PAPER

THE PHYSICAL, OPTICAL AND RECONSTITUTION PROPERTIES OF APPLES SUBJECTED TO ULTRASOUND BEFORE DRYING

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ABSTRACT

The purpose of the study was to present the influence of ultrasound pre-treatment on the physical, optical and reconstitution properties before convective drying of apple slices. The apples were subjected to ultrasonic treatment (35 kHz) for 10, 20 and 30 minutes and dried at a temperature of 70 °C and at an air velocity of 2 m/s. The ultrasonic waves reduced the drying time by 5-13% and affected the properties of dried apples. The longest pre-treatment resulted in colour changes and increased the porosity of dried apples. It also decreased the density, hardness and hygroscopic properties of dried apples.

Keywords: ultrasound, colour, texture, structure, reconstitution properties, drying

1. INTRODUCTION

Apples are one of the most important horticultural crops in the world and they constitute the greater part of the fruit production. Their consumption is increasing in the world, mostly in the form of fresh fruit, juice and dried apples (RODRÍGUEZ *et al.*, 2014). Research conducted by HERTOG *et al.* (1993) showed that the consumption of 110 g of apples a day reduces the risk of heart attack by 49% when compared with the daily consumption of only 18 g of apples.

Dehydration by hot-air is probably the most common and effective preservation method, used to imbue a food product with long shelf-life. Drying adds new values to food by limiting the spoilage and reducing the mass of the product (MULET *et al.*, 2003; CHONG *et al.*, 2008; GAMBOA-SANTOS *et al.*, 2013; KEK *et al.*, 2013, WITROWA-RAJCHERT *et al.*, 2014). However, the convective drying conditions such as temperature and air velocity may negatively affect the quality of a final product, causing changes in the microstructure, physical properties and nutritional value of food products (GAMBOA-SANTOS *et al.*, 2013; CHONG *et al.*, 2014). The texture modification, the degradation of vitamin, the loss of essential amino acids and changes in colour and flavour occur during hot-air drying (AZOUBEL *et al.*, 2010; OZUNA *et al.*, 2014). In order to determine the changes that appear during treatment and after drying food is tested on its reconstitution properties such as rehydration and hygroscopic properties (RZĄCA and WITROWA-RAJCHERT, 2007). Although convective drying is widely used, the method is related to high energy consumption, which results in the high cost of this technique (GAMBOA-SANTOS *et al.*, 2014).

Because of the growing need for the production of higher quality dried food products at lower processing cost, the traditional convective drying is combined with non-thermal techniques of pre-treatment such as high hydrostatic pressure, pulsed electric field and power ultrasound (WITROWA-RAJCHERT *et al.*, 2014).

Due to the low heating effect, the ultrasound treatment is a very promising method in the food industry (OZUNA *et al.*, 2014). Ultrasound waves indicate compression and expansion cycles in the material, which leads to micro-channels formation (FERNANDES *et al.*, 2008a; NOWACKA *et al.*, 2014; NOWACKA and WEDZIK, 2016). This phenomenon improves the rate of mass transfer and accelerates diffusion during dehydration (GAMBOA-SANTOS *et al.*, 2013; RODRÍGUEZ *et al.*, 2014). Moreover, the sonication generates cavitation, which can cause the removal of strongly attached moisture (MULET *et al.*, 2003; GAMBOA-SANTOS *et al.*, 2014). For example, the ultrasound pre-treatment reduced the drying time by 5-40% in the case of dried banana (AZOUBEL *et al.*, 2010), by 31-40% in the case of dried apples (NOWACKA *et al.*, 2012) and in the case of pineapple by over 30% (FERNANDES *et al.*, 2008c).

The ultrasound application reduces the drying time, and the process can be carried out at a lower temperature (NOWACKA *et al.*, 2012), which is relevant for food containing thermo-labile compounds. The ultrasonic effects during dehydration depend on the kind of the product and the ultrasound power. The visual appearance such as colour and texture are important sensory criteria for both the manufacturer and the customer (CYBULSKA *et al.*, 2011; PINGRET *et al.*, 2013). The drying process linked to the ultrasound pre-treatment can improve the quality of dried fruits and modify food properties (OZUNA *et al.*, 2014).

The purpose of the research was to investigate the effects of ultrasound pre-treatment at different treatment times on the quality factors of dried products, which affect the consumers' choice such as colour, mechanical, rehydration and hygroscopic properties. Moreover, the influence of sonication on the kinetics of apple drying was analysed.

2. MATERIALS AND METHODS

2.1. Sample preparation

Apples (var. Idared) from the Experimental Fields (Orchards) located in the district of Wilanow in Warsaw served as the experimental material. The production of apples is carried out by employees of the Faculty Horticulture, Biotechnology and Landscape Architecture (Warsaw University of Life Sciences WULS-SGGW). Apples were harvested and transported to the Faculty of Food Sciences in WULS-SGGW. While the experiments were performed, the apples were stored at 90% air humidity and a temperature of 4-8 °C for 1 month.

The material was cut into slices of a thickness of 0.005±0.001 m and a diameter of 0.030±0.001 m, excluding peel and core. In order to prevent enzymatic browning reactions, apple slices were immersed in the 0.1% citric acid solution, then blotted with filter paper and pre-treated with ultrasound.

2.2. Ultrasound pre-treatment

The material was submitted to ultrasound treatment for 10, 20 and 30 minutes in an ultrasonic bath with a frequency of 35 kHz (InterSonic, Olsztyn, Poland, IS-3 model, internal dimensions: 240×135×100 mm), while the ultrasound intensity equalled 4 W/cm^2. Pre-treatment was carried out in distilled water at room temperature (22±1 °C) and, in order to prevent flowing out of the samples, the slices were covered with a metal net. The ratio of raw material to water was 1:4, as recommended by NOWACKA *et al.* (2014). Afterwards, the samples were blotted with filter paper and placed in a dryer.

The material mass, the content of dry matter and a temperature of medium were measured before and after pre-treatment. The experiments were performed in duplicate.

2.3. Convective drying

The apple slices were dried in a laboratory convective dryer (Warsaw, Poland) at a temperature of 70 °C with parallel air-flow at an air velocity of 2 m/s. The scheme of the dryer is presented in Fig. 1. The main part of the dryer is the chamber within the shelf, where the dried product is placed. The shelf is connected with the balance. The product is dried in the hot air flow, which is heated by the heater system placed on the air inlet. The temperature of the air flow is measured by the thermocouples. The thermal sensors and the balance are connected to the computer, which records the data during the drying process. The heaters and thermal sensors are connected to the control panel, which is used to set up temperature and air velocity. Firstly, the dryer was preheated to a set-point temperature and then loaded with 0.25 kg (1,92 kg/m^2) of apple slices spread over the two nets in a single layer. Drying was carried out until constant weight was achieved. The experiments were conducted in duplicate.

The relative moisture ratio and the effective water diffusivities (D_{eff}) were calculated using the equations (1) and (2), respectively (SLEDZ *et al.*, 2013):

$$MR = \frac{u}{u_0} \qquad (1)$$

where: u – water content during drying (kg moisture/kg d.m.), u_0 – initial water content (kg moisture/kg d.m.)

$$MR = \frac{8}{\pi^2} \cdot \exp\left(\frac{-\pi^2 \cdot D_{eff} \cdot \tau}{4 \cdot L^2} \right) \qquad (2)$$

where: D_{eff} – diffusion coefficient (m^2/s), τ - drying time (s), L – half-thickness of the sample (m).

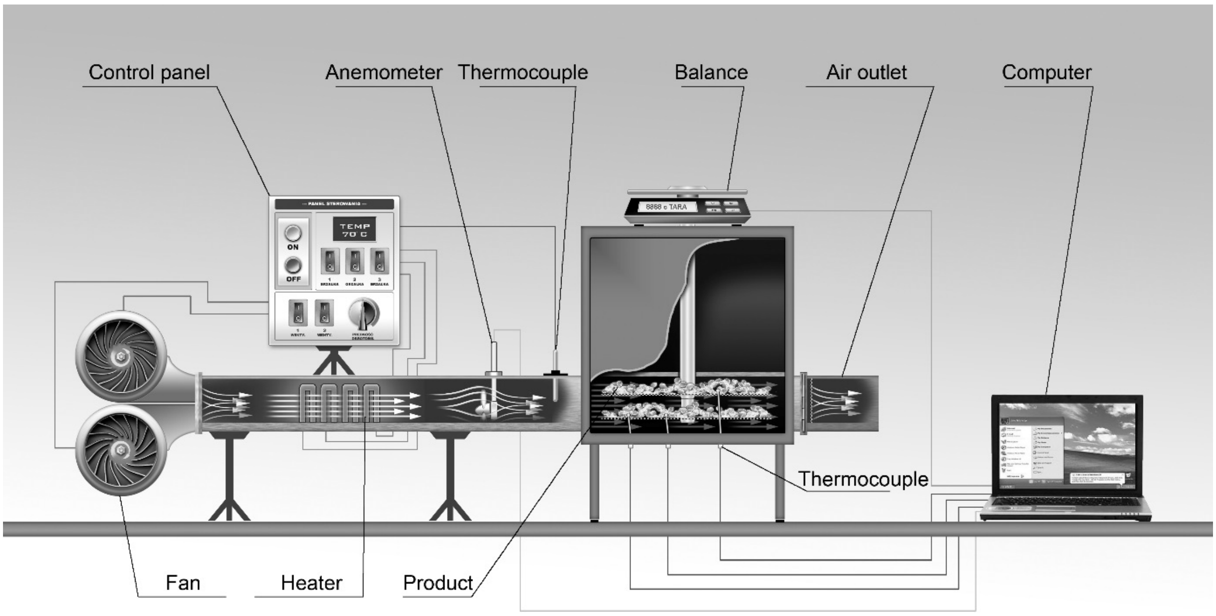

Figure 1. The scheme of a laboratory convective dryer (figure made by www.ct.waw.pl)

2.4. Physical properties

The dry matter in the raw, pre-treated, dried and rehydrated material was measured according to the Polish Standard PN-90/A-75101/03 by drying at a temperature of 105 °C to the constant weight.

The water activity of the untreated, ultrasound treated and dried samples were examined using hygrometer Aqua Lab CX-2 (Dekagon Device Inc., USA) with the accuracy of ±0.001. The equipment was switched on around 30 minutes before measuring and checked with the water. The raw apple slices were placed in a plastic vessel, covering the bottom of the vessel. After ultrasound pre-treatment the samples were blotted with filter paper and placed in the vessel. The apple slices after drying were stored in a sealed bag for three days to compensate the humidity of the sample after drying. The measurements were made thrice for each sample at a temperature of 25 °C.

Based on the measurement of the mass and volume of the dried sample, density and porosity were calculated (ANDRÉS *et al.*, 2004).

2.5. Colour measurement

A hand-held Minolta CR-300 chromameter (Minolta, Japan) was used to measure the colour of the dried apple slices (diffuse illumination, 0° viewing geometry). Colour was recorded with the CIE L*a*b* system. In this colour space, the *L** parameter defines lightness and ranges from 0 to 100, the a^* parameter denotes chromaticity on a green (-) to red (+) axis and the b* parameter represents chromaticity on a blue (-) to yellow (+) axis. The L^*, a^* and b^* coefficient were used to calculate the chroma (C^*) which indicates the purity and saturation of colour and the value of the colour difference (ΔE) (GONÇALVES *et al.*, 2007; FIJALKOWSKA *et al.*, 2016) according to equations (3) and (4), respectively.

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad (3)$$

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (4)$$

where: ΔL^*, Δa^*, Δb^* - the change of lightness, a^* and b^* parameter value between pre-treated and untreated dried apple.
The experiments were performed in 15 repetitions.

2.6. Structure

The internal structure of dried tissue was examined using a scanning electron microscope HITACHI TM 3000 Tabletop Microscope (Tokio, Japan). The internal part of the slices was cut in half with a scalpel and put into the vacuum chamber of the microscope. The images were examined under the magnification of 100.

2.7. Mechanical properties

Mechanical properties were analysed using the cutting test in a texture analyser (TA-TX2i model, Stable Micro Systems, Godalming, England). In order to conduct this test, a knife of 0.062 m in length, 0.024 m in width and 0,0005 m in thickness was slid inside a metal table with a slot. The load cell was calibrated to 250 N and the cutting was applied at a velocity of 0.001 m/s. The cutting began when the sample resisted and carried out to complete intersection. Both the maximum cutting force and the cutting energy were recorded using program "Texture" and then calculated. The mean value for ten replicates of apple slice was averaged for each ultrasound treatment.

2.8. Rehydration properties

In order to analyse rehydration kinetics, two slices of dried apples were weighed with an accuracy of $\pm 0.1 \cdot 10^{-6}$ kg and placed in a glass with 10^{-4} m^3 of distilled water. The process was carried out at a temperature of 20 °C and the samples were immersed for 30, 60 and 180 minutes. After a given rehydration time, the slices were drained on a sieve and then on a blotting paper. The experiments were repeated twice for each kind of the dried material.
The rehydration properties were calculated according to the following equation:

$$X = \frac{X_\tau}{X_0} \qquad (5)$$

where: X_τ – moisture of a rehydrated sample at time τ (kg water/ kg d.m.), X_0 – initial moisture of a fresh sample (kg water/kg d.m.).

The soluble solid loss during rehydration was calculated using the following equation:

$$SSL = \frac{m_\tau \cdot dm_\tau}{m_0 \cdot dm_0} \qquad (6)$$

where: m_τ – sample weight after rehydration at time τ (kg), m_0 – sample weight before rehydration (kg), dm_τ – dry matter content of a sample after rehydration at time τ (%), dm_0 – dry matter content of a sample before rehydration (%).

2.9. Hygroscopic properties

In order to determine the hygroscopic properties of the apple tissue after drying the samples were weighed with an accuracy of $\pm 0.1 \cdot 10^{-6}$ kg and placed in a desiccator over NaCl solution of a water activity $a_w = 0.75$. The kinetics of adsorption was determined for 72 hours at 25 °C. After a specific time of 0.5, 1, 3, 5, 8, 10, 24, 48 and 72 h the samples were weighed again. The experiments were performed in triplicate for each kind of the dried material

2.10. Statistical analysis

The significance of the ultrasound treatment and the drying process were examined by the analysis of variance (ANOVA) using Statgraphics Plus 5.0 programme. The homogeneity of variance was verified using Levene's test. Duncan's multiple range tests with a probability of 0.05 were used to determine homogeneous groups.

3. RESULTS

3.1. Ultrasound treatment

During sonication, the distilled water temperature increased by 4.3, 7.3 and 10.8 °C for 10, 20 and 30 minutes of treatment, respectively (Table 1). Due to a series of rapid compressions and expansions of plant tissue generated by ultrasound waves, water included in the raw material could flow out to the surroundings. After 10 and 20 minutes of pre-treatment, the apples lost 0.89±0.02 and 0.59±0.03% of weight, respectively (Table 1), whereas 30 minutes of ultrasound application increased the weight of the samples (1.47±0.10%). The phenomenon that occurred during a longer time of immersion, can be caused by water penetration into the tissue as a result of osmotic concentration differences. Statistical analysis showed significant differences between mass changes for all pre-treatment time. The similar relation was observed in NOWACKA *et al.* (2012) research where the smallest weight loss of apple tissue (0.8±0.4%) was obtained for samples pre-treated for 30 minutes with an ultrasound frequency of 35 kHz. For 10 and 20 minutes of sonication, the weight loss was equal to 2.3±0.1 and 3.0±0.2%, respectively. The opposite tendency was observed by FERNANDES *et al.* (2008b), who subjected papaya tissue to ultrasound waves with a frequency of 25 kHz. The enhancement of water loss was obtained with increasing time of treatment in the range of 10 to 30 minutes.

Raw apple tissue contains 15.1±0.8% of dry matter. The samples submitted to ultrasonic treatment lost from 26.5 to 28.4% of soluble solids because of their flowing out to a liquid medium. The decrease of this parameter was significant in the case of each time of pre-treatment in comparison with the untreated apple slices (Table 1). The length of ultrasound application did not have statistically meaningful influence on the dry matter content of the material.

Table 1. Changes of mass, dry matter content and medium temperature after ultrasound pre-treatment.

Type of treatment	Weight gain (+)/loss(-) [%]	Dry matter [%]	Medium temperature increase [°C]
Untreated	-	15.1±0.8^{a}	-
US 10 min	-0.89±0.02^{a}	10.8±1.4^{b}	4.3±0.8^{a}
US 20 min	-0.59±0.03^{b}	11.0±0.5^{b}	7.3±0.3^{b}
US 30 min	1.47±0.10^{c}	11.1±0.5^{b}	10.8±0.8^{c}

a, b, c: the same letters indicate homogeneous groups.

3.2. Drying characteristics

The application of ultrasound resulted in a reduction of the convective drying time by 5-13% in relation to the untreated material. The drying time decreased significantly with the increasing time of ultrasound pre-treatment (Table 2). Similarly, the shorter time of drying process after ultrasound treatment was noticed in the literature where a time reduction of 4.5% was observed for banana (AZOUBEL *et al.*, 2010), 3-22% for papaya (FERNANDES *et al.*, 2008b), 7-39% for pineapple (FERNANDES *et al.*, 2008c), 27% for apple cubes, 18-23% for red bell pepper (SCHÖSSLER *et al.*, 2012) and 50-75% for eggplant (PUIG *et al.*, 2012). These examples confirm the assumptions of FEUNTE-BLANCO *et al.* (2006) who noticed in the influence of ultrasound on the fruit tissue facilitating water diffusion during air-drying. This phenomenon can be caused by micro-channels formation during sonication, which can enable easier water diffusion from interior material to the surface (FERNANDES *et al.*, 2008a).

Table 2. Drying time of the apple slices to obtain 0.09 kg moisture/kg d.m., the value of the effective moisture diffusion coefficient (D_{eff}), dry matter content and water activity of the dried apples.

Type of treatment	Drying time [min]	Deff·10^{9} [m^{2}/s]	Dry matter [%]	Density [kg/m^{3}]	Porosity [%]	Water activity [%]
Untreated	133±3^{c}	1.037	92.3±0.9^{a}	524± 100^{bc}	65.6±5.7 ^{a}	0.264±0.012^{b}
US 10 min	126±1^{b}	1.058	92.1±0.2^{a}	464±30^{ab}	69.5±1.8^{ab}	0.286±0.010^{c}
US 20 min	123±1^{b}	1.064	93.2±0.4^{a}	545±60^{bc}	64.2±3.5 ^{a}	0.246±0.011^{a}
US 30 min	116±2^{a}	1.102	93.1±1.0^{a}	388±40^{a}	74.5±2.2 ^{b}	0.290±0.009^{c}

a, b, c: the same letters indicate homogeneous groups.

Furthermore, the values of the effective water diffusivity (D_{eff}) for the ultrasound treated samples were growing with the increase of treatment time, and the highest value of this parameter was noted for the apples subjected to 30 minutes of sonication. In this case the effective moisture diffusion coefficient increased by 6% in comparison with the untreated material. The values of this coefficient were related to drying time (NOWACKA *et al.*, 2012), which was proved by the shortest time of drying in the case of the apples treated by ultrasound for 30 minutes (Table 2).

The apple slices were dried to obtain 0.09 kg moisture/kg d.m., where the dry matter content of untreated tissue equalled 92.3±0.9% and there was no significant influence of ultrasound treatment on this parameter value (Table 2). However, statistical analysis confirmed that sonication caused significant changes in the density and porosity of the dried tissue (Table 2). The density of the material is closely related to its porosity. A low density product must possess high porosity. The tissue exposed to ultrasound waves for 30 minutes after drying exhibited the lowest density of 388±40 kg/m^3 and the highest porosity (74.5±2.2%). The difference between the dried treated samples and the untreated ones was statistically significant. Similar results were reported by NOWACKA *et al.* (2012) for dried cubes of apples. Moreover, the statistical changes were found in the water activity of the ultrasound treated samples. The samples that were subjected to ultrasound for 10 and 30 minutes obtained higher values of water activity in comparison to the untreated material, whereas the tissue treated for 20 minutes was characterized by a lower value of this parameter. However, all dried samples revealed low water activity, which proves the microbiological safety of food.

3.3. Optical properties

Colour is one of the most important factors of raw and dried fruits' quality because the external appearance influences the consumer acceptability (SINGH and REDDY, 2006; NUNCIO-JÁUREGUI *et al.*, 2014).

The colour parameters L^*, a^*, b^*, C^* and ΔE of the untreated and pre-treated dried apple slices are presented in Table 3. In the case on lightness, the L^* value of dried apples significantly increased after 30 minutes of sonication in comparison with the untreated sample. However, a shorter time of ultrasound treatment did not have any significant impact on this colour parameter.

The higher value of a^* parameter denotes the increase of red colour saturation, which can be associated with the enzymatic browning reaction occurring during pre-treatment and the drying process (VADIVAMBAL and JAYAS, 2007). This trend can be observed for the samples treated with ultrasound waves for 20 minutes, where parameter a^* equalled 1.45±0.75, but statistical analysis did not show any significant differences in relation to the untreated dried apple tissue (Table 3). However, the lowest values of this parameter were obtained by the samples subjected to ultrasound for 10 and 30 minutes. As compared to the untreated material the statistically significant effect occurred only after 30 minutes of pre-treatment, where a^* value was equal to -0.53±0.83.

Table 3. L*, a*, b*, chroma C* values of the dried apple slices and total colour differences (ΔE) in comparison to the dried untreated apples.

Type of treatment	L*	a*	b*	C*	ΔE
Untreated	82.07±1.87^{a}	0.91±0,98^{bc}	21.42±3.23^{a}	21.45±2.93^{a}	-
US 10 min	84.27±1.33^{ab}	0.02±0.75^{ab}	19.81±0.92^{a}	19.82±0.81^{a}	2.93±1.42
US 20 min	82.01±1.22^{a}	1.45±0.75^{c}	22.01±1.27^{a}	22.07±1.15^{a}	1.36±1.24
US 30 min	84.57±0.73^{b}	-0.53±0.83^{a}	20.77±2.21^{a}	20.79±1.82^{a}	3.57±0.33

a, b, c: the same letters indicate homogeneous groups.

In the case of b^* parameter, the lowest value was observed after 10 minutes of ultrasound application (19.81±0.92) (Table 3), whereas the highest level of this parameter was noted for the samples subjected to ultrasound for 20 minutes (22.01±1.27). The statistical analysis did not show any significant differences between the untreated and ultrasound pre-treated

samples. The same tendency was noticed for chromaticity C^* (Table 4) which determines the purity or saturation of the colour (GONÇALVES *et al.*, 2007).
The L^*,a^* *and* b^* colour parameters were used to calculate the total colour differences (ΔE). CHOI *et al.* (2002) revealed that ΔE value higher than 2 confirms the visible difference. After 10 and 30 minutes of pre-treatment, the obtained results showed higher ΔE value than 2, which means that the colour was changed noticeably in these cases (Table 3). However, the invisible colour changes were observed for the apple tissue treated with ultrasound for 20 minutes, hence ΔE value was lower than 2.

3.4. Structure of the ultrasound treated apple tissue

Fig. 2 shows a photo of the dried apple tissue with and without ultrasound treatment. Dried untreated apple tissue is characterized by high density and small pores with elongated cell shape. In the case of the dried tissue subjected to ultrasound treatment, the changes in the structure were observed (Fig. 1). The results confirm that the ultrasound treated material exhibited a lower density and more porous form (Table 2). However, it was impossible to clearly determine the effect of ultrasound treatment time on microstructure changes, as it was done by other researchers (FERNANDES *et al.*, 2008a; FENANDES and RODRIGUES, 2009; NOWACKA *et al.*, 2012; NOWACKA and WEDZIK, 2016). Moreover, it was not noticed that ultrasound treatment before drying caused the formation of a microscopic channel in dried tissue as reported by NOWACKA and WEDZIK (2016) in carrot or FERNANDES *et al.* (2008a) in pineapple.

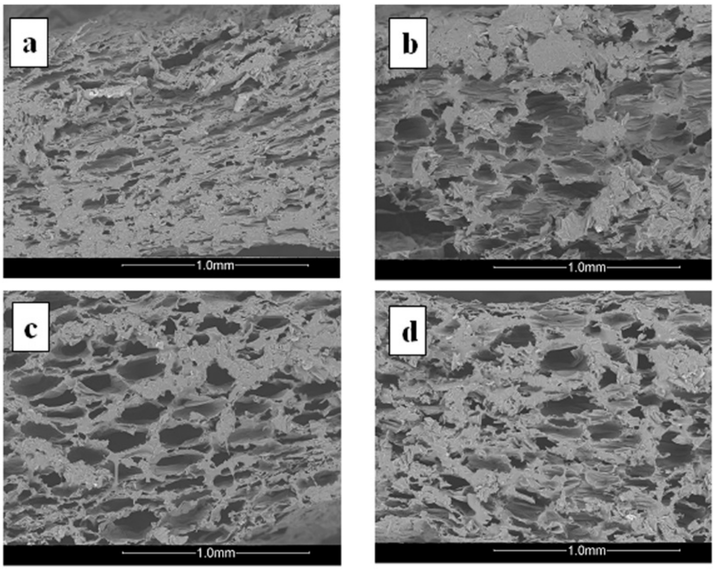

Figure 2. Photos of dried apples taken by using scanning electronic microscopy at a magnification of 100: untreated samples (a), 10 min (b), 20 min (c), 30 min (d) ultrasound treated samples.

3.5. Mechanical properties

Texture evaluation of the product is an important feature to determine the quality of dried fruits (CHONG *et al.*, 2008; KEK *et al.*, 2013). Fig. 3 shows texture changes of the ultrasound treated dried apple slices, where results of the maximum cutting force and the cutting energy of dried samples were presented. The ultrasound treatment caused alteration of apple tissue, which resulted in changes of textural properties of the dried material. Moreover, it was observed that the maximum cutting force and cutting energy decreased with increasing ultrasound treatment time. Taking into account the maximum cutting force and cutting energy, the apple slices subjected to ultrasound for 10 minutes were the most similar to the untreated dried material. The dried material was characterized by the highest hardness; however, the differences were not statistically significant.

The lowest hardness of dried apple slices was observed for the material treated with ultrasound for 30 minutes. These samples had significantly lower values of maximum cutting force (196.0±37.5 N) and cutting energy (233.4±47.2 mJ) in comparison with the untreated dried tissue, which was probably related to lower density and porosity.

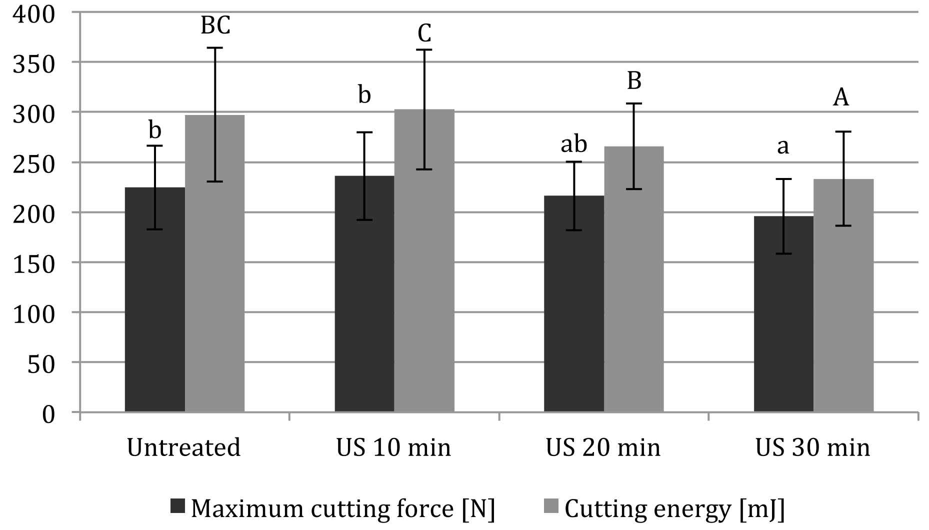

Figure 3. The maximum cutting force and the cutting energy of dried apple; a, b: the same letters indicate homogeneous groups for maximum cutting force; A, B, C: the same letters indicate homogeneous groups for cutting energy.

3.6. Rehydration properties

A rehydration is a significant quality criterion of dried food. High temperature during drying causes irreversible structure changes of plant tissue. In order to determine these changes, the reconstitution characteristics are investigated (CIURZYNSKA *et al.*, 2011). The gain of weight and volume occur during the rehydration process due to water uptake, while the water soluble compounds are removed from the interior of tissue to the surrounding. The rate of the rehydration process is determined by the level of tissue destruction (NOWACKA *et al.*, 2012).

The changes of rehydration properties are presented in Table 4. The obtained results showed that the prolongation of rehydration time resulted in the increase of moisture uptake. The same tendency was observed during rehydration of apple cylinders var. Fuji (Deng and Zhao, 2008) and apple cubes var. Idared (NOWACKA *et al.*, 2012). However, the use of different ultrasound frequencies (FIJALKOWSKA *et al.*, 2016) and different treatment times (NOWACKA *et al.*, 2012) did not significantly influence rehydration properties. The amount of water content in the untreated apple slices after 3 hours of rehydration was equal to 12.0±2.2 kg moisture/kg d.m., while the ultrasound pre-treated samples were characterized by higher levels of moisture content, but the statistical analysis showed that these differences were not significant. The results calculated to the initial moisture of the fresh sample confirmed that after 30 minutes of rehydration the dried apples did not obtain the initial water content. After 60 minutes of rehydration the water content of the samples subjected to ultrasound for 10 and 20 minutes were similar to the fresh apple, while the untreated samples and the samples treated with ultrasound for 30 minutes and after 180 minutes of rehydration were characterized by a higher moisture content than the fresh raw material (Table 4).

The rehydration process is also related to the loss of water soluble components of dry matter - the loss is growing with the increasing time of rehydration. After 30 minutes of dried apple rehydration, the amount of their dry matter content was higher than for the fresh sample. The rehydration for 60 minutes of the samples treated with ultrasound for 10 and 20 minutes resulted in the amount of dry matter content similar to the intact sample. However, the untreated apples and the ones subjected to ultrasound for 30 minutes and rehydrated for 60 minutes and all the samples rehydrated for longer time (180 min) were characterized by lower dry matter content in comparison to the raw material, which was associated with high loss of water soluble solids from the dried tissue (Table 4).

Table 4. Water content and loss of water soluble solids after different time of rehydration expressed in kg moisture/kg d.m. and calculated percentage of the initial moisture recovery compared to the fresh fruit.

Type of treatment	Rehydration time [min]					
	30	**60**	**180**	**30**	**60**	**180**
	Water content [kg moisture/kg d.m.]			**Loss of water soluble solids [kg d.m./kg d.m.]**		
Untreated	4.0 ± 0.6^{a}	6.3 ± 1.0^{a}	12.0 ± 2.4^{a}	0.71 ± 0.03^{ab}	0.58 ± 0.06^{a}	0.39 ± 0.06^{a}
US 10 min	4.5 ± 0.4^{a}	5.5 ± 0.6^{a}	13.3 ± 1.7^{a}	0.67 ± 0.02^{b}	0.65 ± 0.06^{a}	0.37 ± 0.02^{a}
US 20 min	4.2 ± 0.4^{a}	5.5 ± 0.6^{a}	15.3 ± 1.7^{a}	0.73 ± 0.03^{a}	0.64 ± 0.03^{a}	0.32 ± 0.03^{a}
US 30 min	4.7 ± 0.7^{a}	6.5 ± 0.6^{a}	13.7 ± 2.8^{a}	0.67 ± 0.05^{ab}	0.56 ± 0.04^{a}	0.36 ± 0.05^{a}
	Water content [%]			**Loss of water soluble solids [%]**		
Untreated	-29 ± 11^{a}	12 ± 18^{a}	113 ± 43^{a}	34 ± 16^{ab}	-8 ± 13^{a}	-48 ± 9^{a}
US 10 min	-20 ± 8^{a}	-3 ± 11^{a}	136 ± 30^{a}	22 ± 10^{b}	3 ± 9^{a}	-53 ± 6^{a}
US 20 min	-26 ± 8^{a}	-2 ± 11^{a}	172 ± 30^{a}	29 ± 11^{a}	2 ± 10^{a}	-59 ± 5^{a}
US 30 min	-17 ± 12^{a}	16 ± 11^{a}	144 ± 49^{a}	19 ± 16^{ab}	-11 ± 8^{a}	-54 ± 8^{a}

a,b: the same letters indicate homogeneous groups in column.

3.7. Hygroscopic properties

Hygroscopic properties of plant materials can specify the changes induced by the drying process and other treatment. The course of adsorption kinetics is mainly influenced by the method and drying parameters, as well as by the structure, shrinkage and porosity of a dried product. The smaller shrinkage and the higher porosity result in faster absorption of water vapour (RZĄCA and WITROWA-RAJCHERT, 2007; ACEVEDO *et al.*, 2008). According to the creation of microchannels by ultrasonic waves (FERNANDES *et al.*, 2008a; NOWACKA *et al.*, 2014; NOWACKA and WEDZIK, 2016) the hygroscopic properties may provide information about changes in the structure of the tissue.

After 72 hours of water vapour absorption from the NaCl solution with a water activity of 0.75, the dried apple rings absorbed from 0.36 to 0.38 g H_2O/g d.m. (Fig. 4). Analyzing the water sorption curves, it was observed that the process was most intense in the initial phase for 24 hours. At a later stage, there was a decrease in the rate of moisture adsorption. The untreated samples displayed the greatest ability to absorb water. In most cases, the amount of absorbed water did not depend on the type of pre-treatment. However, the apple tissue treated with ultrasound waves for 30 minutes before drying demonstrated lower hygroscopic properties. This dried tissue was characterized by a higher porosity and a lower density (Table 2), which may affect the water binding capacity reduction. At the same time, the lower ability of water absorption could be related to the fact that longer ultrasound treatment resulted in greater damage to the structure of the raw material (Fig. 1), which has been proved by other researchers (FERNANDES *et al.*, 2008a; NOWACKA *et al.*, 2014; NOWACKA and WEDZIK, 2016).

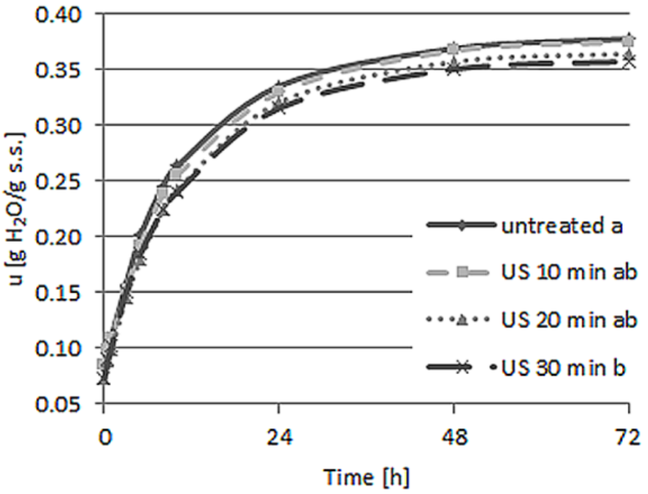

Figure 4. The hygroscopic properties of the ultrasound treated dried apples a, b: the same letters indicate homogeneous groups after 72 h of water vapour absorption.

4. CONCLUSIONS

Ultrasound waves used as a method of pre-treatment enhanced the drying of apple slices. The application of ultrasound induced a reduction of the convective drying time by 5-13% in relation to the untreated material. Moreover, the effective water diffusivity was the highest for the apples treated with ultrasound for 30 minutes and it increased by 6% in comparison with the untreated material.

Furthermore, ultrasound treatment impacted on physical, optical and reconstitution properties of the dried apple tissue; however, the effect of the overall quality of the product was not obviously stated. The ultrasound treatment resulted in the decrease of dry matter content, which is not a very favourable effect due to the loss of the tissue water-soluble components. Moreover, after 30 minutes of treatment the significant decrease of density and increase of porosity was observed, which was confirmed by micro-structure assessment. The changes in the structure had an impact on the acceleration of the drying process.

The conducted research indicated that all dried samples demonstrated low water activity, which provides microbiological safety of food. Additionally, the changes of total colour differences (ΔE) were unnoticeable for the samples sonicated for 20 minutes, or slightly changed for the tissues ultrasound treated for 10 and 30 minutes.

On the other hand, longer time of ultrasound pre-treatment resulted in a significant decrease of dried slices hardness, which could be considered as a negative effect of ultrasonic treatment because a product that should be crispy like apple chips is softened. Furthermore, it was observed that with increasing ultrasound treatment time the maximum cutting force and the cutting energy of the dried samples decreased. Furthermore, the apples subjected to ultrasonic treatment for 30 minutes exhibited lower hygroscopic properties. However, sonication did not influence rehydration properties in comparison to the untreated sample.

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