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ORIGINAL RESEARCH PAPER

APPLICATION OF NOVEL METHODS FOR QUALITY IMPROVEMENT IN EXPLOSION PUFFING DRYING OF APPLE SNACKS

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Abstract

In this study, vacuum drying (VD), microwave drying (MW) and freeze-drying (FD) alternatives to air drying (AD) were applied to apple samples before explosion puffing drying (EPD). The volumes of AD+EPD samples were determined 20% higher than the volume of AD samples. The porosity value and the average pore radius value were obtained by examining the SEM images with the MATLAB program. Porosity values were found between 0.41-0.82 for all drying processes applied. The lowest porosity was found at 180MW, and the highest porosity was found in the FD samples. It is seen that the porosity ratio increases as the microwave power per product increases. Rehydration rates of 180, 360 and 600MW samples were determined as 308, 320 and 336%, respectively. It contributed to the increase in rehydration due to the increase in the porosity of the product with the increase in power density per product in MW drying. There was an increase in the amount of TPC with the combined use of the EPD process. The highest ABTS and DPPH were determined in the FD, FD+EPD and 600MW+EPD samples, respectively. The pre-drying methods and parameters described in the study significantly affected the quality of apples in terms of their physical and chemical properties.

Keywords: apple, microwave drying, air drying, explosion puffing drying, antioxidant activity, total phenolic content

Introduction

Snack products are defined as small, light foods that are ready for consumption, easily accessible, and can satisfy the appetite instantly (Hurtado *et al*., 2001). The snack industry covers a large area such as biscuits, crackers, chips, cookies, nuts, chocolate, dried fruit, cereals, and new healthy snack product designs are needed to

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meet consumer demand, since most of these snacks contain very fatty, sugary or salty content. In recent years, it has been increasing with the increase in some risk factors such as chronic diseases, wrong eating habits, environmental effects, insufficient physical activities and lifestyle. Snack foods containing a lot of fat, salt and sugar can also be considered a risk factor in this context. It has been found that about three quarters of these snack foods do not have the necessary nutrients for human health (Bauer *et al*., 2014). For these reasons, snack foods have started to become an important part of human nutrition today and the snack industry is developing day by day.

In the studies carried out, extrusion, frying, freeze and hot air-drying technologies are generally used in the production of snack products. Since these methods have certain disadvantages, alternative drying technologies are being developed in this area (Seremet *et al*., 2015). In dry food production and especially in snack products, it has become very important to give the porous structure, as it affects the characteristic structure of all dry foods. Explosion puffing drying technology is an environmentally friendly, energy-saving drying technology that has emerged in recent years to produce snacks, especially fruit and vegetable chips, at modified temperature and pressure (Bi *et al.*, 2015).

The basic principle of the puff drying system is based on the principle of loosening the texture of the product with the effect of high pressure and saturated or superheated steam, and removing the moisture from the product as much as quickly under pressure lower than atmospheric pressure (under vacuum). The products dried by this method have a porous structure similar to a honeycomb. After the puff process, the moisture content of the product can be reduced to 3% or less moisture values, usually by vacuum drying method (Du *et al*., 2013).

Air is often used as a pre-drying technology to reduce moisture content prior to EPD. The collapse and shrinkage of fruit tissues, which adversely affect the volume, color and texture of the final product, occur during the air-drying phase (Alp and Bulantekin, 2021). The shrinkage phenomenon causes the hardness of the product to increase significantly. In addition, during the drying process by air drying, the removal of water generally causes serious decreases in physicochemical, organoleptic and nutritional properties (Alonzo-Macías *et al.*, 2014; Mouhoubi *et al.*, 2019). The negative effects of air drying can be reduced by puff drying.

In this study, vacuum, microwave, freeze and air drying were applied for pre-drying the apple samples before explosion puffing drying, and the effectiveness of these pre-treatments was compared. Starting from this point the present study investigated the physicochemical and organoleptic properties of apple snacks dried with EPD method by applying different pre-drying methods.

Materials and methods

Materials and sample preparation

Apples of Granny Smith variety (*Malus x domestica* Borkh.) was used as material in this study. Apples were stored at +2.5 °C in a cold storage (Öz-bay Company,

Isparta, Turkey). After washing the apples, extra water was drained, then the pieces were cut from the part between the peel and the core, all slices sliced at a constant thickness (4.5 mm) were adjusted to be equal.

Pre-drying methods

Apple slices were first pre-drying using air, microwave, vacuum or freeze-drying methods, and their moisture content was reduced to around ~35%. Apple slices were arranged in a single row on 45×45 cm perforated, teflon coated aluminum trays and a forced circulation tray dryer laboratory type was used for the air-drying process, which was conducted at 70 °C, 10% relative humidity, and 2 m/s air velocity (Eksis, Isparta, Turkey). Vacuum oven (Wiseven, WOW-70, Germany) was used for vacuum drying of apple slices. Drying processes were carried out at 70°C and 0.085 Mpa vacuum. Freeze-drying was performed in a laboratory scale lyophilizer (Virtis K2 benchtop, USA) system under 13.33 Pa vacuum at -55^{0}C. Microwave drying (Bosch 5870 GH, Germany) was performed at 180, 360, and 600 W microwave power. The power density applied to the product in the system was determined to be in range of 0.9, 1.8, and 3 W/g product. The codification of the samples if provided in Table 1.

Puff drying methods

After the application of various drying processes, apple slices with a moisture content of 35% were placed in the explosion puffing drying system at 70°C for 15 minutes at 0.6 MPa pressure. Following the generation of a certain amount of steam pressure within the product, the pressure reducing valve was opened. After the decompression process, the samples continued to be dried at 70°C under a vacuum of 95 kPa and the drying was terminated at a final moisture level of ~6%. The images of EPD and AD apples cut in half are shown in Figure 1.

Figure 1. Half-cut images of EPD and AD apples.

Moisture analysis

Moisture and dry matter were determined with a halogen lamp rapid moisture analyzer at 105°C.

Water activity analysis

Thermoconstanter TH 200 (Novasina, Axair Ltd., Switzerland) was used to measure the water activity (a_w) of the fresh and dried apple slices.

Color analysis

Surface color measurements of dried apple slices were taken at multiple locations on randomly selected samples utilizing the NH310 High-Quality Portable Colorimeter (Shenzen 3NH Technology CO., LTD., China).

Apparent volume, bulk density, true volume, true density, and porosity properties analysis

Based on the displacement principle of glass beads (200 µm) as explained by Yan *et al*. (2008), the apparent volume and bulk density of the samples were determined.

The method described by Yan *et al*. (2008) was employed to determine the actual volume and density of apple slices by pycnometry using toluene.

Equation 1 was used to calculate the porosity (ε) values after the apparent and true density values were determined.

$$\varepsilon = 1 - \frac{P_b}{Pg} \quad (1)$$

where ε, p_g, and p_b are porosity, the true density of the sample, and the bulk density of the sample respectively.

Rehydration analysis

Dried apples were soaked in distilled water at 25°C until they reached a constant weight. The samples were then placed on a sieve for 30 s, rinsed gently with a paper towel, and weighed. Equation 2 was used to determine the results as percentages (Jiang *et al*., 2014).

$$RR\ (\%) = \frac{v_t - v_d}{v_d} \times 100 \quad (2)$$

where v_t and v_d represent weight of the product (g) at any time and initial weight (g) respectively.

Ascorbic acid analysis

Amount of Ascorbic acid (AA) of fresh and dried apple samples were determined by Li *et al*. (2014) and Ertekin Filiz and Seydim (2018) with some modifications, by titrimetric method using 2,6 dichloroindophenol.

The dried samples were homogenized with oxalic acid solution (2%), and they were filtered after extraction. The filtrate (15 mL) was titrated with 2,6 dichloroindophenol solution. When the pink color remained constant for 15 seconds, the titration was ended. The volume spent was recorded and Equation 3 was used to calculate the ascorbic acid content of the samples.

$$\text{Ascorbic Acid (mg/100g)} = \frac{\text{V x F}}{\text{m}} \times 100 \quad (3)$$

where m, V, F refers to amount of the sample, the amount spent in the titration, and the dye solution factor, respectively.

Antioxidant activity analysis

Extraction of samples

After weighing two grams of the material, 20 mL of methanol (1:10 v/v) was added (Chong *et al*., 2013). It was extracted in a multiple magnetic stirrer for 4 hours and filtered. The extracts were tested for antioxidant activity (DPPH and ABTS) and total phenolic content (TPC).

Total phenolic content

Total phenolic content (TPC) of fresh and dried apple samples were determined by Singleton and Rossi (1965) and Cherrat *et al.* (2019) with some modifications. 40 µL of the extracts were taken and vortexed by adding 2.4 mL of distilled water, then 0.2 mL of Folin-Ciocalteu solution was added and the vortexing process was repeated. The incubation period was started by adding 0.6 mL of saturated sodium carbonate (Na_2CO_3) to the obtained solution. 0.76 mL of distilled water was added to the mixture and incubated for 2 hours in the dark. Samples were read at 765 nm in a spectrophotometer. The results were given in milligrams gallic acid equivalents per 100 grams of dry weight (mg of GAE/100 g dw).

ABTS assay

The antioxidant activity of dried apple samples was determined using the method described by Re *et al.* (1999). A 7 mM ABTS solution containing 2.45 mM potassium persulfate was prepared and the absorbance of the solution was adjusted to be 0.700 to 734 nm. The absorbance of the solution was adjusted to 0.700 with ethanol. The chronometer was started by taking 10 µl of the prepared apple extracts and adding 990 µL of ABTS solution to it. Readings were taken at zero and six minutes in the spectrophotometer and the results were recorded. The percent decrease rate (inhibition rate) from the first value according to the absorbance value measured at the end of 6 minutes was calculated according to Equation 4. ABTS values were expressed as µ mol Trolox equivalent (TE)/g dw.

$$\text{Inhibition rate (\%)} = \frac{NAV - AV}{NAV} \times 100 \quad (4)$$

where, *NAV:* Initial absorbance value; *AV:* 6th minute absorbance value

DPPH Assay

The DPPH method described by Dorman *et al.* (2003) was used to analyze the antioxidant capabilities of the dried apple samples.

A quantity of 50 µL of the prepared extract was taken into the test tube, and 450 µL of buffer solution (Tris-HCL, 50 mM, pH 7.4), 0.8 ml of methanol, 0.2 ml of DPPH solution was added, then it was mixed rapidly. The mixture was incubated at room temperature for 30 minutes in the dark. The absorbance of the samples was measured at 515 nm using a spectrophotometer following incubation in the dark. Under the same conditions, a control was prepared using 50 µL 80% methanol instead of the sample. As a replicate solution, 80% methanol was utilized. The % inhibition of DPPH was calculated using Equation 5 and the results were expressed as µ mol TE/g dw.

$$\text{DPPH Radical Removal Activity (\%)} = \frac{A_{control} - A_{sample}}{A_{control}} \times 100 \qquad (5)$$

where, $A_{control}$: the absorbance of control; A_{sample}: the absorbance of sample

Texture analysis

Textural characteristics of the products were analyzed according to the method described by Huang and Zhang (2012). A cylindrical probe with a diameter of 5 mm was used to evaluate the hardness of the samples via a puncture test. The initial velocity of the probe was 5 mm/s, final velocity was 2 mm/s, and trigger force of the device was set to 20 g.

SEM analysis

Scanning electron microscope (FEI Quanta FEG 250, Japan) was used to detect the changes in the microstructure caused by the drying process, and the cell structures and shapes of the samples dried with different drying methods were evaluated. The imaging process was performed in the SEM laboratory operating at Süleyman Demirel University.

The MATLAB (R2019) software was used to analyze the obtained SEM images. A crucial detail to note is that various drying conditions were investigated for images with the same scale. The darker areas in the SEM images were assumed to be pore spaces and indicate deeper surfaces during the investigation. Thus, the values of porosity and average pore radius were computed (Rabbani and Salehi, 2017).

Statistical analysis

All analyses were carried out in two replications and three parallels. Statistical analyses were realized with Minitab statistical program (version 18.1, Minitab Inc., State College, PA, USA) and the statistical differences between the means were analyzed with Tukey multiple comparison test ($p<0.05$).

Results and discussion

Drying time, moisture content and water activity

The highest drying time was 1200 min at FD, and the lowest drying time was 30 min at 600MW. The time that was needed to dry the apple slices to reach the ratio of their equilibrium moisture content was 250±3.51, 220±3.17, 1200±10.63 and 180±2.52,

161±2.45, 750±8.43 min for AD, VD, FD and AD+EPD, VD+EPD, FD+EPD respectively (Table 1). Puff drying shortened the time of AD, VD and FD processes by 28, 27 and 29%, respectively. Puff drying reduces the diffusion resistance of the moisture in the material and increases the diffusion of water from the food material. The water in the material is quickly transferred to the vacuum environment with the decompression process. The moisture content of the dried samples was between 5.98-6.56%, and the a_w values were between 0.251-0.305.

Table 1. Apple samples codifications and drying time.

Samples	Drying Time (min)
AD (Air Drying)	250±3.51^{c}
AD+EPD (Air Drying+ Explosion Puffing Drying)	180±2.52^{e}
VD (Vacuum Drying)	220±3.17^{d}
VD+EPD (Vacuum Drying+ Explosion Puffing Drying)	161±2.45^{f}
180MW (180W Microwave Drying)	140±2.05^{h}
360MW (360W Microwave Drying)	55±1.06^{k}
600MW (600W Microwave Drying)	30±0.59^{n}
180MW+EPD (180W Microwave Drying+ Explosion Puffing Drying)	130±1.28^{i}
360MW+EPD (360W Microwave Drying+ Explosion Puffing Drying)	70±0.89^{j}
600MW+EPD (600W Microwave Drying+ Explosion Puffing Drying)	55±0.86^{k}
FD (Freeze Drying)	1200±10.63^{a}
FD+EPD (Freeze Drying+ Explosion Puffing Drying)	750±8.43^{b}

$^{a-l}$ Statistical differences between dried samples in the same columns ($p<0.05$)

Color

The a* value of the samples increased during drying, and it is pointed out that the increase in a* value is indicative of the browning reaction (Krokida and Maroulis, 2000). In our study, the highest a* values were 18.20±0.92^{a}, 15.10±0.98 and 14.20±0.89 in 180MW, 180MW+EPD and AD samples, respectively; the lowest a* values were determined in FD, FD+EPD, and 600 MW samples (Table 2).

FD samples showed a much smaller increase in redness a* than the others, thus freeze drying prevented browning during drying. Since the freeze-drying process is carried out under vacuum and at very low temperatures, it is a method in which the closest results to the fresh product are obtained in terms of color values. 360MW and 600MW, VD and EPD samples caused a smaller increase in redness (a*) than AD samples, meaning the final products were less brown than air dried. The maximum a* increase was observed in 180MW samples. It is thought that the long drying time due to the low processing temperature in 180W power application may cause discoloration of the apple related to the formation of browning products.

Table 2. Color values results of fresh apple and dried apple slices.

Sample	L*	a*	b*	C*	h*	ΔE
Fresh	83.52±2.01	-2.11±0.16	16.99±0.87	17.12±0.53	97.08±4.45	-
AD	70.09±1.25^{l}	14.20±0.89^{c}	34.95±1.59^{c}	36.80±2.27^{c}	67.31±3.89^{j}	27.72±1.85^{c}
AD+EPD	72.77±2.75^{i}	11.99±0.95^{d}	31.36±1.96^{e}	33.58±2.31^{e}	69.07±1.98^{i}	22.82±1.28^{e}
VD	80.74±3.36^{b}	9.78±0.68^{g}	27.52±1.14^{j}	27.81±1.74^{i}	78.28±3.85^{b}	16.12±0.95^{i}
VD+EPD	79.78±2.87^{c}	10.56±0.85^{a}	29.43±1.58^{f}	30.47±1.66^{g}	71.85±3.88^{f}	18.14±0.86^{g}
180MW	70.42±1.69^{k}	18.20±0.92^{a}	40.07±2.26^{a}	44.02±2.58^{a}	65.55±2.67^{l}	33.43±1.97^{a}
360MW	76.05±2.25^{g}	10.20±0.57^{f}	29.17±1.83^{g}	30.90±2.48^{f}	70.72±3.79^{g}	18.85±1.06^{f}
600MW	79.58±1.89^{d}	8.61±0.41^{i}	28.17±1.77^{i}	30.41±2.37^{h}	73.56±4.58^{d}	15.98±0.79^{j}
180MW+EPD	71.29±2.56^{j}	15.10±0.98^{b}	35.12±2.61^{b}	38.23±2.82^{b}	66.72±3.83^{k}	27.82±1.53^{b}
360MW+EPD	74.34±2.97^{h}	10.57±0.62^{e}	33.68±1.94^{d}	35.30±2.49^{d}	72.58±4.75^{e}	22.88±1.74^{d}
600MW+EPD	78.82±3.49^{f}	9.12±0.58^{h}	29.08±1.69^{h}	27.39±2.22^{j}	70.55±3.66^{h}	17.15±0.93^{h}
FD	82.94±2.38^{a}	3.98±0.24^{k}	20.79±1.35^{l}	21.23±1.17^{l}	81.77±4.24^{a}	7.20±0.41^{l}
FD+EPD	79.28±3.84^{e}	7.89±0.49^{j}	22.34±1.39^{k}	25.51±1.25^{k}	76.02±4.27^{c}	12.10±0.66^{k}

Superscript letters in the same columns stand for statistical significant differences between dried samples ($p<0.05$).

The highest b* values were 40.07±2.26, 35.12±2.61 and 34.95±1.59 in 180MW, 180MW+EPD and AD samples, respectively; the lowest b* values were found 20.79±1.35, 22.34±1.39 and 27.52±1.14 in FD, FD+EPD and VD samples, respectively. The highest b* increase was observed in 180MW samples. The highest C* (chroma) values were 44.02±2.58, 38.23±2.82 and 36.80±2.27 in 180MW,

180MW+EPD and AD samples, respectively; the lowest C* values were measured as 21.23±1.17, 25.51±1.25 and 27.39±2.22 in the FD, FD+EPD and 600W+EPD samples, respectively.

The highest tone angle (h*) value was 81.77±4.24, 78.28±3.85 and 76.02±4.27 in the FD, VD and FD+EPD samples, respectively; the lowest values were determined 65.55±2.67, 66.72±3.83 and 67.31±3.89 in 180MW, 180MW+EPD, AD samples, respectively. In the lyophilization and vacuum drying samples, the tone angle value decreased the least compared to the fresh product. It shows that vacuum process plays a big role in drying in these systems. Hawlader *et al.* (2006) stated that decreases in tone angle values can be interpreted as an indicator of a more brownish color and getting away from yellowness.

The highest total color change (ΔE) value in 180MW, 180MW+EPD, AD samples was 33.43±1.97, 27.82±1.53, 27.72±1.85, respectively; the lowest ΔE was measured as 7.20±0.41, 12.10±0.66 and 15.98±0.79 in FD, FD+EPD and 600MW samples, respectively. A product's ΔE value indicates how well it is liked by consumers; high-quality dried apples have the closest color to fresh apples. Freeze drying is the type of drying that has the closest color values to the fresh product and therefore the lowest color change.

Apparent Volume, Bulk Density, True Volume, True Density, Porosity and Porous Properties

The lowest apparent volume was measured as 1.45±0.07 mL at 180MW sample, while the highest apparent volume was 3.13±0.18 mL at FD sample. The apparent volumes of 180, 360 and 600MW samples were found to be 1.45±0.07, 1.70±0.06 and 1.76±0.05 mL, respectively (Table 3). As the microwave power density per product increases, the temperature and vapor pressure of the water in the material create a puffing effect in the samples, and it has been determined that the volume of the samples increases as the microwave power increases. Similar situation has also been reported by Figiel (2010) and Ressing *et al.* (2007).

The apparent volume of AD and AD+EPD samples was measured as 1.54±0.04 mL and 1.85±0.11 mL, respectively. The volumes of AD+EPD samples were determined 20% higher than the volume of AD samples. He *et al.* (2013) reported that the measured apparent volumes of fresh, FD, FD+AD, AD+EPD and AD samples of jujube dried by different methods were 5.4, 3.8, 3.6, 3.2 and 2.6 mL, respectively. These results are similar to our results.

The lowest bulk density was determined that 0.24±0.01, 0.35±0.01, 0.53±0.03 g/ml in FD, FD+EPD and 600MW+EPD samples, respectively. The difference between the bulk density values of the dried samples was found to be statistically significant ($p<0.05$). Chen *et al.* (2017) reported the bulk density values of black mulberry fruit and An *et al.* (2015) for apple fruit 0.84±0.02. 0.38±0.01. 0.29±0.01 g/mL and 0.41±0.02. 0.25±0.02. 0.18±0.01 g/mL after AD, AD+EPD and FD drying, respectively. Similar results were obtained in these studies.

Table 3. Volume, apparent density, porosity, rehydration rate and hardness values of fresh and dried apple slices.

Sample	V (mL)	p_b (g/mL)	ε	Porosity (fraction)	Average Pore Radius (um)	RR (%)	Hardness (g)
Fresh	7.01±0.05	0.85±0.05	-	-	-	-	-
AD	1.54±0.04^{ij}	0.68±0.04^{b}	0.48±0.02^{f}	0.06145	4.402±0,32^{f}	310±10.22^{i}	5647±267^{a}
AD+EPD	1.85±0.11^{e}	0.59±0.05^{e}	0.57±0.03^{cd}	0.06335	4.751±0,28^{cd}	338±11.45^{e}	4005±123de
VD	1.55±0.09^{ij}	0.67±0.02^{bc}	0.5±0.02^{ef}	0.06180	4.465±0,17^{ef}	345±9.37^{d}	4517±127^{b}
VD+EPD	1.57±0.08^{i}	0.66±0.03^{bc}	0.51±0,02^{e}	0.06195	4.503±0,24^{e}	355±12.03^{c}	3944±186^{e}
180MW	1,45±0.07^{k}	0.71±0.04^{a}	0.41±0.02^{g}	0.06030	4.104±0,29^{g}	308±8.98^{j}	3797±105^{f}
360MW	1.7±0.06^{g}	0.63±0.02^{d}	0.51±0.02^{e}	0,06182	4.499±0,32^{e}	320±6.29^{h}	4041±175^{d}
600MW	1.76±0.05^{f}	0.57±0.03^{e}	0.55±0,03^{d}	0.06256	4.678±0,35^{d}	336±21.55^{f}	4139±210^{c}
180MW+EPD	1.6±0.07^{h}	0.65±0.02^{cd}	0.50±0.02^{ef}	0.06178	4.463±0,37^{ef}	324±7.68^{g}	3061±151^{h}
360MW+EPD	1.89±0.08^{d}	0.57±0.03^{e}	0.58±0,03^{c}	0.06351	4.808±0,41^{c}	339±14.32^{e}	3459±229^{g}
600MW+EPD	1.92±0.06^{c}	0.53±0.03^{f}	0.59±0,02^{c}	0.06372	4.846±0,39^{c}	343±10.26^{d}	3810±251^{f}
FD	3.13±0.18^{a}	0.24±0.01^{h}	0.82±0,03^{a}	0.06897	5.825±0,47^{a}	405±9.68^{a}	1602±79^{j}
FD+EPD	2.86±0.17^{b}	0.35±0.01^{g}	0.74±0,04^{b}	0.06764	5.487±0,42^{b}	400±12.92^{b}	2481±200^{i}

Superscript letters in the same columns stand for statistical significant differences between dried samples ($p<0.05$).

Porosity values of apple slices dried with different drying methods were found between 0.41±0.02-0.82±0.03. The lowest porosity was found at 180MW, and the highest porosity was found in the FD samples. The porosity values were in agreement with the values obtained using MATLAB. In Figure 2, the SEM images were analyzed with the MATLAB program, and the geometric structure, dimensions and distribution of the porous in the materials were examined. The porosity (fraction) and pore radius values of apple slices dried with different drying methods were found to be between 0.06030-0.06897 and 4.104±0,29-5.825±0.47 um. Porosity values and pore radius showed similar with each other. Puff drying contributes to the expansion and porosity of the product. The porosity values of 180, 360, 600MW dried samples were determined 0.41±0.02, 0.51±0.02, 0.55±0.03, respectively. It is seen that the porosity ratio increases as the microwave power per product increases. Marzec *et al.* (2010) indicated in their study that the increase in microwave power in the drying process causes a decrease in apparent density and an increase in volume and total porosity. In our research, a similar situation was observed.

Rehydration

The rehydration rates of the samples were measured in the range of 310±10.22-405±9.68%. The lowest rehydration rates were measured as 308±8.98% and 310±10.22% in 180MW and AD samples, respectively. The highest rehydration rate was measured as 405±9.68% in FD samples. Since porosity was determined most in FD samples, the highest rehydration rate was measured in FD samples. Rehydration rates of 180, 360, 600MW samples were determined 308±8.98, 320±6.29, 336±21.55%, respectively. It contributed to the increase in rehydration due to the increase in the porosity of the product with the increase in power density per product in MW drying. Yi *et al.* (2016a) reported the rehydration rates of jack fruit samples dried by AD, AD+EPD, VD+EPD and FD methods 275, 310, 325 and 350%, respectively. The results in this study were similar to the results in our study, and there was an improvement in rehydration with EPD.

Ascorbic acid, Total phenolic content, DPPH and ABTS values of apple samples

The AA, TPC, DPPH and ABTS results of samples are given in Table 4. The lowest AA (ascorbic acid) amount was 4.49±0.21, 5.71±0.19 and 6.12 mg/100g dw in 180MW, 180MW+EPD and AD samples, respectively; the highest amount of AA was determined at 14.45±0.87, 11.02±0.36 and 10.21±0.34 mg/100g dw in FD, FD+EPD and 600MW samples, respectively. Ertekin Filiz and Seydim (2018) reported that the AA content of Golden Delicious, Starking Delicious, Granny Smith apple cultivars with initial AA content of 15.7-16.3 mg/100g dw after air drying at 70°C ranged from 5.57-5.88 mg/100g dw. After the apple samples were dried, a large amount of AA loss occurred and the lowest AA loss was determined in the FD samples. The degradation reactions of ascorbic acid accelerate during drying due to high temperature and oxidation (Kuşçu and Bulantekin, 2021).

TPC amount of dried products processed at AD, 180MW, 360MW and 600MW samples were 249.02±10.23, 256.15±9.88, 263.66±8.63 and 411.37±5.89 mg GAE/100g dw, respectively; TPC amount of dried products processed at AD+EPD, 180MW+EPD, 360MW+EPD and 600MW+EPD samples were 269.55±8.67,

308.45±11.41, 368.22±12.79 and 421.09±13.78 mg GAE/100g dw, respectively. Here, there was an increase in the amount of TPC with the combined use of the EPD process. The reason for this is that temperature and pressure during EPD cause a change in the chemical composition of the material. For example, Du *et al.* (2013) reported that the total polyphenol content of jujubes increased significantly with puff drying, resulting in a corresponding increase in antioxidant capacity. It has been reported that the puff drying technique contributes to the release of abundant phenolic acids bound insoluble in the cell wall and makes it possible to increase the availability and extractability of high-value biomolecules (Gong *et al.*, 2012).

Table 4. Ascorbic acid (AA), Total phenolic content (TPC), DPPH and ABTS antioxidant activity values of fresh and dried apple samples.

Sample	AA (mg/100g dw)	TPC (mg/100g GAE dw)	DPPH (µmol TE/g dw)	ABTS (µmol TE/g dw)
Fresh	35.21±0.98	560.12±22.89	35.34±1.07	30.77±1.78
AD	6.12±0.39^{j}	249.02±10.23^{l}	13.67±0.87^{h}	12.66±0.97^{de}
AD+EPD	8.17±0.43^{d}	269.55±8.67^{i}	14.66±0.63^{gh}	13.65±0.68^{cd}
VD	7.25±0.52^{f}	343.12±20.09^{f}	16.85±0.37^{fg}	14.63±0.54^{cd}
VD+EPD	7.12±0.33^{g}	303.07±15.56^{h}	15.14±0.38^{gh}	13.45±0.72^{cd}
180MW	4.49±0.21^{l}	256.15±9.88^{k}	13.87±0.47^{h}	9.48±0.43^{f}
360MW	6.94±0.23^{h}	263.66±8.63^{j}	18.37±0.31^{ef}	14.97±0.77^{cd}
600MW	10.21±0.34^{c}	411.37±5.89^{d}	22.07±0.55^{cd}	15.49±0.86^{cd}
180MW+EPD	5.71±0.19^{k}	308.45±11.41^{g}	14.22±0.78^{gh}	10.27±0.38^{ef}
360MW+EPD	6.53±0.21^{i}	368.22±12.79^{e}	19.96±0.93^{de}	15.31±1.02^{cd}
600MW+EPD	7.76±0.24^{e}	421.09±13.78^{c}	23.11±1.05^{c}	15.87±0.76^{c}
FD	14.45±0.87^{a}	475,69±14.65^{a}	32.53±1.25^{a}	27.25±1.24^{a}
FD+EPD	11.02±0.36^{b}	428.78±18.29^{b}	26.77±0.95^{b}	20.78±1.05^{b}

Superscript letters in the same columns stand for statistical significant differences between dried samples ($p<0.05$).

Total antioxidant capacity values of samples in terms of DPPH and TEAC are given in Table 4. The lowest DPPH value of dried products processed at AD, 180MW and 180MW+EPD samples were 13.67±0.87, 13.87±0.47 and 14.22±0.78 µmol TE/g dw, respectively; the highest DPPH value of dried products processed at FD, FD+EPD and 600MW+EPD samples were determined 32.53±1.25, 26.77±0.95 and 23.11±1.05 µmol TE/g dw, respectively. The lowest ABTS value of dried products processed at 180MW, 180MW+EPD and AD samples were determined 9.48±0.43, 10.27±0.38 and 12.66±0.97 µmol TE/g dw, respectively; the highest ABTS value of dried products processed at FD, FD+EPD and 600MW+EPD samples were determined 27.25±1.24, 20.78±1.05 and 15.87±0.76 µmol TE/g dw, respectively. Gramza-Michałowska and Człapka-Matyasik (2011) reported the DPPH and ABTS values of commercial apple chips 20.00±0.14 and 46.87±0.12 µmol TE/g dw, respectively. The results in this study are similar to the DPPH and ABTS results in our study.

Garau *et al.* (2007) reported in their study that an almost opposite relationship was observed when the ΔE values of the products after drying were compared with the DPPH radical scavenging activity. As reported by some authors, long drying times associated with low processing temperature can cause a decrease in antioxidant activity (Vega-Gálvez *et al.*, 2012). In our study, it was determined that AD, 180MW+EPD and 180MW samples with the highest ΔE values, respectively, had the lowest DPPH and ABTS values. These results in our study were similar to the situation indicated by Garau *et al.* (2007).

It was observed that DPPH and ABTS values increased as the microwave power density per product increased in microwave drying processes (Table 4). Similar situation, Figiel (2010) reported the antioxidant capacity value 54.50 and 59.07 µmol TE/100g dw, respectively, at 360W and 480W powers in the microwave drying process of apples. It is thought that the release of phenolic components due to the more heat released due to the increase in power density per product causes an increase in antioxidant capacity.

Texture

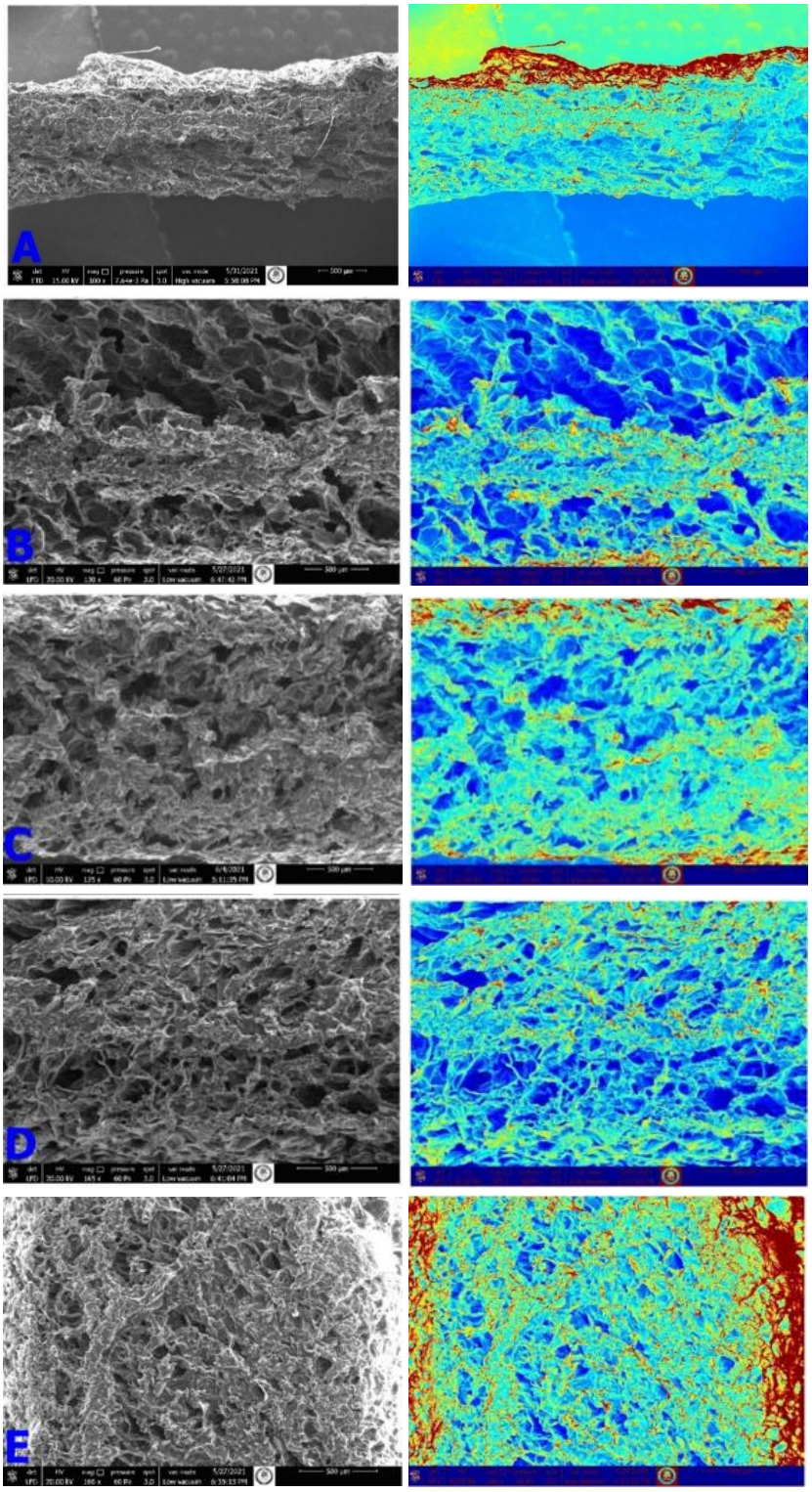
During drying, shrinkage may occur in the final product due to deformation of the product, collapse of cells and pores, loss of specific volume and increase in hardness. All these events cause a negative impression on consumers in many cases. Texture properties, including structural and mechanical properties, greatly affect the quality of dried products.

The highest hardness value of dried products processed at AD sample was measured as 5647±267 g and the lowest hardness value of dried products processed at FD sample was measured as 1602±79 g. In the freeze-drying process, due to the drying by sublimation of frozen water under vacuum, the collapse and shrinkage of the solid matrix is prevented and the structural hardness is reduced.

The hardness values of 180, 360 and 600MW samples were measured as 3797±105, 4041±175 and 4139±210 g, respectively, and were lower than AD samples. In the microwave drying process, unlike air drying, since moisture transfer occurs from the inside to the outside, surface hardening is less than air drying.

Microstructure

SEM images of the samples are given in Figure 2. In AD samples, low porosity, tight microstructure between cells and a hard tissue were observed. With the image analysis method, the geometric structure, dimensions and depth map of the poros in the material were examined using the MATLAB program.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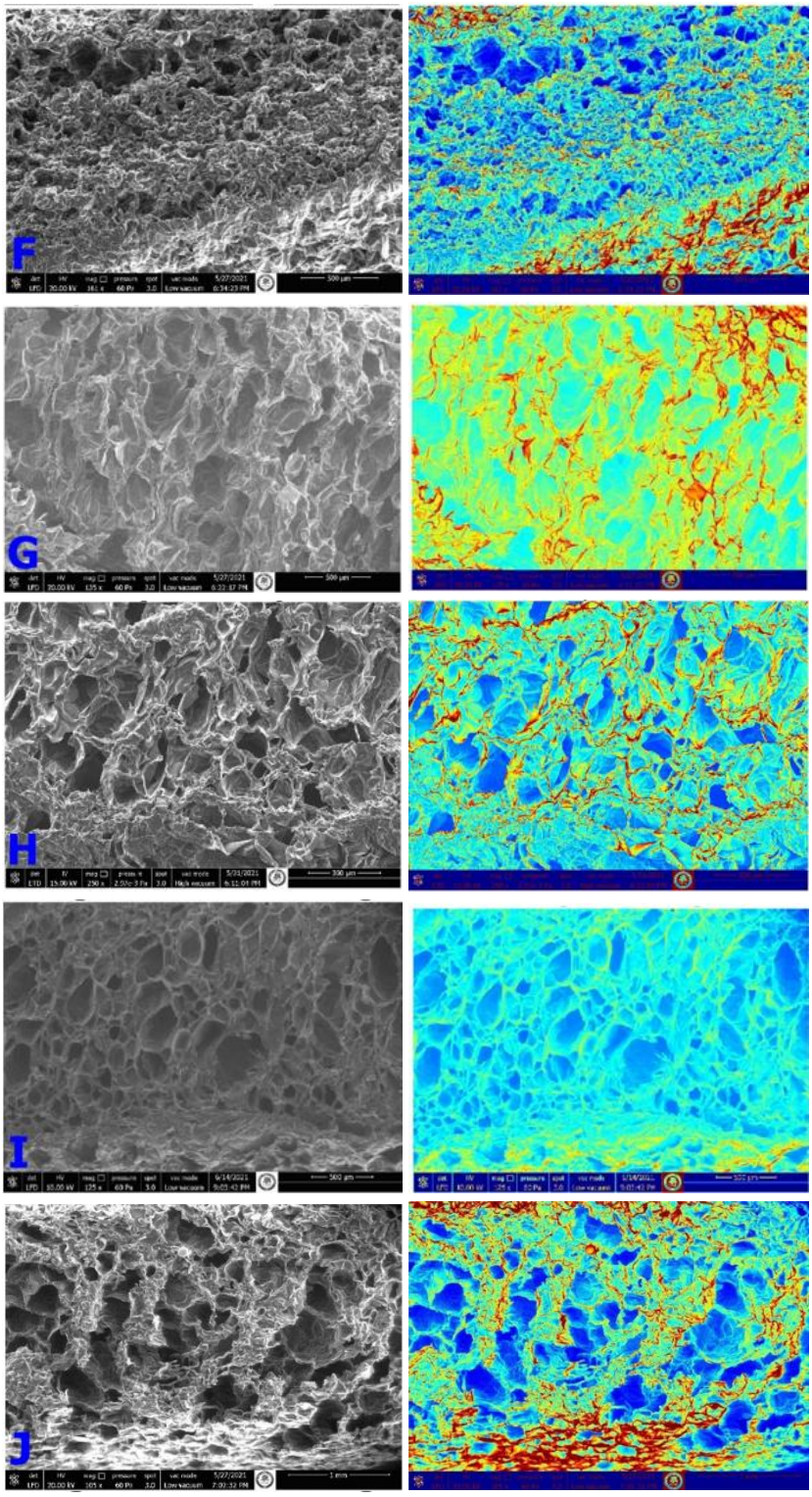
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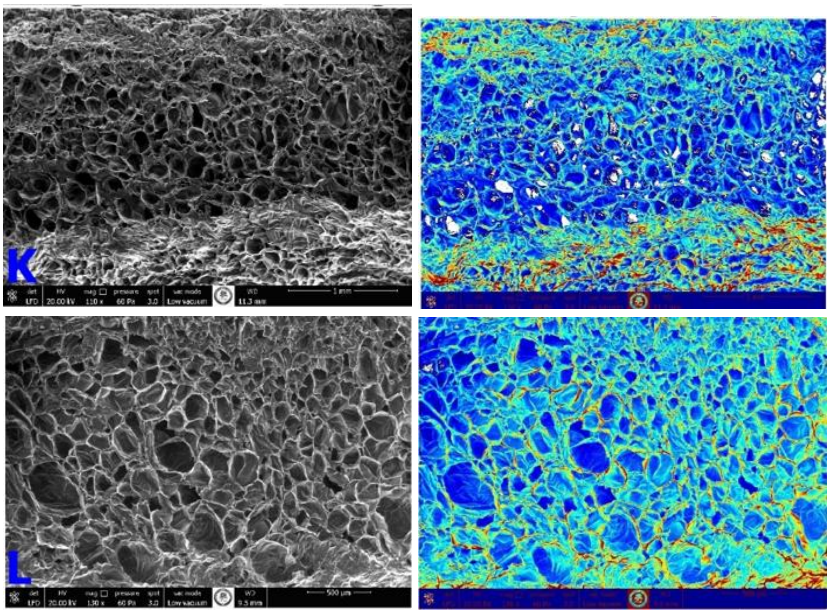

Original SEM image **Depth map**

Figure 2. SEM images (100 x magnification) of samples of AD (A), AD+EPD (B), VD (C), VD+EPD (D), 180MW (E), 180MW+EPD (F), 360MW (G), 360W+EPD (H), 600 MW (I), 600MW+EPD (J), FD (K), FD+EPD (L).

The tight, non-porous microstructure of dried apples strengthens their structure and makes them harder, thereby increasing the hardness value. An irregular microstructure was obtained in the apple samples, which swelled by expanding the volume with the puff drying process applied after air, vacuum and microwave. Numerous large and heterogeneous cavities were formed by the puff drying process. Lewicki and Pawlak (2003) and Yi *et al.* (2016b) stated that an increase in the porosity of the material was observed, similar to the one in our study, with puff drying applied after air and microwave drying. The pre-drying methods affected the number of pores and the pore size that would affect the capillary pathways and volume expansion during the puff drying process, which affected the hardness of the products. Significant differences in density and porosity of the material dried using different methods were confirmed by analyzes of tissue images generated by scanning electron microscopy.

Conclusions

The pre-drying methods and parameters described in the study significantly affected the quality of apples in terms of their physical and chemical properties. During air drying, irreversible structural damage occurred in apple tissue more than other drying processes and this caused the product to lose its rehydration ability. The results of porosity, rehydration and texture analysis prove this. As the moisture turns into steam with a sudden pressure drop with puff drying, paths and voids were

formed by the escaping steam, the porous microstructure increased and the material swelled, resulting in low shrinkage. A product with heterogeneous cavities and porosity obtained by puff drying is evident in the SEM images. There was an increase in the amount of TPC the combined use of the EPD process with AD and MW. This is because EPD contributed to the release of abundant phenolic acids bound insoluble in the cell wall and increased the availability and extractability of high-value biomolecules. FD samples were superior to the others in terms of physical and chemical properties. Considering that freeze drying takes a long time and has high processing costs, the FD+EPD combination can be a solution to these disadvantages and may be one of the best alternatives to freeze drying used alone. Apple snacks from Granny Smith apples can be a good and healthy alternative to other fruit or deep-fried potato snacks for people young or old.

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References

Alonzo-Macías, M., Montejano-Gaitán, G., Allaf, K. 2014. Impact of Drying Processes on Strawberry (*F ragaria* var. *C amarosa*) Texture: identification of crispy and crunchy features by instrumental measurement. *Journal of Texture Studies*, **45**(3), 246-259.

Alp, D., Bulantekin, Ö. 2021. The microbiological quality of various foods dried by applying different drying methods: A review. *European Food Research and Technology*, **247**, 1333-1343.

An, F., Qiu, D., Song, H., Wu, X., Tong, J., Guo, R. 2015. Effects of ınstant pressure drop puffing with super-heated vapor on the physical properties of Granny Smith apple chips. *Journal of Food Process Engineering*, **38**(2), 174-182.

Bauer, U.E., Briss, P.A., Goodman, R.A., Bowman, B.A. 2014. Prevention of chronic disease in the 21st century: elimination of the leading preventable causes of premature death and disability in the USA. *The Lancet*, **384**(9937), 45-52.

Bi, J.F., Wang, X., Chen, Q.Q., Liu, X., Wu, X.Y., Wang, Q., Yang, A.J. 2015. Evaluation indicators of explosion puffing Fuji apple chips quality from different Chinese origins. *LWT-Food Science and Technology*, **60**(2), 1129-1135.

Chen, Q., Li, Z., Bi, J., Zhou, L., Yi, J., Wu, X. 2017. Effect of hybrid drying methods on physicochemical, nutritional and antioxidant properties of dried black mulberry. *LWT*, **80**, 178-184.

Cherrat, S., Boulkebache-Makhlouf, L., Zeghichi, S., Walker, G. 2019. Effect of different drying temperatures on the composition and antioxidant activity of ginger powder. *The Annals of the University Dunarea de Jos of Galati. Fascicle VI-Food Technology*, **43**(2), 125-142.

Chong, C. H., Law, C. L., Figiel, A., Wojdyło, A., Oziembłowski, M. 2013. Colour, phenolic content and antioxidant capacity of some fruits dehydrated by a combination of different methods. *Food Chemistry*, **141**(4), 3889-3896.

Dorman, H.J.D., Peltoketo, A., Hiltunen, R., Tikkanen, M.J. 2003. Characterisation of the antioxidant properties of de-odourised aqueous extracts from selected Lamiaceae herbs. *Food Chemistry*, **83**(2), 255-262.

Du, L.J., Gao, Q.H., Ji, X.L., Ma, Y.J., Xu, F.Y., Wang, M. 2013. Comparison of flavonoids, phenolic acids, and antioxidant activity of explosion-puffed and sun-dried jujubes (*Ziziphus jujuba* Mill.). *Journal of Agricultural and Food Chemistry*, **61**(48), 11840-11847.

Ertekin Filiz, B., Seydim, A.C. 2018. Kinetic changes of antioxidant parameters, ascorbic acid loss, and hydroxymethyl furfural formation during apple chips production. *Journal of Food Biochemistry*, **42**(6), e12676.

Figiel, A. 2010. Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. *Journal of Food Engineering*, **98**(4), 461-470.

Garau, M.C., Simal, S., Rossello, C., Femenia, A. 2007. Effect of air-drying temperature on physico-chemical properties of dietary fibre and antioxidant capacity of orange (*Citrus aurantium* v. *Canoneta*) by-products. *Food Chemistry*, **104**(3), 1014-1024.

Gong, L., Huang, L., Zhang, Y. 2012. Effect of steam explosion treatment on barley bran phenolic compounds and antioxidant capacity. *Journal of Agricultural and Food Chemistry*, **60**(29), 7177-7184.

Gramza-Michałowska, A., Człapka-Matyasik, M. 2011. Evaluation of the antiradical potential of fruit and vegetable snacks. *Acta Scientiarum Polonorum Technologia Alimentaria*, **10**(1), 63-72.

Hawlader, M.N.A., Perera, C.O., Tian, M. 2006. Properties of modified atmosphere heat pump dried foods. *Journal of Food Engineering*, **74**(3), 392-401.

He, X., Liu, J., Cheng, L.L., Wang, B.J. 2013. Quality properties of crispy winter jujube dried by explosion puffing drying. *International Journal of Food Engineering*, **9**(1), 99-106.

Huang, L.L., Zhang, M. 2012. Trends in development of dried vegetable products as snacks. *Drying Technology*, **30**(5), 448-461.

Hurtado, M.L., Escobar, B., Estévez, A.M. 2001. Mezclas legumbre/cereal por fritura profunda de maiz amarillo y de tres cultivares de frejol para consumo" snack". *Archivos Latinoamericanos de Nutrición*, **51**(3), 303-308.

Jiang, H., Zhang, M., Mujumdar, A.S., Lim, R.X. 2014. Comparison of drying characteristic and uniformity of banana cubes dried by pulse-spouted microwave vacuum drying, freeze drying and microwave freeze drying. *Journal of the Science of Food and Agriculture*, **94**(9), 1827-1834.

Jribi, S., Gliguem, H., Szalóki-Dorkó, L., Naàr, Z., Kheriji, O., Debbabi, H. 2022. Impact of drying method on bioactive compounds, functional and thermal properties of durum wheat (*Triticum durum*) sprouts. *The Annals of the University Dunarea de Jos of Galati. Fascicle VI-Food Technology*, **46**(1), 79-92.

Krokida, M., Maroulis, Z. 2000. Quality changes during drying of food materials, In *Drying technology in agriculture and food sciences*. Mujumdar, A.S. Eds. Science Publishers, Inc. Enfield, USA – Plymouth, UK, p. 61-106.

Kuşçu, A., Bulantekin, Ö. 2021. Determination of phenolics, organic acids, minerals and volatile compounds of jujube (*Ziziphus jujuba* miller) jam produced by under vacuum evaporation compared with open pan method. *Journal of Food Measurement and Characterization*, **15**(2), 1127-1138.

Lewicki, P.P., Pawlak, G. 2003. Effect of drying on microstructure of plant tissue. *Drying Technology*, **21**(4), 657-683.

Li, R., Huang, L., Zhang, M., Mujumdar, A.S., Wang, Y.C. 2014. Freeze drying of apple slices with and without application of microwaves. *Drying Technology*, **32**(15), 1769-1776.

Marzec, A., Kowalska, H., Zadrożna, M. 2010. Analysis of instrumental and sensory texture attributes of microwave–convective dried apples. *Journal of Texture Studies*, **41**(4), 417-439.

Mouhoubi, K., Boulekbache-Makhlouf, L., Guendouze-Bouchefa, N., Freidja, M.L., Romero, A., Madani, K. 2019. Modelling of drying kinetics and comparison of two processes: Forced convection drying and microwave drying of celery leaves (*Apium graveolens* L.). *The Annals of the University Dunarea de Jos of Galati. Fascicle VI-Food Technology*, **43**(2), 48-69.

Rabbani, A., Salehi, S. 2017. Dynamic modeling of the formation damage and mud cake deposition using filtration theories coupled with SEM image processing. *Journal of Natural Gas Science and Engineering*, **42**, 157-168.

Re, R., Pellegrini, N., Proteggente, A., Pannala, A., Yang, M., Rice-Evans, C. 1999. Antioxidant activity applying an improved ABTS radical cation decolorization assay. *Free Radical Biology and Medicine*, **26**(9-10), 1231-1237.

Ressing, H., Ressing, M., Durance, T. 2007. Modeling the mechanisms of dough puffing during vacuum microwave drying using the finite element method. *Journal of Food Engineering*, **82**(4), 498-508.

Seremet, L., Botez, E., Nistor, O.V., Gogus, F., Andronoiu, D.G., Mocanu, G.D. 2015. Influence of drying conditions on the effective diffusivity and activation energy during convective air and vacuum drying of pumpkin. *The Annals of the University Dunarea de Jos of Galati. Fascicle VI-Food Technology*, **39**(2), 20-29.

Singleton, V.L., Rossi, J.A. 1965. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American journal of Enology and Viticulture*, **16**(3), 144-158.

Vega-Gálvez, A., Ah-Hen, K., Chacana, M., Vergara, J., Martínez-Monzó, J., García-Segovia, P., Di Scala, K. 2012. Effect of temperature and air velocity on drying kinetics, antioxidant capacity, total phenolic content, colour, texture and microstructure of apple (var. *Granny Smith*) slices. *Food Chemistry*, **132**(1), 51-59.

Yan, Z., Sousa-Gallagher, M.J., Oliveira, F.A. 2008. Shrinkage and porosity of banana, pineapple and mango slices during air-drying. *Journal of Food Engineering*, **84**(3), 430-440.

Yi, J., Zhou, L., Bi, J., Chen, Q., Liu, X., Wu, X. 2016a. Influence of pre-drying treatments on physicochemical and organoleptic properties of explosion puff dried jackfruit chips. *Journal of Food Science and Technology*, **53**(2), 1120-1129.

Yi, J., Zhou, L., Bi, J., Liu, X., Qinqin, C., Wu, X. 2016b. Influences of microwave pre-drying and explosion puffing drying induced cell wall polysaccharide modification on physicochemical properties, texture, microstructure and rehydration of pitaya fruit chips. *LWT*, **70**, 271-279.