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INVESTIGATION OF EFFECTS OF VARIOUS DRYING METHODS ON THE QUALITY CHARACTERISTICS OF APPLE SLICES AND ENERGY EFFICIENCY

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Abstract: In this study, the effects of tray drying, heat-pump drying, freeze drying, and microwave drying methods on the quality characteristics of apple slices were investigated and energy efficiencies of drying methods were determined. Drying time of samples were calculated as 50 min, 90 min, 270 min, and 20 min for tray, heat-pump, freeze, and microwave drying respectively. Quality characteristics of apple slices were determined by physical (moisture content, color values, water activity, rehydration, bulk density), chemical (total phenolic, total and invert sugar, pectin) and sensory analysis. Energy efficiencies of drying methods were evaluated by calculating the Specific Moisture Extraction Rate (SMER), Moisture Extraction Rate (MER), Specific Energy Consumption (SEC), energy consumption, and energy cost. Considering the quality characteristics of the products, the results showed that dried apple slices which were produced by using microwave and freeze drying methods had a better quality comparing to the tray and heat-pump drying methods. On the other hand, the lowest energy consumption and the highest SMER and MER values were obtained from the heat-pump dryer. According to the purpose of the production obtained quality and cost values will help us in selecting the dryer.
Keywords: Apple slices, tray dryer, heat-pump dryer, freeze drying, microwave drying, energy efficiency.

FARKLI KURUTMA TEKNİKLERİNİN ELMA DİLİMLERİNİN KALİTE ÖZELLİKLERİ VE ENERJİ VERİMLİLİĞİ ÜZERİNE ETKİLERİNİN İNCELENMESİ

Özet: Bu çalışmada, tepsili kurutucu, ısı pompalı kurutucu, dondurarak kurutma ve mikrodalga kurutma tekniklerinin elma dilimlerinin kalite özellikleri ve enerji verimliliği üzerine etkileri araştırılmıştır. Kuruma süreleri; tepsili, ısı pompalı, dondurarak ve mikrodalga kurutmada sırasıyla 50, 90, 270 ve 20 dakika olarak belirlenmiştir. Elma dilimlerinin kalite özellikleri; fiziksel (nem içeriği, renk, su aktivitesi, rehidrasyon, yığın yoğunluğu), kimyasal (toplam fenolik madde, toplam şeker, invert şeker, pektin miktarı) ve duyusal analizler yapılarak belirlenmiştir. Kurutma metotlarının enerji verimlilikleri; Özgül Nem Alma Hızı (SMER), Kuruma Hızı (MER), Özgül Enerji Tüketimi (SEC), enerji tüketimi ve enerji maliyetleri hesaplanarak değerlendirilmiştir. Ürünün kalite özellikleri incelendiğinde, elma dilimlerinin kalite karakteristiklerinin mikrodalga kurutma ve dondurarak kurutma yöntemlerinde, tepsili ve ısı pompalı kurutucuda kurutma işlemine göre daha iyi korunduğu saptanmıştır. Bunun yanısıra, en düşük enerji tüketimi ve en yüksek SMER ve MER değerleri ısı pompalı kurutucuda elde edilmiştir. Elde edilen kalite ve maliyet değerleri, üretim amacına göre kurutucu seçiminde bize yardımcı olacaktır.

Anahtar kelimeler: Elma dilimleri, tepsili kurutucu, ısı pompalı kurutucu, dondurarak kurutma, mikrodalga kurutma, enerji verimliliği.

NOMENCLATURE

a^*	redness
a_w	Water activity
b^*	yellowness
C_{op}	Operating costs [TL/kWh]
H°	Hue angle
L*	lightness
m	Mass [g]
R	Drying rate [kg water/m^{2}h]
V	Volume [cm^3]
ρ_b	Bulk density [g/cm^3]
FD	Freeze drying
HPD	Heat-pump dryer
MER	Moisture Extraction Rate [kg/h]
MWD	Microwave drying
RH	Relative humidity [%]
SMER	Specific Moisture Extraction Rate [kg/kWh]
SEC	Specific Energy Consumption [kJ/kg]
TD	Tray dryer
ΔE	Color difference
ΔC	Chroma

INTRODUCTION

Preserving by drying is one of the oldest method of preserving foods in the technological, microbiological and nutritional values. Drying fruit and vegetable products is an important means of enhancing resistance to degradation due to a decrease in water activity. Drying is the process of removing the moisture in the product to lower limit value by evaporation. In this way, the product can be stored for a long period since the activities of the microorganisms and enzymes in the material are suppressed by drying. Easier processing, lower transport costs as well as quality improvements can also be achieved (Alibas, 2007, Kaleta *et al.*, 2013).

Studies are usually conducted to determine the best quality of the end-product as well as reduction in process time. The high temperature of the drying process is an important cause of loss of quality. Lowering the process temperature has great potential for improving the quality of dried products (Nindo *et al.*, 2003), however in such conditions the operating time and the associated cost become unacceptable.

Every drying technique has its own advantages and disadvantages. Hot-air drying is widely used for drying fruits and vegetables. The disadvantages of hot-air drying is that it takes a long time even at high temperatures which results in degradation of the dried product quality (Sharma and Prasad, 2006). Freeze-drying also has been widely used to obtain high quality and high value dehydrated fruits and vegetables. However, freeze-drying is an expensive and very slow dehydration process because of its low drying rates, which may result to small outputs and high capital and energy costs due to the refrigeration and vacuum systems (Huang *et al.*, 2011).

Microwave drying have been studied for achieving fast drying and reducing quality loss of fruits and vegetables (Baysal *et al.*, 2003). Microwave energy is rapidly absorbed by water molecules which results in rapid evaporation of water and thus higher drying rates. Therefore microwave drying offers significant energy savings with a potential reduction in drying time of up to 50 % in addition to the inhibition of surface temperature of treated material (Mcloughlin *et al.*, 2003).

Heat pump drying technology is energy efficient system due to low energy consumption and also it is environmentally friendly system due to low emmision of gases and fumes into the atmosphere. Heat pump dryer is a co-existence of two engineering systems: the heat pump and the dryer. Heat pump assisted-drying provides a controllable drying environment (temperature and humidity) for better products' quality at low energy consumption (Prasertsan and Saensaby, 1998). Heat pumps are devices for raising the temperature of low grade heat energy to a more useful level using a relatively small amount of high grade energy (Eisa, 1996).

It is apparent that drying itself is an energy-intensive process because the latent heat has to be supplied to the material to evaporator the moisture. Since drying is an energy intensive process, much attention is given to the development of energy-efficient drying processes (Chua *et al.*, 2002). In terms of energy efficiency the performance of the drying models can be determined by the specific moisture extraction rate (SMER), the moisture extraction rate (MER), specific energy consumption (SEC), energy consumption and energy cost.

There is a growing interest in the food industry in the development of economical methods for food production with high organoleptic and nutritional value. Generally, dried apples can be consumed directly or treated as a secondary raw material, since dried apples form important components in numerous prepared food including snack preparations, integral breakfast foods and other varieties (Kaleta *et al.*, 2013, Velic *et al.*, 2004).

Although several studies about drying methods have been taken part in literature, there is limited information reported about effects of various drying methods on quality of apple slices and investigation of energy efficiencies of various drying systems. Therefore, the main objectives of this study were: (1) to determine the effects of tray dryer, heat-pump dryer, microwave drying and freeze drying methods on the quality characteristics of apple slices, and (2) to make analysis of energy efficiency taking into account of energy consumption and compare to the results for each drying method.

MATERIAL AND METHODS

Material

Apples (Starking variety) were purchased from a local market and stored at 4±1 °C and 85 % RH (relative humidity) before processing. The apples were washed with water, separated from part of seeds and then manually peeled. Samples were sliced into 2 mm thickness by using a laboratory type slicer. The sliced apples were immersed into solution of 2.5 % ascorbic acid in order to avoid undesirable enzymatic browning.

Drying process

Drying experiments were performed in a tray dryer, heat-pump dryer, freeze dryer and microwave dryer. Before drying process, apple slices were divided into 4 groups: (1) Drying with tray dryer (TD), (2) Drying with heat-pump dryer (HPD), (3) Freeze drying (FD) and (4) Microwave drying (MWD). Processing scheme of dried apple slices is shown in Figure 1.

Figure 1. Drying process of apple slices

Microwave drying process was carried out with using a microwave oven (ARÇELİK MD 595, 2450 MHz) (Fig.2). Apple slices were placed in 20 cm diameter glass tray and were submitted in microwave oven. Microwave application was carried out at 360 W. During drying period the microwave power was turned on for 30 sec and turned off 15 sec. The total drying time was 20 min. At the end of drying time, moisture content of apple slices were below 10±1 %.

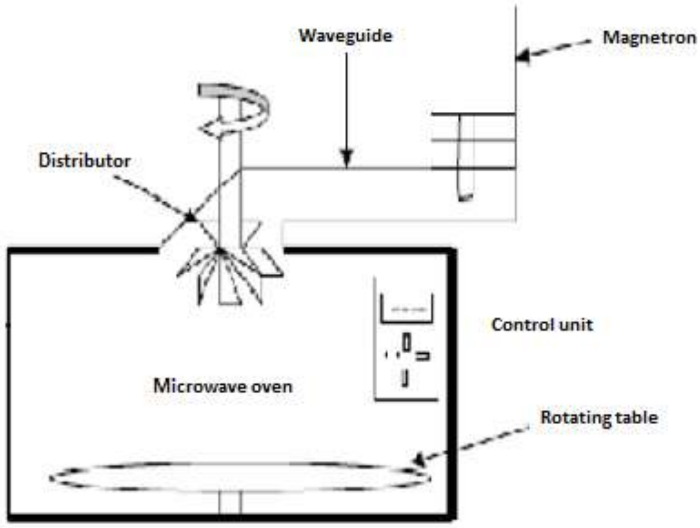

Figure 2. Microwave drying system

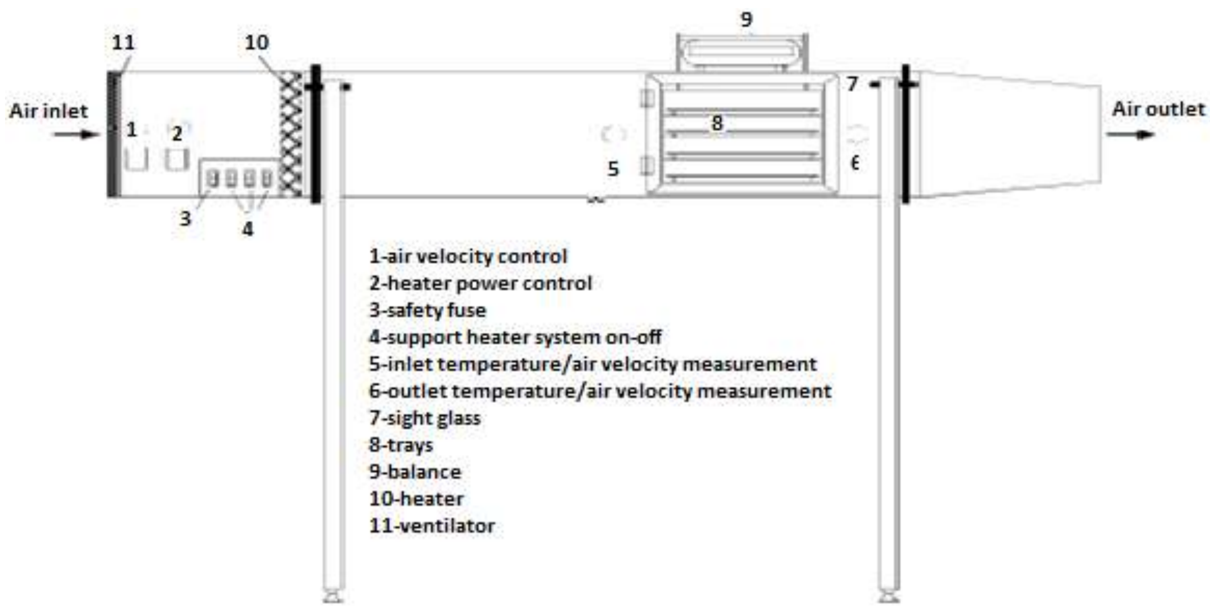

Figure 3. Tray dryer system

Heat-pump drying system consists of a heat-pump and a drying chamber (Fig.4). The air was heated by the heat-pump system which included a compressor, condenser, an expansion valve, evaporator, and a heat recovery unit. The drying air velocity was regulated by a fan and fan speed control unit. The dryer compartment dimensions were 3 m x 1 m x 1 m. Heat-pump drying was achieved with using a heat-pump dryer at 50 °C with 2 m/sec air velocity. Dimensions of four trays were the width of 0.64 m x 0. 67 m and also consist of four sample trays (0.24 m x 0.24 m).

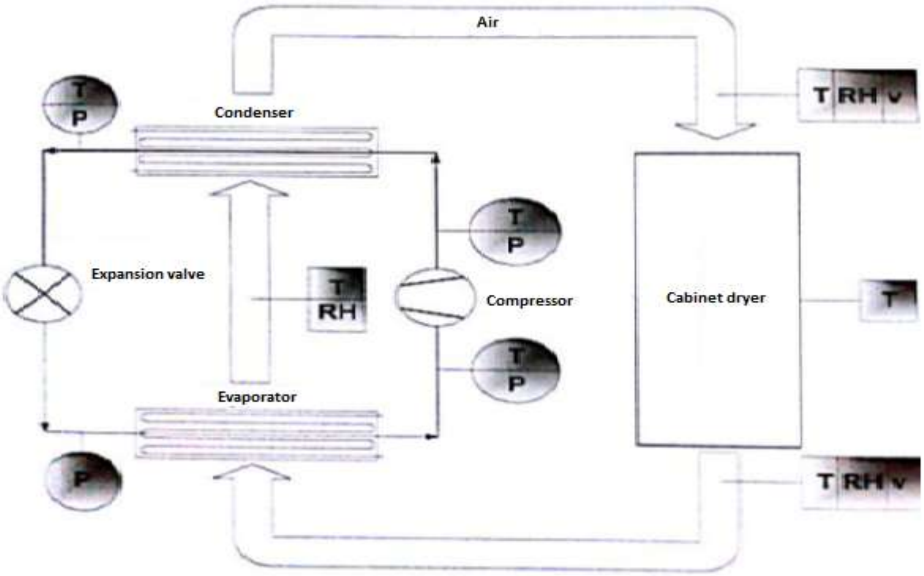

Figure 4. Heat-pump dryer system

Freeze drying experiments were performed in a pilot scale freeze-dryer (ALPHA 1-2 LD_{Plus}, Germany) (Fig.5). Treatment conditions were absolute pressure (100 kPa) at -56 °C condenser temperature for six hours.

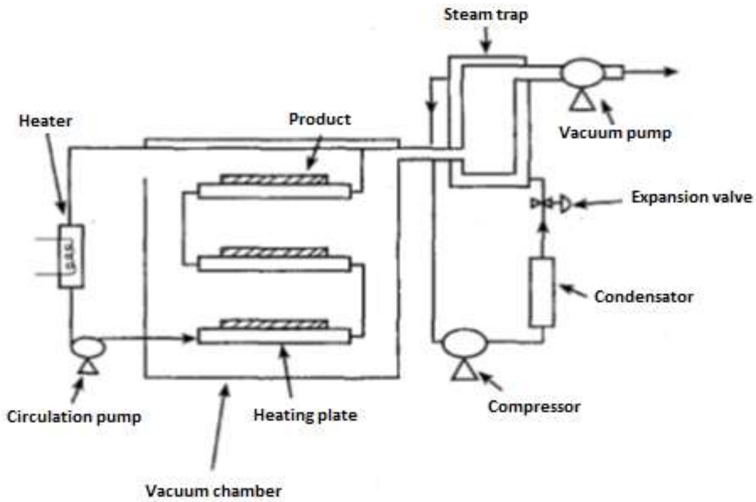

Figure 5. Freeze-dryer system

Physical, chemical, sensory and statistical analyses

Moisture content of dried apple slices was determined by using an infrared moisture meter (Shimadzu MOC 63U) at 105 °C. The colors of dried apple slices were measured with a Hunter Lab Color flex (CFLX 45-2 Model Colorimeter, Hunter Lab, Reston, VA). Color parameters were recorded as L* (lightness), a^* (redness) and b^* (yellowness). After standardization L*, a*, b* values were measured for fresh and dried products. Color values (ΔE), color intensity (chroma, ΔC) and Hue angle (H°) were calculated according to equations 1, 2, and 3:

$$\Delta E = [(L^*-L^*_{ref})^2+(a^*-a^*_{ref})^2 + (b^*-b^*_{ref})^2]^{0.5} \quad (1)$$

$$\Delta C = [(a^*-a^*_{ref})^2 + (b^*-b^*_{ref})^2]^{0.5} \quad (2)$$

$$\text{Hue angle}=\tan^{-1}(b^*/a^*) \quad (3)$$

Water activity values were measured using a Testo 610 relative humidity and temperature measurement device and results were calculated according to equation 4:

$$a_w=ERH/100 \quad (4)$$

The rehydration properties were determined by water immersion at 25±1 °C.

$$R=(M_2-M_1)/M_1 \tag{5}$$

M_1 is the initial weight of apple slices; M_2 is the final weight of after immersion.

A glass measuring cylinder was used for bulk density measurements.

$$\rho_b = m/V \quad (g/cm^3) \tag{6}$$

Polyphenol content of the samples was determined by the Folin–Ciocalteu method (Cemeroglu, 2010). Gallic acid was used as a standard for the preparation of a calibration curve. Two grams of dried apple slices was dissolved in 100 mL of ethanol 80 %, extracted and filtered. One milliliter of filtrate was added to 75 mL distilled water in a 100 mL volumetric flask. Then, 5 mL of Folin–Ciocalteu reagent was added to the mixture which was held at room temperature for 3 min. After 10 mL of saturated Na_2CO_3 solution was added to the volumetric flask, absorbance values were determined at 760 nm after 60 min. Results were calculated and expressed as "mg of gallic acid/g dry matter". Pectin content was investigated according to Anon (1968). The method is based on the extraction of pectin with ethanol after centrifugation (4000 rpm, 15 min, 20 °C); the precipitated was treated with 5-mL NaOH and completed with 100-mL deionized water. After filtration, samples were prepared with 0.5-mL carbazol and 0.5-mL ethanol. Sulfuric acid (6 mL) was added to both samples, then they were placed in a water bath at 85 °C for 5 min. Absorbance values were taken at 525 nm with a Varian Cary 50 Scan (Sydney, Australia) spectrophotometer and the pectin content was calculated with the calibration curve that was made by using gallacturonic acid anhydrate standards. Results were calculated and expressed as "mg of GA-AH/g dry matter". Total sugar and invert sugar content of dried apple slices were investigated according to Cemeroglu (2010). The sensory qualities of various dried apple slices were analyzed in terms of appearance (1-4 points), texture (1-3 points) and flavor (1-3 points). Dried products were evaluated by ten panelists. Dried products with at least 7 points were accepted as good products (Huang *et al.,* 2011). The results were submitted to ANOVA and Duncan test to evaluate differences between drying treatments using SPSS 18 (SPSS Inc., Chicago, USA); and significance level was set at $p<0.05$. Statistically significant differences were compared with each drying method.

Determination of drying rate

The drying rate of apple slices were determined by using equation 7 and 8.

$$R = -\frac{Ws}{A}\frac{\Delta Xf}{\Delta t} \quad (kg\ water/m^2h) \tag{7}$$

$$X_t=(W-W_s)/W_s \quad (kg\ total\ water/kg\ dry\ solid) \tag{8}$$
$$X_f=X_t-X_e$$

Where R is drying rate in kg $H_2O/min.m^2$, W_s is the weight of the dry solid in kilograms, A exposed surface area for drying in m^2, X_f in kg free water/kg dry solid, X_e in kg equilibrium moisture/kg dry solid and t is drying time in minute (Geankoplis, 1983).

Determination of energy efficiencies of drying systems

In order to determine the effectiveness of dryer systems the specific moisture extraction rate (SMER), the moisture extraction rate (MER), specific energy consumption (SEC) were used. Specific moisture extraction rate (SMER) describes the effectiveness of the energy used in the drying process. SMER is defined as kilogram of moisture removed per kilowatt-hour consumed energy and is related to the total power to the dryer including the fan power and the efficiencies of the electrical devices (Prasertsan and Saensaby, 1998, Chua *et al.,* 2002, Tosun, 2009).

SMER is described by the following equation 9:

$$SMER = \left(\frac{\text{Amount of water removed during drying}}{\text{Total energy supplied in drying process}}\right), \frac{kg}{kWh} \tag{9}$$

Moisture extraction rate (MER) is defined as kilogram of moisture removed per hour and indicates the dryer capacity or throughput rate (Prasertsan and Saensaby, 1998, Tosun, 2009). MER is described by equation 10:

$$MER = \left(\frac{\text{Amount of water removed during drying}}{\text{Drying time}}\right), \frac{kg}{h} \tag{10}$$

Specific energy consumption (SEC) which is the reciprocal of the SMER is used to compare energy efficiencies of different types of dryer (Chua *et al.,* 2002, Jindarat *et al.,* 2011). The SEC is defined as the total energy required to remove one kg of water. SEC is calculated according to equation (11):

$$SEC = \left(\frac{\text{Total energy supplied in drying process}}{\text{Amount of water removed during drying}}\right), \frac{kW}{kg} \tag{11}$$

Determination of amount of energy consumption is important method to make analysis of energy efficiency and to compare to the results for each drying method. Considering of the effect of drying conditions on the energy cost is important in order to produce the product at least cost and high quality. Annual operating costs are determined by the following formula:

$$C_{op} = (C_S Q + C_e E)t \tag{12}$$

where C_e (Turkish Lira / kWh) is electricity costs and C_s (Turkish Lira / kWh) is the cost of heating steam. In our study, the energy cost analysis was conducted by taking into account of electricity costs. Electricity price was taken as 0.2224 Turkish Lira (TL)/ kWh (Anonymous, 2013).

RESULTS AND DISCUSSION

Effects of drying methods on drying rates of apple slices

Drying rate is described as the amount of water removed per time and per drying area. The drying rate values were calculated for different dryer types. Drying curves shown in Figure 2 indicate the drying time for the MD process was the shortest (20 min) while the drying time of FD process was the longest (4.5 h). Therefore, microwave drying is the fastest drying option based only on drying time. As shown in Figure 2, drying rate values of microwave application were higher than the other drying methods. The decrease in total moisture content of samples was determined in all drying methods typically as reported by Geankoplis (1998).

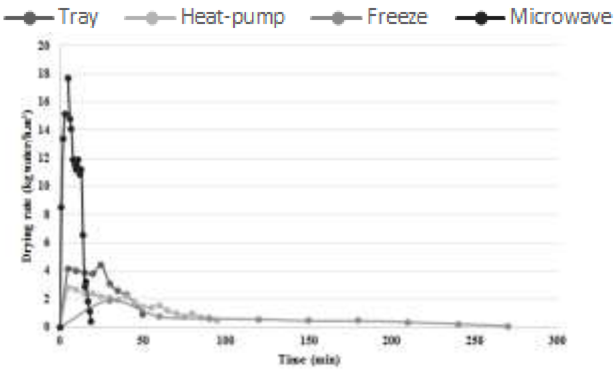

Figure 6. Drying rate for different drying methods

The drying behavior for various drying applications was determined from the mass loss in samples of known initial moisture content. Relationship between average free moisture content for 5 minutes interval is plotted on Figure 7. The higher percentage of weight loss of moisture content occurs in the early stages of drying and the moisture content decreased considerably with increasing the drying time.

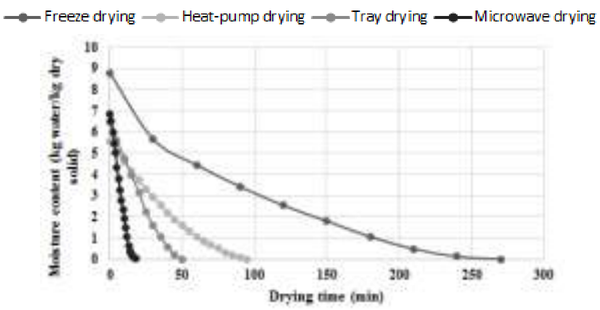

Figure 7. The variation of free moisture content as a function of drying time for apple slices

During microwave drying, the volumetric heat generation in the wet sample due to the directly transmitted and absorbed energy by the water molecules results in higher interior temperatures, thus reaching the boiling point of water definitely faster than would be possible by convective drying (Ersus *et al.*, 2004). In our study, the longtime drying process was observed in the freeze-drying method on the other hand the microwave drying process took quite short time. According to the general trend, the drying time decreases with increasing drying rate. Huang *vd* (2011) reported the material needs to be frozen before FD and the dielectric loss for ice was much lower than that for water. Accordingly, frozen materials absorb little microwave energy, which results in longer drying time. Drying time of apple slices were calculated as 50 min, 90 min, 270 min, and 20 min, respectively.

Effects of drying methods on quality characteristics of apple slices

As seen in Figure 8, microwave drying instead of tray and heat-pump drying caused the rehydration ratio of apple slices to increase under the same rehydration condition. It can be explained that the microwave application provides dehydrated foods with expanded macroscopic porous structure. And the macroscopic porous structure of these products often results in a shorter rehydration time and higher water retention (Huang et al., 2011). The rehydration ratio of apple slices dried by FD and MWD reaches the highest value after 30 sec.

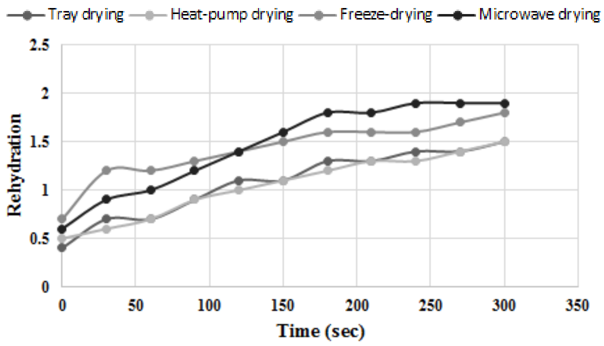

Figure 8. Rehydration ratio of dried apple slices

Moisture content of dried apple slices were found as 10.79%; 10.13%; 10.3%; 9.16% for TD, HPD, FD and MWD, respectively. There were no significant differences evaluated between drying methods ($p>0.05$). Water activity has a direct relationship with the equilibrium moisture content. As shown in Table 1, water activity results of dried apple slices were changed between 0.46-0.53. Water activity of microwave dried samples was found to be the lowest and significantly different from the other methods. It was found to be statistically different for all drying methods when compared to each other ($p<0.05$).

Color of apple slices before processing is: L*=71.63±0.15; a*=4.01±0.07; b*=23.27±0.07. L* values which shows lightness of product were ranged between 58.89-71.41. It can be seen that L* value of freeze dried product is very similar to raw material. Higher L* values are desirable in the dried products (Doymaz *et al.*, 2006). The lowest L* value evaluated for heat-pump dried product because of occuring Maillard reaction caused by longer drying time. The differences of L^* values between the different drying methods were found statistically significant ($p<0.05$). Significantly, a* value of product dried by HPD turned red due to the browning reaction during drying process. b* values of dried products were found as 30.53; 30.16; 32.87; 31.91 for TD, HPD, FD and MWD, respectively. There were no significant differences measured b* values between the drying methods ($p<0.05$).

Hue angle values which shows degree of browning, in other words increasing yellowness results in high hue angles (Baysal *et al.* 2002). Total color differences (ΔE) were calculated between 9.38 and 16.73. The minimum ΔE values were evaluated for samples dried by tray dryer and the highest ΔE values were evaluated for heat-pump dried samples. There were no significant changes in ΔE values for TD and FD ($p>0.05$). ΔC values between the different groups were also found statistically significant ($p<0.05$). The minimum ΔC calculated for tray dryer. H° value of fresh apple slices was determined as 80.22. H° values of apple slices dried by TD and FD were very similar to fresh apple. The difference between H° values of samples dried by different methods were statistically significant ($p<0.05$).

It can be seen that the bulk density of apple slices dried by MWD was the lowest, followed by FD. Microwave application leads to reduced shrinkage and thus provides a more porous structure in vacuum environment (Huang *et al.* 2011). This can be used to explain that the bulk density of MWD was lower than that of FD. On the other hand, Schulze *et al.* (2014) reported that the apple chips showed a porous structure which is characterized by a low bulk density after freeze drying. Titratable acidity results of dried apple slices were ranged between 1.034-2.93% as expressed malic acid. Malic acid of microwave dried samples was found to be the highest and significantly different from the other dried samples. It was found to be statistically different for all drying methods when compared to each other ($p<0.05$). As reported, decreasing in organic acids in thermally treated fruit and vegetables could be explained by the consumption of these compounds as reactants in the maillard reactions (Igual *et al.* 2012).

As seen in Table 1, total phenolic content of dried apple slices were changed between 1.265-1.694 mg GAE/g dry matter. Apple slices dried by MWD presented the highest total phenolic content. It is thought to result from high drying temperature which phenolic compounds were tend to transformed into, which may be related with the increase in chlorogenic acid, catequin and epicatequin increase. Total phenolic content of apple slices dried by different drying methods were found statistically significant ($p<0.05$). Arslan and Özcan (2010) reported that the short time required for microwave drying might have increased the phenolic content of microwave oven dried samples. Other authors also observed a decrease in phenolic compounds during drying and storage of dried product, mainly attributed to enzymatic oxidation and the rapid degradation of phenolic compounds after being subjected to high temperatures and oxygen (Igual et al., 2012). Also, Erbay and Icier (2009) reported that a long term effect of temperature should cause a complete damage of the phenolics, so both degree of heat intense and heat treatment time were important.

Table 1. Effects of drying methods on the quality characteristics of apple slices

Drying methods	Tray drying	Heat-pump drying	Freeze drying	Microwave drying
Moisture content (%)	10.79 ± 0.27^a	10.13 ± 1.56^a	10.30 ± 0.26^a	9.16 ± 0.37^a
Water activity (a_w)	0.50 ± 0.001^b	0.54 ± 0.001^a	0.49 ± 0.001^c	0.47 ± 0.001^d
L*	65.94 ± 0.42^b	58.89 ± 0.21^d	71.41 ± 0.21^a	64.80 ± 0.34^c
a*	5.65 ± 0.09^c	12.38 ± 0.02^a	4.29 ± 0.07^d	6.84 ± 0.143^b
b*	30.53 ± 0.34^c	30.16 ± 0.12^d	32.87 ± 0.04^a	31.91 ± 0.14^b
ΔE	9.38 ± 0.15^c	16.73 ± 0.13^a	9.61 ± 0.04^c	11.37 ± 0.33^b
ΔC	7.45 ± 0.35^d	10.84 ± 0.07^a	9.60 ± 0.04^b	9.09 ± 0.17^c
H°	79.51 ± 0.06^b	67.68 ± 0.10^d	82.56 ± 0.12^a	77.91 ± 0.2^c

% Malic acid	1.32±0.1^{c}	1.03±0.0^{d}	1.61±0.1^{b}	2.93±0.17^{a}
Bulk density (g/cm^3)	0.41±0.01^{b}	0.42±0.02^{a}	0.40±0.05^{b}	0.37±0.01^{c}
Total phenolic content (mg GAE/g dry matter)	1.374±0.01^{c}	1.265±0.04^{d}	1.447±0.01^{b}	1.694±0.05^{a}
Total pectin content (GA-AH mg/g dry matter)	2.73±0.03^{c}	4.99±0.10^{b}	1.18±0.08^{d}	8.58±0.07^{a}
Total sugar content (%)	49.1±0.46^{c}	42.45±0.55^{d}	77.92±0.17^{a}	73.70±0.38^{b}
Invert sugar content (%)	41.63±0.35^{c}	28.1±0.25^{d}	49.49±0.34^{a}	44.48±0.37^{b}

$^{a\ to\ d}$Different letters within rows are significantly different (p<0.05)

Total pectin content of dried apple slices were ranged between 1.18-8.584 mg GA-AH/g dry matter. It was found to be statistically different for all drying methods when compared to each other (p<0.05). The highest pectin content evaluated for apple slices dried by MWD. Total pectin content of microwave dried product increased by depending on enzyme activity which transformed into soluble pectin at high temperature and short time. Total pectin content of apple slices dried by FD was lower when compared to other methods due to decrease in enzymatic activity, which depending on low temperature. Total sugar and invert sugar content of dried apple slices were changed between 42.45-77.92 % and 28.1-49.49%. Total sugar content of apples dried by TD and HPD were found lower comparing to FD and MWD samples. Decreasing in the total sugar content of these samples could be due to the caramelization reactions during drying process.

The data of the sensory analysis of dried products are listed in Table 2. It can be seen that the total points for apple slices dried by FD is the highest followed by MWD. As for the sensory points, apple slices dried by HPD have the lowest points. The numerical value exceeds 7 points, which means that these products are generally acceptable to the consumers.

Table 2. Results of sensory analysis

Quality characteristics	Drying methods			
	Tray dryer	Heat-pump dryer	Freeze drying	Microwave drying
Appearance (1-4 points)	1.9	1.8	3.5	2.7
Texture (1-3 points)	2.2	1.7	2.4	2.1
Flavor (1-3 points)	2.2	1.7	2.3	2.4
Total points	6.3	5.2	8.2	7.2

Effects of drying methods on energy efficiency of apple drying

Specific moisture extraction rate values for four different drying methods are demonstrated in Table 3. As shown in table 3, specific moisture extraction rate (SMER) values were found to vary between 0.014 and 2.261 kg/kWh. The best SMER value was obtained during heat pump drying process. SMER value was found as 2.261, 0.045, 0.014, 0.580 kg/kWh for heat pump drying system, tray drying system, freeze drying system and microwave drying system, respectively. The results obtained showed good agreement with the results of the studies in the literature (Yamankaradeniz *et al.*, 2012, Jolly *et al.*, 1990).

Moisture extraction rates of the four different drying methods were given in Table 3. It becomes obvious that the MER was very high at the heat pump drying method and the lowest MER value was obtained during freeze drying. MER value was found as 0.541, 0.154, 0.015, 0.209 for heat pump drying system, tray drying system, freeze drying system and microwave drying system, respectively. According to the kilogram of moisture removed per hour, it has been seen that using heat pump dryer is more efficient than conventional dryer systems. Tosun (2009) used heat pump dryer system for drying apple and found MER values as 0.65, 0.99, 0.94 and 1.2 kg/h for four different temperature degrees, respectively. The obtained results showed similarity with the results of our study.

Table 3. Results of energy consumption of various drying methods

Drying methods	SMER (kg/kWh)	MER (kg/h)	SEC (kJ/kg)	Energy costs (TL/kg water)
Tray drying	0.05	0.16	79.9	4.94
Heat-pump drying	2.26	0.54	1.6	0.1
Microwave drying	0.58	0.21	6.2	0.38
Freeze-drying	0.01	0.02	259.2	16

Specific energy consumption (SEC) values for four different drying methods are shown in Table 3. As reported in table, SEC values were found to vary between 1.592 and 259.181 MJ/kg. SEC values were found as 1.592, 79.928, 259.181, 6.206 MJ/kg for heat pump drying system, tray drying system, freeze drying system and microwave drying system, respectively. The specific energy consumption associated with drying time. Because of that the highest value of SEC was found by freeze dryer and the low value was obtained by microwave dryer. Due to the principle of energy recovery in heat pump system, the lowest energy consumption has been with the use of heat-pump dryer. The most appropriate method for saving at energy consumption is understood that the heat-pump dryer.

Energy cost per kilogram of removed water for different drying methods is shown in Table 3. Energy cost values were calculated as 0.10, 4.94, 16.01 and 0.38 TL/kg $_{water}$ for heat pump drying system, tray drying system, freeze drying system and microwave drying system, respectively. According to the results obtained from the figure, microwave drying and heat pump drying have low energy consumption. This energy saving occurs in microwave dryer due to application of energy intermittently. Due to the energy recovery in heat-pump system, low energy consumption and low energy cost have been achieved with the use of heat-pump dryer. The energy costs in freeze drying method were found to be too high. The results obtained showed good agreement with the results of Basaran *et al.,* (2004).

CONCLUSIONS

The effects of different drying methods on the quality characteristics of apple slices and energy efficiencies were investigated. Based on our experimental analysis reported in this paper, the quality of FD and MWD products were found better than the others according to evaluated quality characteristics. This study indicates that the industrial processing of dried apples may be improved by using microwave, as the drying time is reduced and the obtained product has a higher phenolic content. According to the analysis results, the quality characteristics of apple slices dried by using tray and heat-pump dryers were similar. The rehydration rate of freeze dried samples was about the same as that of MW dried products. In addition, it can be seen that FD and MW dried samples preserved their nutritional features better than the others. TD is appropriate method for large scale production due to its short drying time and low energy consumption when compared to FD. Due to the energy recovery in heat-pump system, lower energy consumption as compared to other dryers and low energy cost have been obtained with the use of heat-pump dryer. Although FD products were found best quality, the cost of energy is very high compared to other dryers. On the other hand, the quality of dried product with HP dryer which has lowest energy consumption is very low compared to other dryers. According to the purpose of the production obtained quality and cost values will help us in selecting the dryer. The lowest energy consumption and the highest SMER and MER values were obtained from the heat-pump dryer. The cost of evaporation of water per kg from dried apple slices which were produced by using heat-pump dryer and microwave dryer has shown a very low values. The possible uses of combination of these methods in food systems and storage potential of dried products might be studied in future research.

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