/kg,

respectively, similar to that in our presented study. In another previous study performed by Clary *et al.* [2007], grapes dried at 71 °C using microwave-vacuum dehydration had higher contents of Ca, Na, and K than sundried and fresh grapes. However, lower values were reported for Fe in that study.

Protein analysis

Figure 3 demonstrates that the protein content of the dried “Deveci” pears was higher than that of the fresh fruit because of the decreased water content. Compared with the protein content, an increase in common or individual microwave power and vacuum level provided higher protein values. Between drying treatments, the values obtained at “200 W - 400 mmHg - PR=3” and “100 W - 400 mmHg - PR=3” did

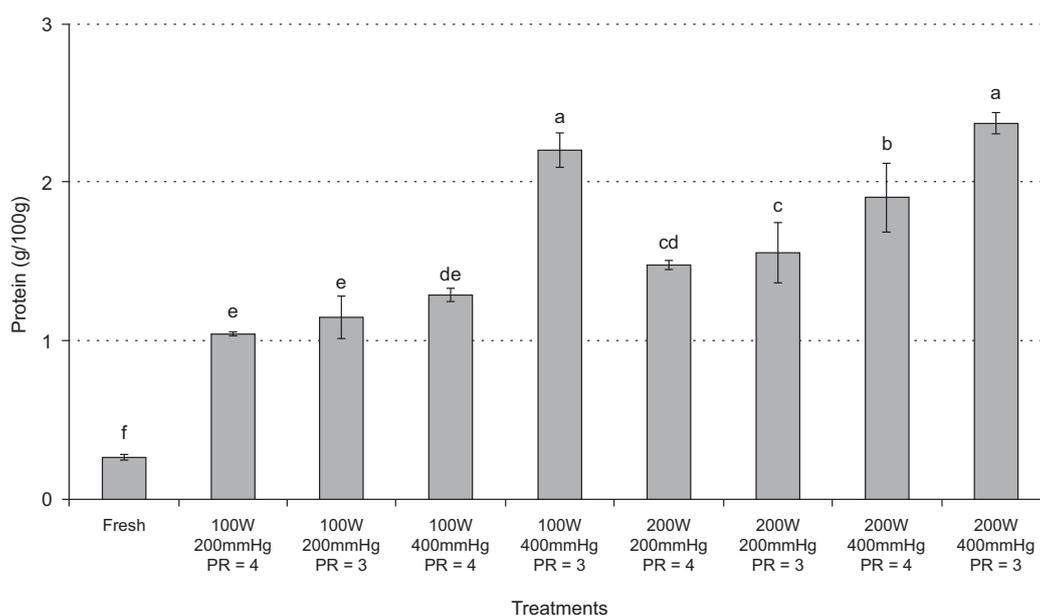


FIGURE 3. Protein content of “Deveci” pears fresh and dried under different conditions of pulses (PR=3 and 4), microwave powers (100 and 200 W), and vacuum levels (200 and 400 mmHg).

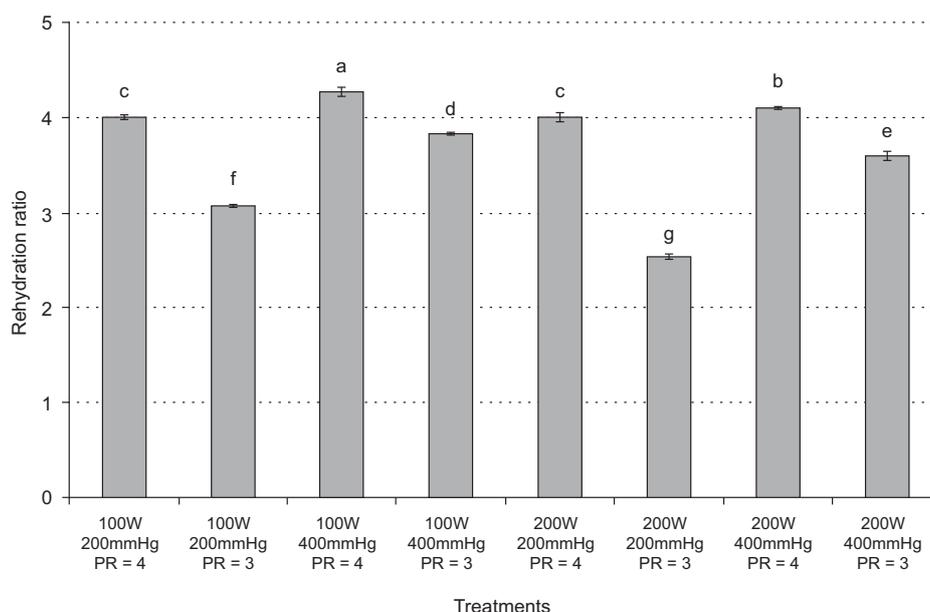


FIGURE 4. Rehydration ratio of “Deveci” pears dried under different conditions of pulses (PR=3 and 4), microwave powers (100 and 200 W), and vacuum levels (200 and 400 mmHg).

not differ significantly ($P>0.05$) and these process conditions resulted in the highest protein content of pears, whereas treatments at “100 W - 200 mmHg - PR=4” and “100 W - 200 mmHg - PR=3” caused the lowest protein content with comparable values ($P>0.05$). The possible reason for such a result might be the longer drying time. In an earlier study, protein content of fresh “Deveci” pear cultivar was found to be 3.8 g/L as reported by Öztürk *et al.* [2009], and an intermittent microwave-vacuum effect on the protein results was reported by Dermelj *et al.* [1995] and although impulse technique was gentler, a virtual increase was not observed in the protein content.

Rehydration ratio

The change in the rehydration ratio with change in the microwave power, pulse ratio, and vacuum level is shown in Figure 4. The rehydration ratio was found to be different between the drying treatments, and a higher rehydration ratio was observed at “100 W - 400 mmHg - PR=4”. The higher pulse ratio (PR=4) increased the rehydration ratio values, but the microwave power modes did not show any meaningful influence. However, the increased vacuum level experiments presented a higher rehydration ratio. Similarly, Changrue *et al.* [2008] found for strawberry drying with a microwave-vacuum method that the generated power modes were inadequate to affect the rehydration property. According to Jiang *et al.* [2014], the pulse-spouted microwave vacuum-dried banana cubes had a lower final rehydration ratio (3.6) than freeze (3.9) and microwave freeze dried samples (3.7).

Color analysis

The color parameters of the fresh “Deveci” pears and these dried by intermittent microwave-vacuum are presented in Table 2. All drying experiments provided higher values of redness (a^*) and yellowness (b^*) but lower lightness (L^*). Drying conditions significantly ($P<0.05$) affected color values

of “Deveci” pear samples. Using higher microwave power at a constant pulse ratio and vacuum level caused lower values of L^* . Furthermore, the maximum a^* value for the dried samples was $a^* = 17.3$ ($P<0.05$) in the drying experiment at “200 W - 200 mmHg - PR=3”. Meanwhile, the significantly ($P<0.05$) higher b^* and C values were achieved at “100 W - 200 mmHg - PR=3”. Compared with the fresh sample, a significant ($P<0.05$) decrease was determined in the α value in all experiments. In the present study, the flesh color of the fresh “Deveci” pears was found to be higher in L^* and a^* values but lower in b^* , C and α values than those previously reported by Ulubaş Serçe *et al.* [2010] using the same method. A similar effect of the microwave-vacuum drying method on the L^* value was found by Bai-Ngew *et al.* [2015].

Energy and specific energy analyses

Table 3 shows the effects of the microwave power, pulse ratio, and vacuum level on the energy and specific energy consumption values of the dried “Deveci” pear. The lowest energy consumption value was at “200 W - 400 mmHg - PR=3”, likely due to the shortest drying time, despite the large power and pulse ratio input of the devices used in these processes. The energy consumption values of the “100 W - 400 mmHg - PR=3” and “200 W - 400 mmHg - PR=4” experiments were found to be approximately 1.4 and 1.5 times higher. The effect of the vacuum level clearly demonstrated that a strong relationship exists to reduce the energy consumption. For the same reason, the energy consumption values in the constant microwave power and pulse ratio experiments at a higher vacuum level were lower. Considering the specific energy consumption of “Deveci” pear drying, a higher vacuum level with a constant microwave power and pulse ratio resulted in a decreased consumption. The specific energy consumption, however, was increased by raising the microwave power from 100 W to 200 W. Because of the shorter drying times,

TABLE 3. Energy and specific energy consumption values of “Deveci” pears dried under different conditions of pulses (PR=3 and 4), microwave powers (100 and 200 W), and vacuum levels (200 and 400 mmHg).

Drying methods	Drying time (min)	Energy consumption (kWh)	Specific energy consumption (MJ/kg)
100 W 200 mmHg PR=4	460	2.6	1.6
100 W 200 mmHg PR=3	350	2.3	1.6
100 W 400 mmHg PR=4	390	2.2	1.4
100 W 400 mmHg PR=3	210	1.3	1.0
200 W 200 mmHg PR=4	280	1.6	1.9
200 W 200 mmHg PR=3	200	1.3	1.9
200 W 400 mmHg PR=4	230	1.3	1.6
200 W 400 mmHg PR=3	150	0.9	1.4

similar energy consumption results were reported by Liu *et al.* [2017] to dry asparagus cookies, and the lowest value was defined in pulse-spouted microwave vacuum drying. Additionally, microwave-vacuum drying time of the tomato was found to be approximately 4.8 times shorter than

hot air drying as reported by Orikasa *et al.* [2018] because of the large power input of the devices used in that process.

Scanning electron microscopy (SEM) analysis

The effect of various drying conditions on the tissue structure of the dried “Deveci” pear slices was observed using scanning electron microscopy (Figure 5). The micrographs were examined by 1000× microscopy. The microwave-vacuum dried samples were demonstrated to be more regular in pore size and pore distribution in general. The cause may be rapid and extensive vaporization during microwave vacuum drying [Bai-Ngeu *et al.*, 2011]. Similarly, Jiang *et al.* [2014] provided better drying uniformity and production quality with pulsed microwave vacuum dried samples of banana. Again, the microwave-assisted vacuum-dried Litchis’ structure was revealed to be clear and porous as shown by Song *et al.* [2015].

CONCLUSIONS

Quality analyses of “Deveci” pears regarding intermittent microwave-vacuum drying were performed. Overall, according to the experimental results, the “200 W - 400 mmHg - PR=3” drying condition showed the lowest drying time, the lowest energy consumption, and a higher protein content. When comparing the mineral content, the K, Mg, Fe, Cu and Zn levels were high at “100 W - 400 mmHg - PR=3”. Moreover, higher microwave power usage did not have a meaningful influence on the rehydration ratio. Total color difference (ΔE) ranged between 35.7 (“200 W - 200 mmHg - PR=3”) and 21.2 (“100 W - 400 mmHg - PR=3”). However, the structure of the dried samples was revealed to be clear and porous. Under these conditions, intermittent microwave-vacuum drying was proven to be an alternative for “Deveci” pear drying by some quality comparisons.

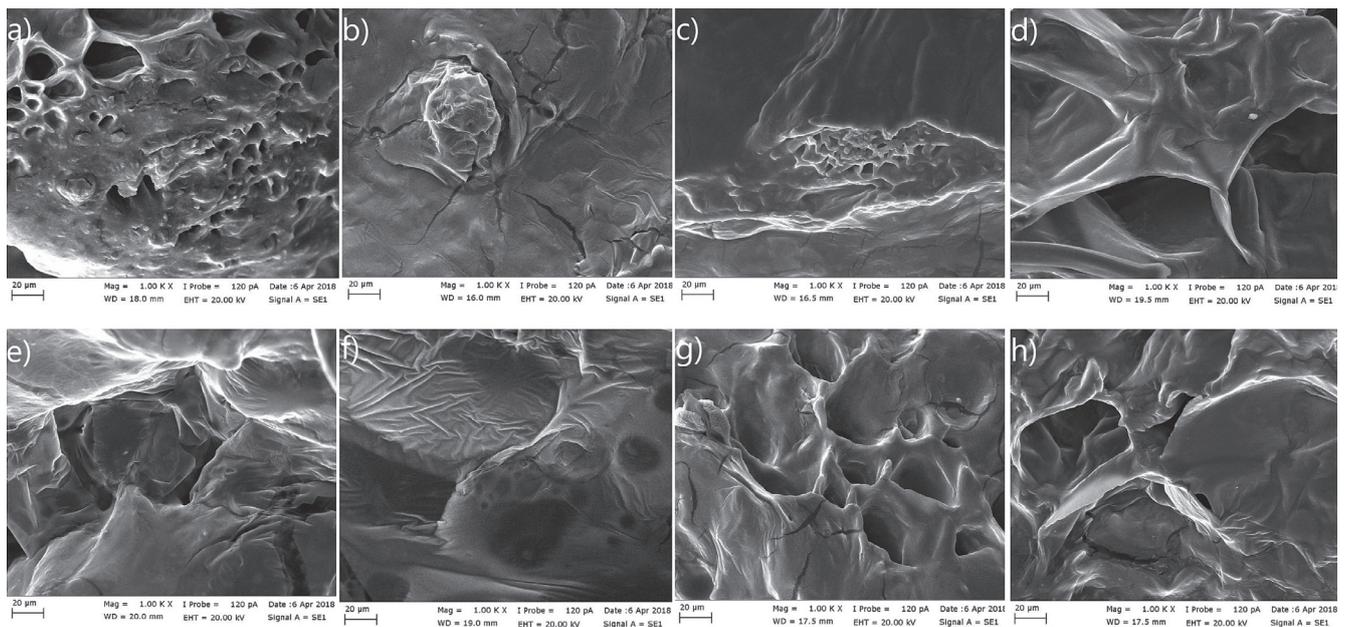


FIGURE 5. SEM images of dried pears: (a) 100 W - 200 mmHg - PR=4, (b) 100 W - 200 mmHg - PR=3, (c) 100 W - 400 mmHg - PR=4, (d) 100 W - 400 mmHg - PR=3, (e) 200 W - 200 mmHg - PR=4, (f) 200 W - 200 mmHg - PR=3, (g) 200 W - 400 mmHg - PR=4, and (h) 100 W - 400 mmHg - PR=3.

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CONFLICT OF INTERESTS

The authors report no declarations of interest.

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