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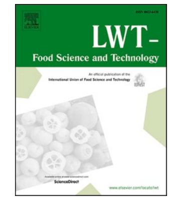

Pulsed electric field pre-treatment improves microstructure and crunchiness of freeze-dried plant materials: Case of strawberry

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ABSTRACT

In this study the effect of PEF pre-treatment on the microstructure of freeze-dried strawberry dices was investigated. The PEF treatment has been performed at an electric field intensity of 1.07 kV/cm and a specific energy input of 1 kJ/kg. The samples were freeze-dried at a temperature of 45 °C and a pressure of 1 mbar. The microstructure of dried material was evaluated by different physical and optical methods, such as SEM, μ-CT and thermogravimetry. Moreover, mechanical and acoustic properties as well as the colour of processed material have been analyzed. PEF pre-treated strawberry dices showed a more uniform shape, a better retention of volume and a visual better quality compared to untreated ones. Moreover, PEF pre-treatment led to a more homogeneous distribution and a greater thickness of pores. In accordance, analysis of textural properties evidenced that PEF treated freeze-dried strawberry dices were crispier than untreated ones. Measurement of L**a***b**-values showed that PEF treated material was characterized by a more preserved colour after freeze-drying than untreated ones.

1. Introduction

Food companies can no longer rely on producing a small number of strong brands to remain successful. Consumers increasingly demand a large variety of high-quality and healthy products. For this reason, food industry must constantly innovate and launch new products to maintain profits and market share. A food's microstructure has an influence over the key attributes of a product as evaluated by consumers. By food microstructure, we understand the spatial arrangement of identifiable elements in a food and their interactions at levels below 100 μm (Aguilera & Stanley, 1999). Typical microstructural elements in foods are cell walls, starch granules, proteins, water and oil droplets, fat crystals, gas bubbles, etc. The concept of a "food matrix" points to the fact that nutrients are contained into a larger continuous medium that may be of cellular origin (in fruits and vegetables) or a microstructure produced by processing, where they may interact at different length scales with the components and structures of the medium (Aguilera, 2019).

In general, most of the plant (i.e. fruits, vegetables, grains and tubers) and animal (i.e. meat or fish) origin food are consumed around the globe with minor processing, therefore, their microstructure has been largely imparted by nature (Parada & Aguilera, 2007). Processed foods (i.e., confectionery products, dried pasta, processed meats, etc.) are multicomponent structured matrices where the individual components have been reassembled as colloidal dispersions, emulsions, amorphous or crystalline phases, or gel networks by heating and/or cooling and the application of shear. The microstructure of a material and how it evolves through a process will define the characteristics of the transfer phenomena in processing equipment. Structure-property relationships can strongly affect these foods' physiochemical, functional, technological and even nutritional properties (Aguilera, 2005; Parada & Aguilera, 2007). The design of a food product must account for all these relationships whilst maintaining the high standards the consumer expects. Therefore, from an engineering perspective, the microstructure of any food is paramount.

The food microstructure most commonly analyzed by microscopy techniques, i.e. scanning electron microscope (SEM), transmission electron microscopy (TEM), etc. (Aguilera, 2006). However, internal

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microstructure of dried food products can be analyzed by means of more sophisticated device that provide more information about structure, such as X-ray microtomography technique (μ-CT). μ-CT has been used to nondestructively observe the structure of various porous dried materials (Calín-Sánchez et al., 2015; Voda et al., 2012).

Freeze drying is widely used in food technology as one of the food transformation methods that allows obtaining high quality dried products (Marin, 2003). Due to ice formation the primary (initial) structure and shape of the product can be maintained (Ratti, 2008). Despite many advantages of this technique, the high operating and maintenance costs and possible deterioration of product are the main drawbacks of this process (Michailidis & Krokida, 2015). Therefore, the optimization of freeze-drying process is in high important.

Numbers of research studies have demonstrated, that the application of pulsed electric fields (PEF) as a pre-treatment can improve freeze-drying processes significantly (Barba et al., 2015; Lammerskitten, Mykhailyk, et al., 2019a; Lammerskitten, Wiktor, et al., 2019b; Liu, Grimi, Lebovka, & Vorobiev, 2018; Parniakov, Bals, Lebovka, & Vorobiev, 2016; Yu, Jin, & Xiao, 2017). The PEF treatment is based on the application of short electrical pulses of high voltage to a liquid or solid product, that is placed between two electrodes. The polarisation of the cell membrane leads to permeabilization and disruption of cellular tissue (Toepfl, Siemer, & Knorr, 2014). Thereby, mass and heat transfer processes can be improved without undesirable changes in food quality (Toepfl et al., 2014; Vorobiev & Lebovka, 2011). Lammerskitten, Wiktor, et al., (2019) has demonstrated that PEF assisted freeze-drying of apples resulted in good texture and structure retention.

However, to the best of our knowledge it is a first study that are describing the impact of PEF pretreatment on the microstructure by means of different methods. Therefore, the aim of this study was to investigate the effect of PEF pre-treatment on the microstructure of strawberry dices. Moreover, different physical and optical methods, such as μ-CT, SEM, thermogravimetry are used in order to better understand the changes in structure of PEF pre-treated freeze-dried materials.

2. Materials and methods

2.1. Materials

Commercial strawberries were purchased from a wholesale store in Osnabrueck, Germany. The strawberries were stored at 4 °C until required and washed before each experiment. The dry matter content of the raw strawberries was measured according to AOAC 920.15. The initial average water content was equal to 90 ± 0.8%.

2.2. PEF treatment

PEFPilot batch system (Elea Vertriebs-und Vermarktungsgesellschaft mbH, Germany) was used to treat samples before drying. The system provided high-voltage exponential decay, monopolar pulses with an interval of 0.5 s (2 Hz) and pulse duration of 40 μs? The pulses were applied to the product in a batch treatment chamber consisting of two parallel stainless-steel electrodes (10 × 10 cm), with a distance of 28 cm. In each experiment, 2000 g of strawberries ($\sigma = 178.5$ μS/cm and $T = 21 \pm 1$ °C) were placed in the treatment chamber and 5000 mL of tap water ($\sigma = 222$ μS/cm and $T = 22 \pm 1$ °C) was added as a conductive medium. The specific energy intake (kJ/kg) applied to the product was adjusted by adapting the number of pulses taking into consideration the total mass of the cell and was equal to 1 kJ/kg. In this study, the PEF treatment with electric field strengths of 1 kV/cm was applied. The specific energy intake W_{spec}(kJ/kg) was calculated according to the following equation:

$$W_{spec} = \frac{U^2 C\, n}{2m} \quad (1)$$

where n is the number of pulses [−]; m is the mass of the treated samples [kg]; U is the voltage [kV] and C is the capacitance [μF]. After treatment procedure samples were placed in a sieve for reduction of excess water.

2.3. Freezing and freeze-drying

After PEF treatment strawberries were manually cut in dices of a thickness of 6 ± 0.5 mm for further freezing. Strawberry dices were individual quick-frozen (IQF) using blast freezer (7/10KGCW, Alpeninox, Vallenoncello, Italy). The samples were placed inside the freezer at −34 °C with an air flow rate of 2 m/s. The temperature in the geometrical center of the product was recorded during the whole freezing process by fiber optical temperature sensor (FOTEMP 4 Kompakt TS4, Optocon AG, Germany). Initial temperature of the sample before freezing was 20 °C. The total freezing time, from the beginning of the cooling was ≈30 min and the final temperature of the samples was −30 °C. When product has been completely frozen it has been loaded in freeze dryer.

Freeze-drying was performed in the DEVEX pilot freeze-dryer with 1.25 m^2 of drying area. The construction of freeze-dryer included 6 contact heating zones, 4 radiation heating zones and 1 cooling zone. The temperature of shelves during freeze-drying varied in time between 25 and 130 °C and vacuum was equal to 1 mbar. Drying was performed until temperature of the product was equal to 40 °C. Temperature of ice condenser was set to −45 °C.

2.4. SEM

Microscopic images of the freeze-dried strawberry tissues were obtained by scanning electron microscopy (SEM). Strawberry cubes were frozen in liquid nitrogen and inserted into the cryo preparation system (Emitech K 1250), where the samples were broken, and free water was removed by sublimation. Finally, the surface was sputtered with gold in deep frozen state. The prepared samples were transferred into the SEM (Jeol JSM 6460 LV) at approx. −180 °C. The generated image is saved electronically. The microscopic images of freeze-dried samples has been performed at magnification ×100.

2.5. Micro-CT - image acquisition and reconstruction

SkyScan 1272 system (Bruker microCT, Kontich, Belgium) was used for X-ray micro-CT measurements. Scanning was performed at a pixel resolution of 25.0 μm, 40 keV source voltage and 193 μA current. A stack of about 1500 flat projection images (1008 × 1008 pixels) was obtained after 180° rotation with 0.3° steps, each time averaging 4 frames. Nine individual samples, randomly selected, of every variant were scanned. The projection images were loaded in NRecon 1.6.3.2 software (Bruker, Kontich, Belgium) to reconstruct virtual cross-sections of the sample. The images were corrected for rings and beam hardening, the common artefacts in X-ray CT images.

2.5.1. μ-CT - image visualization and analysis

3D visualization of individual samples was performed using CTvox software (Bruker, Kontich, Belgium). Reconstructed data-sets were loaded in CTAnn software (Bruker, Kontich, Belgium) and binarized in a threshold range 50–255. Voxels with a grey value higher or lower than that threshold value were considered sample tissue or background/pores, respectively. The region of interest was adjusted by custom processing using a shrink-wrap internal plugin. To calculate the total porosity and the thickness of the walls, a 3D analysis was performed. Afterward, the reversed thresholding was done by bitwise operations plug-in, which followed by 3D analysis resulted in the determination of the thickness of the pores. For analysis, 9 randomly selected samples of each variant were used.

2.6. Thermogravimetry

Thermal analysis was carried out with a Q-1000 Derivatograph (MOM, Hungary) in static air. Sample for the analysis has been stamped out from the dried samples. Platinum crucibles were used to hold the samples, with Al_2O_3 as reference. A rising-temperature method of thermal analysis was used, with a heating rate of 3.6 °C/min in the temperature diapason 20–250 °C. The calibration of the temperature scale was carried out at the melting point of benzoic acid (122.4°C). It should be noted that, temperature deviation did not exceed ±0.5 °C. The data acquisition and processing were carried out using thermal analysis software "Derivatograph" (IET, Ukraine) (Lammerskitten, Mykhailyk, et al., 2019).

2.7. Mechanical and acoustic properties

The mechanical properties of dried strawberry cubes were determined on the basis of a penetration test by using the texture analyser (TA.HD plus, Stable Micro Systems, Godalming, England) equipped with the penetration probe (P/6, Stable Micro Systems, Godalming, England). Test-speed equalled 1 mm/s and the penetration was 3 mm depth. Based on the obtained penetration curve, the following parameters were determined: work, number of peaks (drop in force higher than 0.8 N), average drop off and maximum force (Varela, Salvador, & Fiszman, 2008). The experiment was repeated 10 times for each kind of analyzed material.

During mechanical tests, acoustic properties of samples were analyzed. Average acoustic energy, total number of acoustic events, amplitude and average duration of acoustic event registered by contact (piezoelectric) method were used as acoustic descriptors (Wiktor et al., 2018).

Since texture, can be defined as a combination of acoustic and mechanical properties, following equation was used to determine crunchiness index (CI) (Lewicki, Marzec, & Kuropatwa, 2007):

$$CI = \frac{NAE_c}{W} \tag{2}$$

where: *CI* –crunchiness index (mJ^{-1}); NAE – average number of acoustic events (–); *W* – average work of penetration (mJ);

2.8. Colour measurements

The colour of the samples was measured in the reflectance by KonicaMinolta CM-5 (Osaka, Japan) chromameter. The colour was expressed by using CIE L*a*b* scale (L* is the lightness, a* is the redness–greenness and b* is the yellowness–blueness parameter of colour measurement). The CIE Standard Illuminate D65, di:8° (diffuse illumination/8° viewing angle), CIE: 2° Standard Observer and the 8 mm measuring area was used. The samples have been measured as dices and in a powdered form after their grinding in a laboratory grinder (A11, IKA). In the case of powder form, the material was put into quartz petri-dish. On the basis of obtained colour coordinates, the total colour difference (Δ*E*) was calculated according to the following equation:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{5}$$

where ΔL*, Δa*, Δb* are the differences between L*, a* and b* measured for untreated and PEF treated freeze-dried material.

The measurements were done in 6 repetitions.

2.9. Statistical analysis

The ANOVA procedure at $\alpha = 0.05$ and the Tukey test were applied to assess significant differences between all investigated parameters. The relevance of the impact of selected processing parameters on the selected analyzed variables was evaluated on the basis of the MANOVA procedure. In order to evaluate the dependence between selected parameters of analyzed material, the PCA and Pearson's correlation procedure was employed. The statistical analysis was done with STATISTICA 13 (Statsoft, USA) and MS Excel software.

3. Results and discussion

3.1. Microstructure

Fig. 1b presents macroscopic images of untreated and PEF pre-treated dried strawberry dices. It is visible, that the untreated sample was characterised by noticeable deformation and shrinkage. In contrast, the PEF pre-treated strawberry dice showed a more uniform shape, an inhibition of shrinkage and a visually better quality. This preservation in macro shape might be explained by phenomenon occurring due to PEF pre-treatment. Lammerskitten, Wiktor, et al., (2019) reported that PEF treatment leads to a homogenous distribution of sugar and water inside the sample due to electroporation phenomenon. Thus, a uniform drying of the sample can be achieved, that could result in a reduced shrinkage. The SEM images (Fig. 1a) show that the microstructure of the untreated sample was characterised by a high density and a compact structure. In contrast, the PEF pre-treated sample showed the presence of large pores in freeze-dried material. These observations prove aforementioned retention of macro shape by the application of PEF prior to freeze-drying. Moreover, these results are in a good correspondence with previously published studies. For example, Lammerskitten, Wiktor, et al., (2019), Parniakov et al. (2016), Wu and Zhang (2019) reported the same macrostructure preservation after PEF assisted freeze-drying of apples.

Images obtained from μCT and the process of their processing are visualized in Fig. 2. Although, freeze-drying is considered as the less invasive drying method it still provokes some structural changes that lead to shrinkage of the material (Cui, Li, Song, & Song, 2008). As shown on raw μCT images, PEF pre-treated samples exhibited better retention of shape and volume, which means that drying shrinkage was limited when compared to untreated material. Drying shrinkage is associated with different factors that may be related to process parameters or raw material properties. However, its mechanism is attributed to the heat and mass transfer that occurs during removal of water and stress/strain effects that it cause on the matrix (Yuan, Tan, Xu, Yuan, & Dong, 2019).

In the case of freeze-drying, the properties of dried material play predominant role since the processing parameters are set to hinder shrinkage. Among the material properties that may affect the shrinkage, the viscosity of the matrix – that is also linked to the chemical composition of the product - and integrity of cellular structure need to be listed (Ciurzyńska, Lenart, & Kawka, 2013). For instance, freeze-dried pumpkin that were blanched before lyophilization were characterized by higher shrinkage in comparison to untreated samples (Ciurzyńska & Lenart, 2013) whereas for apples no such (Moreira, Figueiredo, & Sereno, 2000) or opposite results were reported (Wang, Fu, Chen, Hu, & Xie, 2018). Electroporation ruptures cellular structure of the product and when applied prior to freezing that precedes freeze-drying may affect the water crystallization process, geometry and distribution of ice crystals (Wiktor, Schulz, Voigt, Knorr, & Witrowa-Rajchert, 2015). It was also demonstrated that PEF may change the distribution of compounds that can crystallize, e.g. disaccharides, which also affects the shrinkage of freeze-dried products as it affects not only the glass transition point but also viscosity of the dry matter (Aguiló-Aguayo et al., 2014; Lammerskitten, Mykhailyk, et al., 2019; Ullrich, Seyferth, & Lee, 2015). Hence, it should be stated that mechanism of PEF impact on the shrinkage prevention during freeze-drying should be further studied in order to get clear answer.

Pore sizes distribution was typical for freeze-dried materials (Voda et al., 2012) (Fig. 3). The distribution of pores inside the sample was more homogenous in the case of fruits that were subjected to PEF

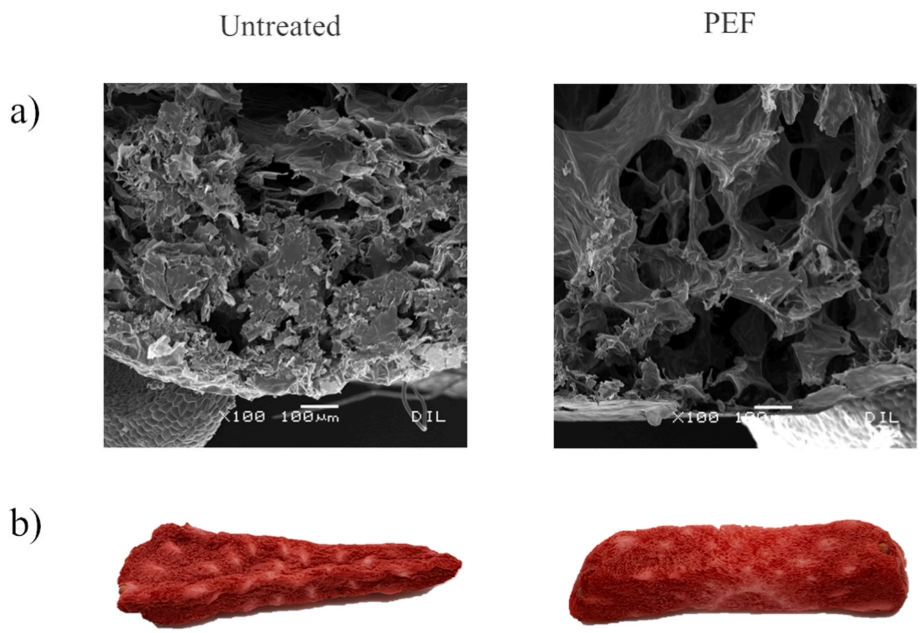

Fig. 1. Micro-(a) and macro- (b) images of untreated and PEF pre-treated freeze-dried strawberry dices.

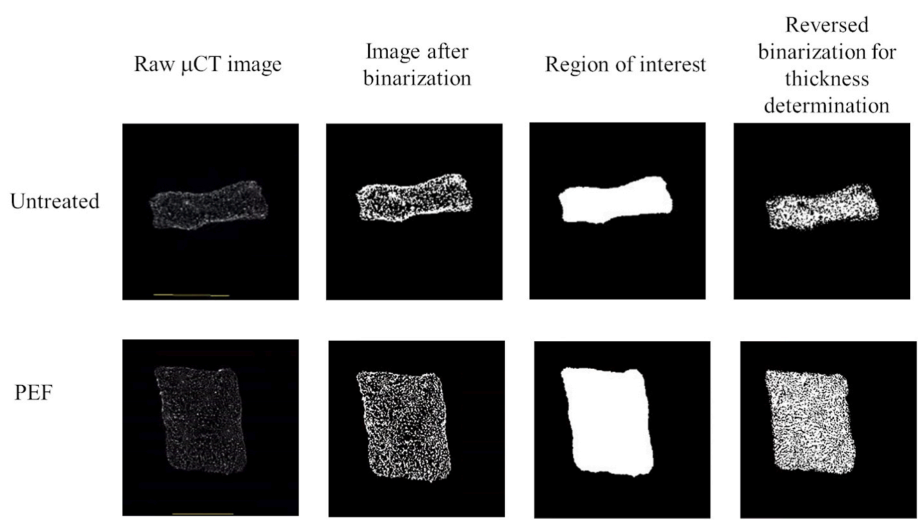

Fig. 2. Example of raw, and binarized µCT images of untreated and PEF pre-treated freeze-dried strawberry dices.

pre-treatment before freeze-drying. 79 and 87% of pores population for untreated and PEF pre-treated material, respectively, had the dimensions between 0.1 and 0.2 mm. Moreover, 36% of total pores population of PEF pre-treated freeze-dried fruits had a thickness of 0.15 mm. While in the case of untreated it was found for 27% of all pores. What is interesting, the biggest differences in walls size between PEF and untreated materials were stated for walls with thickness of 0.05 mm and 0.15 mm. The number of walls with thickness of 0.05 mm was 24.4 and 36.7%, for untreated and PEF pre-treated strawberries, respectively. In turn, number of pores with bigger – 0.15 mm – thickness was higher in the case of untreated samples. The differences may be related with the formation of smaller crystals during freezing of the PEF pre-treated material. It has been proved before that PEF decreases phase transition time during freezing, which affects the ice crystal size (Parniakov et al., 2016). Overall porosity of investigated materials was equal to 60.5 and 71.2%, for reference and pre-treated material, respectively. It means that microstructure of PEF pre-treated material was more delicate and typical for crispy products – as also described in the further part of the manuscript. It is also worth emphasizing that different contrast and lightness of raw µCT images is associated with X-ray absorption. Brighter regions correspond to regions with higher density (Schoeman, Williams, du Plessis, & Manley, 2016) which means that untreated samples, were also characterized by higher density than strawberries pretreated by PEF before freeze-drying.

3.2. Thermal properties

Fig. 4 shows derivatogramm of untreated and PEF pre-treated freeze-dried strawberry tissues. The DTG curve for both untreated and PEF pre-treated samples shows continuously decreasing slope since the beginning of the heating (21 °C), that indicates an increase in the rate of the mass change in the samples (Lammerskitten, Mykhailyk, et al., 2019). The average rate of the mass change in the temperature range of 21–132.1 °C is equal to 0.17%/min and 0.19%/min for untreated and PEF pre-treated samples, respectively (Fig. 4 a,b). The weight loss in this temperature range for sample with PEF pre-treatment, calculated after

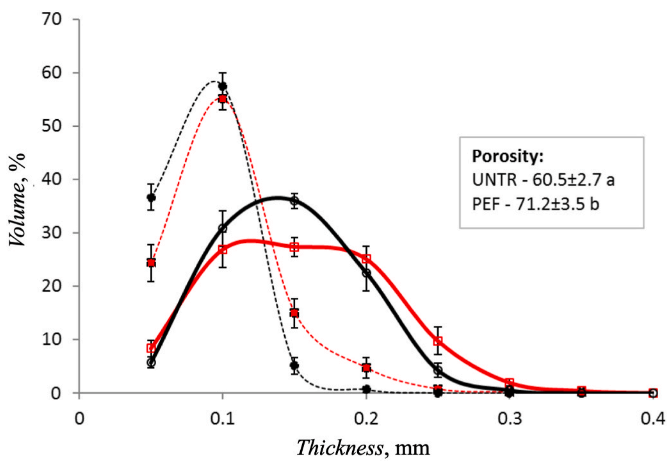

Fig. 3. Percentage of walls and pores of specific thickness in the untreated and PEF pre-treated freeze-dried strawberry dices. Red lines represent untreated samples and black one represent PEF pre-treated material. Dashed lines represent the values for walls whereas solid lines represent pores.

reaching the first break on the DTG curve (131.4°C), was 6.45% and for the untreated sample, (at 132.1°C) was 6.09%. It can be speculated that it corresponds only to the evaporation of bound water from the samples. However, during these experiments it was noticeable intense aroma in the air, therefore it can be assumed that part of the weight loss of the samples is associated with the evaporation of aromatic substances.

The resulting thermal effect associated with the simultaneous presence of endothermic and exothermic processes, during thermal analysis of PEF pre-treated sample, is reflected on the DTA curve (T = 21–170.8 °C) (Fig. 4b). Actually, evaporation of bound water and aromatic substances (21–131.4 °C), melting of fructose (102–132 °C) and glucose (144–170.8 °C) has been accompanied by an exothermic process of thermal decomposition of the organic substances in the PEF pre-treated sample. After the end of glucose melting (170.8 °C for PEF and 174.1°C for untreated samples), there is a sharp increase in the rate of the mass and heat change of the sample associated with its thermal decomposition, which reaches a maximum at 192.1 °C and 198.6 °C, for PEF pre-treated and untreated samples, respectively. The steep rise of the DTA curve confirming the thermal decomposition of freeze-dried samples (Fig. 4 a,b). The relative weight loss of the samples before the completion of glucose melting, i.e. in the range of 21–170.8 °C for the PEF pre-treated sample and in the range of 21–174.1 °C for the untreated sample, is 17.04% and 13.19%, respectively. The rate of the mass change in these temperature ranges is 0.39 and 0.31%/min for PEF pre-treated and untreated samples, respectively. This means that the freeze-dried strawberry sample with PEF pre-treatment lost 17.9% more in mass than the untreated sample. At the same time, the rate of the mass change of PEF pre-treated sample is 20.9% higher than this one of untreated sample. Such difference in the depth and rate of thermal decomposition of the samples could be connected to preserved internal structure of freeze-dried strawberry dices pre-treated by PEF that is in the good correspondence to the aforementioned data from μCT images.

3.3. Mechanical and acoustic properties

Textural properties of freeze-dried strawberries, expressed as mechanical properties, acoustic properties and crunchiness index are presented in Table 1. Because of the specific way of water removal, texture of freeze-dried product is completely different than texture of materials dried by most of the drying methods. Usually, materials dried by the means of sublimation are characterized by more crispier and/or crumbling texture than samples subjected to air drying (Lin, Durance, & Scaman, 1998).

Moreover, hardness of freeze-dried materials is lower in comparison to food dried by convective, fluidized or microwave assisted methods (Marzec & Pasik, 2008). These textural properties determine the specific applications of freeze-dried materials as snacks or ingredients of breakfast cereals. Untreated freeze-dried strawberries were characterized by greater hardness in comparison to PEF pre-treated dried fruits as they have exhibited more than two times higher value of maximum force of mechanical load (Cui et al., 2008). At the same time, as a consequence of PEF pre-treatment, work of penetration decreased from 17.08 to 10.44 mJ, which means that it was reduced by 38.9% when compared to the reference. It is worth noticing that the differences were significant from statistical point of view for work and maximum force alike. Drop off and number of peaks are usually used to describe the jaggedness of the deformation curves that correlates with the crunchiness (Jakubczyk et al., 2015). Texture of products that are described as crunchy/crispy usually is described by high number of peaks and small values of drop off (Gondek et al., 2018). PEF pre-treated freeze-dried strawberries exhibited relevantly higher number of peaks and smaller drop off value. Together with aforementioned parameters (work and maximum force), values of drop off and number of peaks stand that strawberries pre-treated by PEF before freeze-drying were less resistant for mechanical load. It means that PEF pre-treated samples were crispier as they better fit to the definition of crispiness which is very often highly associated to the mechanical properties part of texture (Mallikarjunan, 2004). However, texture of materials described as dry does not simply reveal from mechanical properties alone. The acoustic sensation play very important role when it comes to consumer perception of texture (Duizer, 2001; Saeleaw & Schleining, 2011). In that manner specific acoustic signal emitted during deformation of the product shapes the crunchiness of the product (Mallikarjunan, 2004). Depending on the spectral characteristic of this signal food can be described as crispy, crunchy or crackly (DACREMONT, 1995). In presented study, acoustic properties of PEF pre-treated freeze-dried strawberries were significantly different in comparison to control samples regardless of the acoustic descriptor. In general, acoustic properties stayed in accordance with mechanical parameters. Untreated dried strawberries demonstrated higher value of average event energy and higher average amplitude in comparison to PEF pre-treated fruits. These results indicate that the rupture of the structure during material deformation was sudden and loud. Average time of acoustic event emission was longer in the case of untreated samples. On contrary, acoustic emission of PEF pre-treated strawberries was characterized by higher total number of acoustic events and lower average amplitude. It means that during deformation of fruits subjected to PEF pre-treatment before freeze-drying rupture of the structure was more homogenous and rather progressive. In the case of untreated material the deformation lead to steep, sharp and rugged ruptures which are characteristic for crackly materials (Chauvin, Younce, Ross, & Swanson, 2008). Since texture, and especially crunchiness/crispiness issue, should be interpreted as a complex property that consist of two major components: namely mechanical and acoustic, Crunchiness Index (CI) is a descriptor provides more comprehensive evaluation of the texture. Hence, the implementation of PEF as a pre-treatment prior to freeze-drying resulted in more than four times higher CI of the dried material than in the case of untreated ones. Similar findings were reported for laboratory scale freeze-drying of PEF pre-treated apples frozen inside the drying chamber by pressure drop (Lammerskitten, Wiktor, et al., 2019). It is worth emphasizing that the results of texture analysis stay in accordance with the microstructure of the investigated materials as examined by microtomography and SEM imaging (Figs. 1 and 2) – namely PEF pre-treated material that was characterized by greater porosity was more crispy than untreated which was less porous.

3.4. Optical properties

The material structure also influenced the optical properties of the analyzed samples. Table 2 presents the optical properties (in CIE L*a*b*

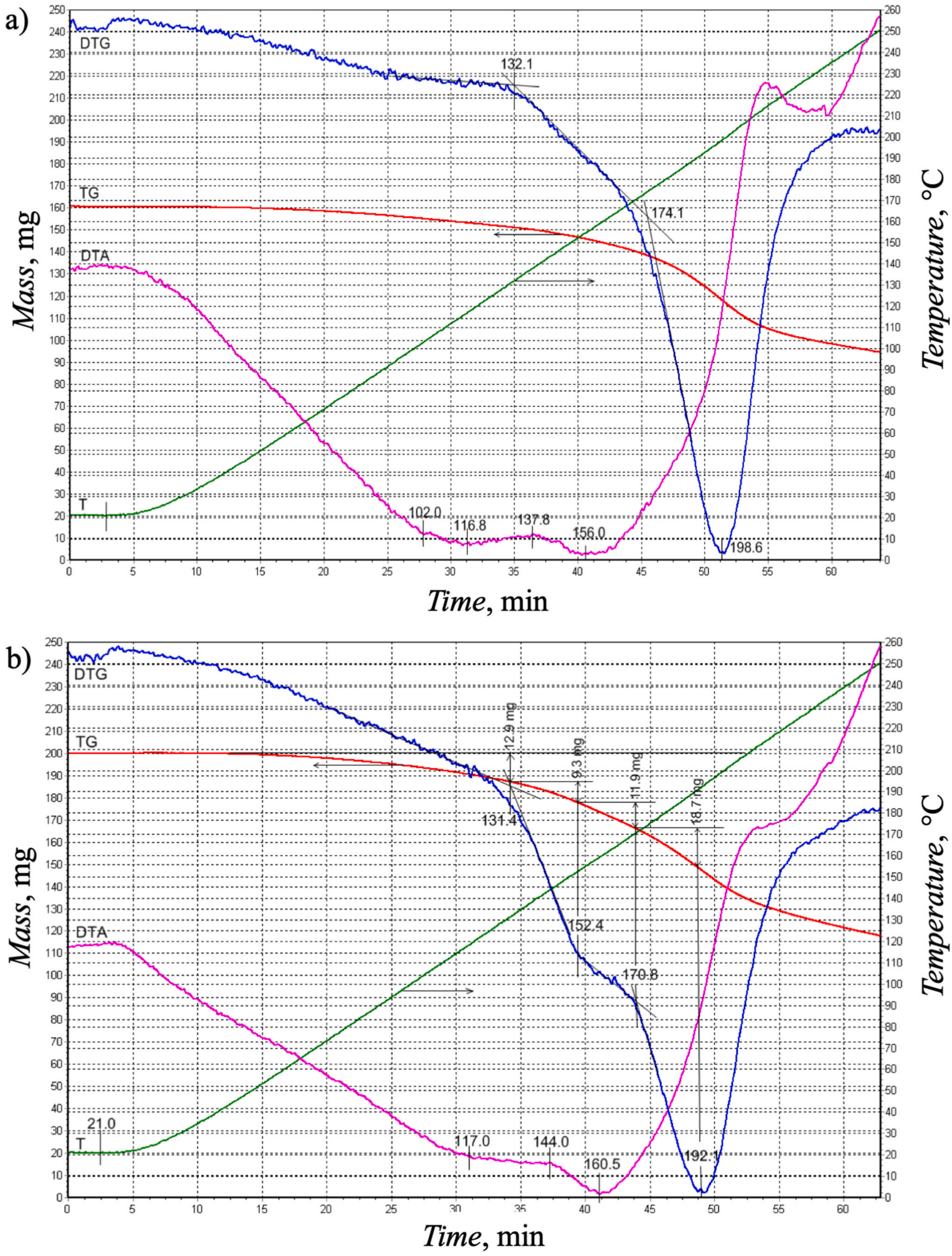

Fig. 4. Derivatogramm of untreated (a) and PEF pre-treated (b) freeze-dried strawberry tissues.

Table 1
Mechanical, acoustic properties and crunchiness index of the analyzed untreated and PEF treated freeze-dried strawberry dices.

	Mechanical properties				
Sample	Work [mJ]	Maximum force [N]	Drop off [N]	Number of peaks	
U	17.08 ± 4.92[a]	13.6 ± 5.75[a]	0.83 ± 0.17[a]	13±5[a]	
PEF	10.44 ± 3.23[b]	6.25 ± 1.8[b]	0.48 ± 0.20[b]	18±4[b]	
Sample	Acoustics Properties				Crunchiness Index [mJ^{-1}]
	Average event energy [a.u.]	Total Number of Acoustic Events	Average amplitude [mV]	Average event time [μs]	
U	436 ± 77[a]	3125 ± 1117[a]	127 ± 41[a]	95±2[a]	203 ± 73[a]
PEF	178 ± 58[b]	8744 ± 904[b]	61 ± 19[b]	88±5[b]	876 ± 200[b]

Different letters indicate statistically significant difference (t-student test; $\alpha = 0.05$), $n = 10$.

Table 2
Colour of untreated (U) and PEF pre-treated (PEF) freeze-dried strawberries in a form of dices and grinded into powder.

Sample		L^*	a^*	b^*	ΔE
Dices	U	44.28 ± 3.25[a]	36.09 ± 1.91[a]	15.49 ± 0.91[a]	–
	PEF	40.48 ± 2.14[b]	37.78 ± 1.06[a]	16.22 ± 0.44[a]	4.22
Powder	U	57.88 ± 0.22[a]	38.28 ± 0.11[a]	16.36 ± 0.07[a]	–
	PEF	56.05 ± 1.01[b]	40.91 ± 1.25[b]	16.99 ± 0.35[b]	3.26

Different letters indicate statistically significant difference (t-student test; $\alpha = 0.05$), $n = 6$.

scale) of untreated and PEF pre-treated dried strawberry tissue. It has been reported before that PEF pre-treatment can alter the colour of fresh tissue due to electroporation phenomenon and release of substrates for chemical and enzymatical reactions (Nowacka et al., 2019; Velickova et al., 2018; Wiktor, Sledz, et al., 2015). In current research, the PEF pre-treated freeze-dried samples showed lower lightness (L^*) value than untreated one by around 10% for dices and 1% for powder. These results, could be considered as unexpected since the porosity of PEF pre-treated samples, as aforementioned, was higher than reference dried strawberries and what more, the observed results are different to the previously reported data, which stated a positive trend between lightness and PEF pre-treatment (Lammerskitten, Wiktor, et al., 2019; Wiktor et al., 2016). However, colour and brightness of dried materials depends not only on physical (e.g. porosity) but also on chemical properties (Joshi & Brimelow, 2002). Therefore, registered difference in lightness between PEF and untreated materials can be explained by the influence of natural pigments that are presented in strawberry - anthocyanins. The influence of composition of matrix is even more visible for grinded material. PEF pre-treated powdered freeze-dried strawberries exhibited slightly but significantly lower L^* values, which confirms that lightness is superposition of porosity and pigments concertation and composition with predominant role of the last one. It should be emphasized also that grater lightness of powder than dices is related to more developed area that reflects light better than porous material that traps it inside (Joshi & Brimelow, 2002). Moreover, with regards of a^* value, that provides information about the red/green colour channel, PEF pre-treated samples showed higher value for both matrices (dices and powder) compare to untreated sample. Therefore, the combination of results of $L^*$and b^* can be associated with colour preservation of the PEF pre-treated freeze-dried strawberries. As for discussion, there are some reports that show that PEF impacts the distribution of anthocyanins in fruits (Jin, Yu, & Gurtler, 2017) which may be further progressed and preserved after freeze-drying. Better preservation of colour in the case of PEF pre-treated strawberries may be related to more homogenous heat distribution during freeze-drying. It has been reported that PEF pre-treated carrots exhibited higher thermal conductivity coefficients that untreated vegetables (Wiktor et al., 2016). As demonstrated for red bell pepper more homogenous heat and mass transfer of PEF pre-treated samples during water evaporation resulted in better optical properties (Won, Min, & Lee, 2015). The values of ΔE show that the colour change of PEF treated is distinct and can be noticed by unexperienced observer with "naked eye" ($2 < \Delta E < 3.5$) (Mokrzycki & Tatol, 2011).

4. Conclusion

Freeze-dried strawberry dices subjected to PEF pre-treatment showed a better retention of shape and volume and a better visual quality compared to untreated ones, which were mainly characterized by a dense and compact structure. It can be assumed that PEF induced electroporation phenomenon leads to a more homogenous distribution of sugar and water inside the sample, resulting in a more uniform drying. In accordance, the distribution of pores was more homogenous in PEF pre-treated samples compared to untreated ones. Moreover, PEF pre-treated product had higher mass loss while thermal decomposition that could be connected to preserved internal structure. Texture and acoustic analysis evidenced, that the PEF pre-treated material, characterized by a greater porosity, was crispier, whilst the untreated sample was rather hard. In contrast to previously reported data, PEF treated material showed a lower lightness and higher a* values in comparison to untreated once.

CRediT author statement

Alica Lammerskitten: Investigation, Formal analysis, Writing - original draft. **Artur Wiktor:** Writing - original draft, Writing - reviewing & editing, Formal analysis, Supervision. **Viacheslav Mykhailyk:** Investigation, Formal analysis, Writing. **Katarzyna Samborska:** Investigation, Formal analysis. **Ewa Gondek:** Investigation, Formal analysis. **Dorota Witrowa-Rajchert:** Methodology, Conceptualization. **Stefan Toepfl:** Resources, Conceptualization. **Oleksii Parniakov:** Resources, Supervision, Writing - original draft, Writing - reviewing & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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