https://doi.org/10.17221/93/2021-RAE

Application of pulsed electric field prior to vacuum drying: Effect on drying time and quality of apple tissue

Aleksandra Matys[1], Dorota Witrowa-Rajchert[1], Oleksii Parniakov[2], Artur Wiktor[1]*

[1]Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences (SGGW), Warsaw, Poland
[2]Elea Technology GmbH, Quakenbrück, Germany

**Corresponding author: aleksandra_matys@sggw.edu.pl*

Citation: Matys A., Witrowa-Rajchert D., Parniakov O., Wiktor A. (2022): Application of pulsed electric field prior to vacuum drying: Effect on drying time and quality of apple tissue. Res. Agr. Eng., 68: 93–101.

Abstract: The study aimed to determine the influence of a pulsed electric field (PEF) treatment on vacuum drying (VD) of apples and their selected quality parameters. The apples were treated with a PEF at 1 kV·cm^{-1} (with a variable amount of the specific energy input: 1, 3.5, and 6 kJ·kg^{-1}) before VD at 4 kPa (with a variable drying temperature: 40 °C, 55 °C, and 70 °C). The drying time, microstructure, retention of total phenolics (TPC) as well as the antioxidant activity of the obtained dried materials were studied. As a result of opening the cell structure of the apple tissues, the PEF significantly ($P < 0.05$) reduced the drying time – depending on the used process parameters – by 6–22%. Moreover, an increase in the drying temperature also shortened the drying time. The electroporation led to obtaining porous materials after drying, and with the higher amount of specific energy during the PEF pre-treatment that was applied, a higher porosity was observed in the dried apples. After the PEF-assisted VD, a significant ($P < 0.05$) decrease in the TPC (by 12–40%) and antioxidant activity (by 23–81%) were observed.

Keywords: antioxidant activity; CDI; dehydration; microstructure; PEF; polyphenols

Among all the drying methods, convective drying is the most used method of food preservation in the food industry. The use of hot air in this process, thereby causing the long-term exposure of the material to oxygen and high temperatures, conduces the formation of adverse changes in the physical and chemical properties of the treated material (Matys et al. 2021). The quality of the obtained dried material can be improved by drying under a vacuum. Under reduced pressure, water boils at a lower temperature (T_b – the boiling temperature of water). Thus, the use of sub-atmospheric pressure allows the drying process to be carried out at lower temperatures. This is especially important for the removal of water from food containing heat-sensitive compounds that are usually partially or completely degraded at high temperatures. Limiting the exposure of the dried material to oxygen reduces the risk of oxidation occurring during drying and allows for the better preservation of properties (Delgado and da Silva 2014; Liu et al. 2018). Piotrowski et al. (2007) studied the effect of various parameters of vacuum drying on the temperature of defrosted and osmotically dehydrated strawberries. The authors showed that, depending on the pressure, it was observed that the dried material cooled down (4 kPa) or heated up (20 kPa) in the first of three different temperature change phases during vacuum drying. The cooling of the dried sample at the beginning of drying process was also noted by Parniakov et al. (2016) during the drying of apples

Suported by the European Union's Horizon 2020 research and innovation program under grant agreement No. 817683 (acronym FOX).

https://doi.org/10.17221/93/2021-RAE

under a pressure of 1 kPa. Apart from examining the impact of significantly reduced pressure on the specific properties of the dried material, moderate levels of this parameter have also been analysed, for example, 30 kPa (T_b ≈70 °C) (Liu et al. 2018; Liu et al. 2020a; Liu et al. 2020b) and 96 kPa (Yu et al. 2017).

Various treatments before the drying process are applied more and more often. By modifying the properties of a particular tissue, they increase the drying rate and improve the quality of the material. Recently, the application of a pulsed electric field (PEF) has been used more frequently as a pre-treatment method before drying. It is one of the most promising non-thermal treatments before drying. The main mechanism of PEF is based on the gentle opening of the cell membrane as a result of electroporation, i.e. forming irreversible or reversible pores in the cell membrane. Therefore, the pulsed electric field induces an increase in the permeability of the cell membrane. As a result, fluid leaks from the inside of the cells towards the extracellular environment, which escalates the efficiency of the processes based on mass and/or heat transfer, e.g. drying (Wiktor et al. 2018; Liu et al. 2019; Llavata et al. 2020; Martín-García et al. 2020; Wiktor et al. 2020; Ostermeier et al. 2021).

Pulsed electric fields can induce physical modifications in the treated tissue. Electric pulses of appropriate intensity damage the cell membrane of the material, which enhances the diffusion of water. This accelerates the drying process and, thus, reduces the degradation of important bioactive compounds, e.g. flavonoids in mangoes (Lammerskitten et al. 2020). The application of a pulsed electric field before vacuum drying also allowed the authors to increase the retention of β-carotene in the obtained dried carrot (Liu et al. 2020a). Research carried out on the blueberry (Yu et al. 2017) shows the possibility of improving vacuum drying by using electric pulses as a pre-treatment, without adversely affecting the quality of the obtained dried material (the contents of anthocyanin and vitamin C). However, the amount of energy supplied by the PEF should be carefully dosed, because of the "overtreatment" phenomenon of the material that may lead to the destruction of important food ingredients (Lammerskitten et al. 2020).

So far, the impact of the pulsed electric fields on the course of freeze-drying apples have been studied (Lammerskitten et al. 2019a; Lammerskitten et al. 2019b) as well as on convective drying of that fruit (Ostermeier et al. 2020). However, there are no reports on the possibility of applying this non-thermal pre-treatment to improve the vacuum drying of apples. Therefore, this research aimed to determine the effect of a pulsed electric field pre-treatment on the vacuum drying of apples and the selected properties of the obtained dried material (total phenolic content – TPC, antioxidant activity, microstructure).

MATERIAL AND METHODS

Material. The research was performed on the apple variety "Golden delicious", grown in the experimental fields of the Department of Fruit Growing at the Warsaw University of Life Sciences (SGGW, Warsaw, Poland). The fruits were stored for one week in cold storage (5 ± 1 °C). The most standard apples in terms of shape, colour, and maturity were selected for the tests. Before starting the technological operations, the apples were removed from the cold storage and left to reach room temperature (about 20 °C), and then washed with tap water (21 ± 1 °C). The initial dry matter content of the fresh apples was 14.5 ± 0.1%.

Pulsed electric field pre-treatment. The pulsed electric field pre-treatment of apples was carried out in a batch system (PEFPilot™ Dual System, Elea Technology GmbH, Quakenbrück, Germany). To achieve this, one apple was placed inside a chamber with 2 L capacity, which was equipped with two parallel stainless-steel electrodes (with a distance between the electrodes of 24 cm). The treatment chamber was then filled with tap water (21 ± 1 °C; 718 μS·cm^{-1}), which was the conductive medium. The total input of the chamber was approximately 1.5 kg each time. The pulsed electric field parameters were: an electrode voltage of 24 kV, an electric field strength of 1 kV·cm^{-1} – which corresponds with the mean electric field strength inside the chamber (Grimi et al. 2010), a pulse frequency of 20 Hz, and a pulse width of 7 microseconds. The number of rectangular pulses depended on the amount of supplied energy (1, 3.5, 6 kJ·kg^{-1}).

The specific energy intake W_{spec} (kJ·kg^{-1}) and electric field strength E (kV·cm^{-1}) were calculated according to the following Equations (1–2):

$$W_{spec} = \frac{IUtn}{m} \quad (1)$$

$$E = \frac{U}{d} \quad (2)$$

where: n – the number of pulses (–); m – the mass of the treated samples (kg); U – the voltage (kV); I – the

https://doi.org/10.17221/93/2021-RAE

current (A); t – a pulse duration (s); d – the distance between the electrodes (cm).

The conductivity of the untreated and PEF-treated whole apples was measured using the dual needle platinum electrodes method at a frequency of 100 Hz (pH/conductivity meter CPC-401, Elmetron, Zabrze, Poland) (Wiktor et al. 2013). Based on the obtained results, the CDI (cell disintegration index) was calculated according to Equation (3) (Lebovka et al. 2007):

$$CDI = \frac{\sigma - \sigma_i}{\sigma_d - \sigma_i} \quad (3)$$

where: σ – the conductivity of the tissue after applying the pulsed electric field (μS); σ_i – the conductivity of the intact tissue (μS); σ_d – the conductivity of the maximally ruptured tissue (sample treated with an energy input of 50 kJ·kg^{-1}) (μS).

Vacuum drying. The drying procedure was performed on apple quarters, prepared by cutting the fruits into 5 mm thick slices, stripping them of their cores, and then cutting the slices into four equal pieces.

The vacuum drying of the untreated and PEF-treated apples was carried out in a laboratory vacuum dryer SPT-200 (Conbest, Poland). The drying was performed under pressure set at 4 kPa in all the variants, but the temperature was varied (40 °C, 55 °C, and 70 °C). This level of pressure should provide a relatively low boiling temperature of water (T_b ≈30 °C) (Agrawal and Menon 1992), and significant cooling of the material during the water evaporation may also occur (Liu et al. 2018). The sliced apples were placed in a single layer on a perforated tray and the sieve load was 2.1 kg per square meter. During the drying, the weight of the apples was continuously (without any interruption in the drying process, using the same sample throughout the entire process) recorded every 10 min, which served to determine the drying time (time to achieve MR = 0.02 by dried apples) (Sacilik and Elicin 2006; Piotrowski et al. 2007; Schultz et al. 2007; Beigi 2016). The MR (moisture ratio) was calculated according to Equation (4) (Matys et al. 2021):

$$MR = \frac{M_\tau}{M_0} \quad (4)$$

where: M_τ – the water content in samples during the drying (kg H_2O per kg of dry matter); M_0 – the initial water content in the samples (5.9 kg H_2O per kg of d.m.).

The vacuum drying procedure was repeated three times.

Dry matter content. The dry matter (d.m.) content was determined by the gravimetric method following the AOAC 920.15, 2002 standard (Mannozzi et al. 2017) with three repetitions.

Preparation of the extracts. The ethanol extracts of the obtained dried apples were prepared according to the methodology presented in the study (Dadan et al. 2018). They were used to determine the total phenolic content and antioxidant activity. The extracts were prepared in two replicates for each sample.

Total phenolic content. The total phenolic content (TPC) in the obtained dried apples was determined according to Folin-Ciocalteu's method (Singleton et al. 1999). Gallic acid was used as a standard. The exact procedure and the amounts of reagents used have already been described in a previous study (Nowacka et al. 2019). The absorbance of the prepared solutions against the blank sample was measured with a spectrophotometer Heλios Thermo Electron 7.03 (Thermo Electron Corporation, USA) at a wavelength of 750 nm. The analysis was performed in four replications (two times for each extract) and the obtained results were expressed in mg of gallic acid per 100 g of dry matter.

Antioxidant activity. The antioxidant activity of the obtained dried apples was assayed following the method described in the studies (Brand-Williams et al. 1995; Dadan et al. 2018) after selecting the appropriate extract volume to the type of the tested matrix (0.1, 0.2, 0.3, 0.4 mL). The analysis consisted of determining the degree of scavenging DPPH• (2,2-diphenyl-1-picrylhydrazyl synthetic radical) by the antioxidants contained in the prepared extracts. The absorbance of the prepared solutions was measured with a spectrophotometer Heλios Thermo Electron 7.03 (Thermo Electron Corporation, USA) at a wavelength of 515 nm. The determination was carried out in four replicates (two times for each extract), and the obtained results were expressed as the EC_{50} coefficient (extract concentration necessary for a 50% reduction of the initial amount of the DPPH• radicals) – which is expressed as mg of dry matter per 1 mL of extract in this article. Therefore, the higher the EC_{50} values, the lower the antioxidant activity.

Microstructure. The structure analysis was carried out on the untreated and pre-treated with PEF apples (energy input: 1 and 6 kJ·kg^{-1}) and dried at 55 °C. The tested samples were at first coated

https://doi.org/10.17221/93/2021-RAE

with a thin layer of gold using a Cressington sputter coater 108 auto (Cressington Scientific Instruments Ltd, UK). Images of cross-sections of the selected samples were taken at a magnification of 50× and 200× with a scanning electron microscope SEM TM-3000 with a digital image record (HITACHI, Japan), at a voltage of 15 kV.

Statistical analysis. To determine the statistical differences between the obtained results, the results were subjected to a one-way analysis of variance (ANOVA) ($\alpha = 0.05$) and a post hoc analysis using Tukey's test (Statistica 13.3, TIBCO Software, Palo Alto, USA). Moreover, a two-factor analysis of variance was used to assess the significance of the impact of two variable factors (PEF energy input, drying temperature) on the tested parameters. Additionally, the dependence between the TPC and the EC_{50} was evaluated using Pearson's correlation coefficient.

RESULTS AND DISCUSSION

Cell disintegration index. The cell disintegration index indicates the cell damage and ranges from zero to one. Zero stands for the intact tissue and one stands for the maximally ruptured material (Lebovka et al. 2007). As can be seen from Table 1, the degree of damage to the apple tissue through the application of electric pulses during the pre-treatment increased along with the increase in the amount of supplied energy (CDI ranged between 0.29–0.55). The obtained results correlate with previous published studies (Lammerskitten et al. 2020; Shorstkii et al. 2022).

Drying time. Figure 1 shows the drying process of the untreated and PEF-treated apples in a curve diagram, while drying time is presented in Table 1. Both the amount of specific energy during PEF pre-treatment and the drying temperature significantly influenced the time of the vacuum drying of the apples ($P < 0.05$). Increasing the drying temperature and, thus, intensifying the convective heat transfer (Lebovka et al. 2007; Liu et al. 2020a), shortened the drying time. For example, vacuum drying the untreated samples at 40 °C, 55 °C, and 70 °C lasted 710, 460, and 320 min, respectively. Moreover, the use of a PEF as the pre-treatment considerably reduced the drying time in each analysed variant. For instance, the drying time of the 40 °C 6 kJ·kg^{-1} sample was shorter by 22% than that of 40 °C 0 kJ·kg^{-1} sample. The PEF technology applied before vacuum drying allowed one to decrease the drying time of various materials, such as in potatoes (Liu et al. 2018), carrots (Liu et al. 2020b), blueberries (Yu et al. 2017), and basil leaves (Telfser and Galindo 2019). The increased permeability of the cell membrane and the damaged structure of the material caused by PEFs (more specifically by electroporation) affected the transfer of mass and heat and, thus, led to an improvement in the drying rate (Lammerskitten et al. 2020; Liu et al. 2020a). Nevertheless, in some cases, the application of a higher energy input did not reduce the drying time any further. For example, the drying time of the 40 °C 3.5 kJ·kg^{-1} sample was longer by 20 min than that of 40 °C 1 kJ·kg^{-1} sample. Such a situation may be associated with the saturation of electroporation (Lebovka et al. 2004a; Beitel-White et al. 2021) and may indicate that a treatment with an energy input higher than 1 kJ·kg^{-1} does not bring any further effect. However, it should also be considered that the delivery of high energy during the treatment may result in the overtreatment of the tissue, its collapse, and cause a loss of turgor (Lebov-

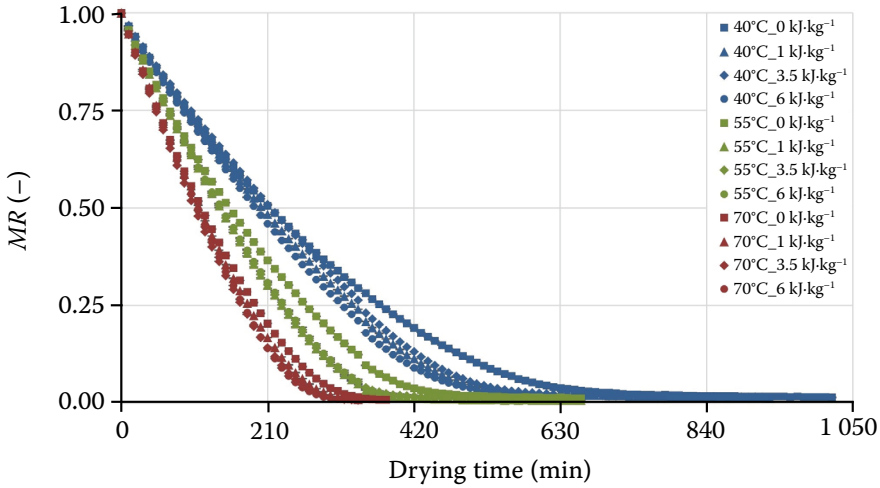

Figure 1. Drying kinetics of the vacuum-dried apples untreated and pre-treated with PEF

MR – moisture ratio

https://doi.org/10.17221/93/2021-RAE

Table 1. The pre-treatment and drying parameters, values of the cell disintegration index, drying time and drying time reduction of the apples untreated and treated with PEF prior to the vacuum drying and the dry matter content in the obtained dried materials

Drying temperature (°C)	Energy input (kJ·kg^{-1})	Sample code	*CDI* (–)	Drying time (min)	Drying time reduction (%)	Dry matter content (%)
40	0	40°C_0kJ·kg^{-1}	–	710 ± 0^{j}	–	92.6 ± 0.1^{ab}
	1	40°C_1kJ·kg^{-1}	0.29 ± 0.01	580 ± 0^{h}	18 ± 0de	92.4 ± 0.1^{ab}
	3.5	40°C_3.5kJ·kg^{-1}	0.46 ± 0.02	600 ± 0^{i}	15 ± 0^{c}	92.3 ± 0.1^{ab}
	6	40°C_6kJ·kg^{-1}	0.55 ± 0.01	557 ± 6^{g}	22 ± 1^{f}	93.0 ± 0.1^{ab}
55	0	55°C_0kJ·kg^{-1}	–	460 ± 0^{f}	–	93.4 ± 0.5^{ab}
	1	55°C_1kJ·kg^{-1}	0.29 ± 0.01	370 ± 0^{d}	20 ± 0^{ef}	95.7 ± 0.1^{b}
	3.5	55°C_3.5kJ·kg^{-1}	0.46 ± 0.02	381 ± 8^{e}	17 ± 2^{cd}	91.9 ± 2.8^{a}
	6	55°C_6kJ·kg^{-1}	0.55 ± 0.01	380 ± 0de	17 ± 0^{cde}	96.0 ± 0.1^{b}
70	0	70°C_0kJ·kg^{-1}	–	320 ± 0^{c}	–	95.0 ± 0.2^{ab}
	1	70°C_1kJ·kg^{-1}	0.29 ± 0.01	300 ± 0^{b}	6 ± 0^{a}	94.6 ± 0.1^{ab}
	3.5	70°C_3.5kJ·kg^{-1}	0.46 ± 0.02	280 ± 0^{a}	13 ± 0^{b}	96.0 ± 0.1^{b}
	6	70°C_6kJ·kg^{-1}	0.55 ± 0.01	280 ± 0^{a}	13 ± 0^{b}	93.5 ± 0.5^{ab}

Results are shown as the mean ± standard deviation (SD), the different letters within the columns indicate statistically significant differences ($P < 0.05$); *CDI* – cell disintegration index

ka et al. 2004b), which will hinder the water evaporation. Therefore, it is very important to properly select the process parameters.

Chemical properties. The dry matter content of all the investigated samples varied from 92% to 96% (Table 1). Figures 2–3 show the total phenolic content and antioxidant activity in the obtained untreated and PEF-treated dried apples prior to vacuum drying. Both of these parameters were influenced by the drying temperature as well as the amount of energy supplied during the pre-treatment ($P < 0.05$).

In all the dried samples, the TPC ranged from 500.0 mg to 881.7 mg gallic acid equivalent (GAE) per 100 g of d.m. and varied significantly ($P < 0.05$). For the fresh apple, the TPC was equal to 564.0 ± 34.0 mg GAE per 100 g of dry matter. Thus, in most variants, an increase in the TPC was observed after drying the materials. During drying, browning products are formed, which may have reacted with the Folin's reagent used in this assay (Wiktor et al. 2020; Matys et al. 2021). This may explain the increased content of these compounds in the dried apples. In compari-

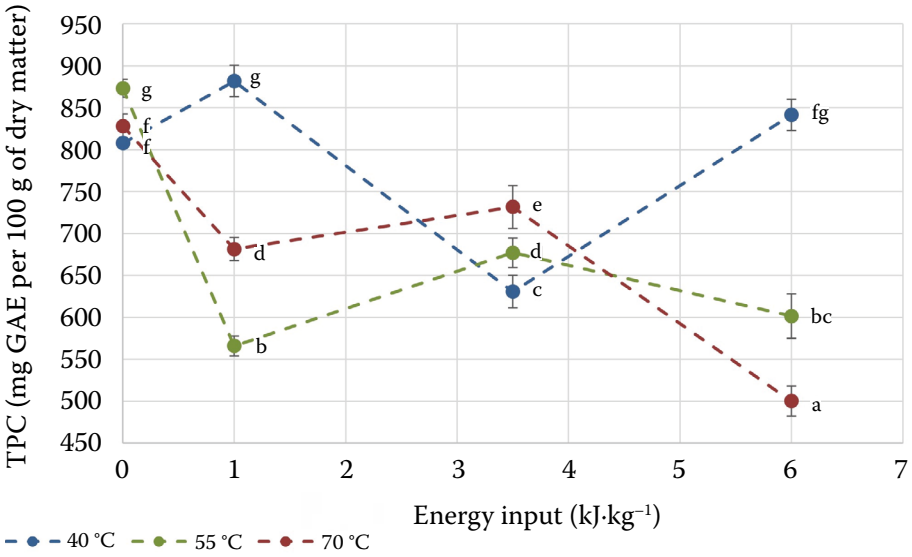

Figure 2. Total phenolic content (TPC) in the obtained dried apples

Results are shown as the mean with standard deviation (SD), the different letters indicate statistically significant differences ($P < 0.05$)

https://doi.org/10.17221/93/2021-RAE

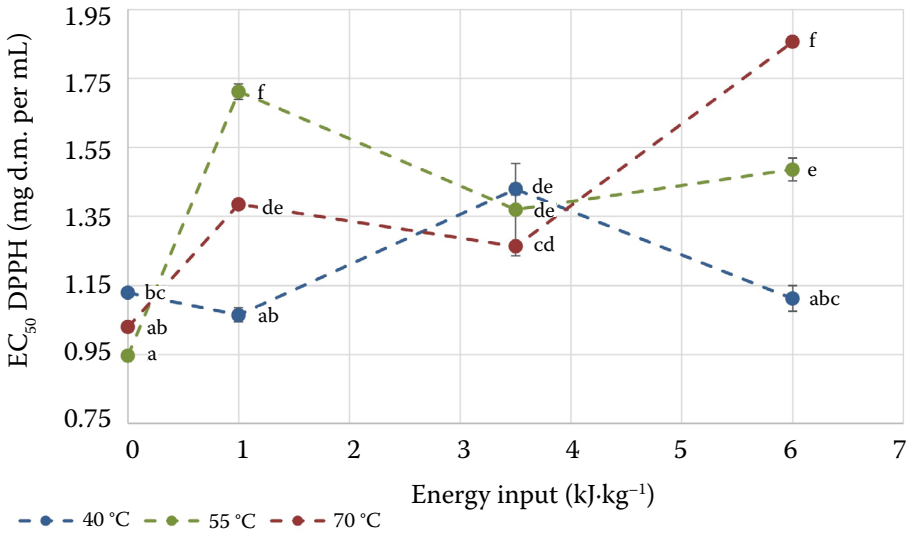

Figure 3. Antioxidant activity of the obtained dried apples

Results are shown as the mean with standard deviation (SD), the different letters indicate statistically significant differences ($P < 0.05$); EC_{50} DPPH – extract concentration necessary for a 50% reduction of the initial amount of the DPPH• radicals

son with the untreated samples, the TPC in the PEF-treated apples decreased by 12–40%. Most probably, these bioactive compounds were more prone to degradation during drying, which would explain the reduced retention obtained in this study. Such a situation can be related to their release from the vacuoles, due to the damage to the structure of the material subjected to the PEF. Such electrically induced liberation of the vacuole content cannot occur in the untreated material. An additional explanation of this theory is related to the polyphenol oxidase activity, which, as demonstrated previously in the literature, remains active even after the PEF treatment (Yu et al. 2017) and also remains active during drying. There was one exception in the results – the samples 40°C_1kJ·kg^{-1} (881.7 mg GAE per 100 g of d.m.) and 40°C_6kJ·kg^{-1} (841.5 mg GAE per 100 g of d.m.), which had a TPC statistically higher by 9% and 4%, respectively, than the sample 40°C_0kJ·kg^{-1} (807.7 mg GAE per 100 g of d.m.). This could have occurred due to the considerable reduction in the drying time (18–22%) that resulted from applying the PEF pre-treatment. Phenolics are sensitive to high temperatures (Deng et al. 2018), so a combination of a mild PEF treatment and low drying temperature may preserve them. The gentle drying caused by electroporation may decrease the materials' temperature and exposure time during the drying and, thus, improve the TPC retention (Lammerskitten et al. 2020). Despite a higher reduction in the drying time of sample 40°C_6kJ·kg^{-1} than of sample 40°C_1kJ·kg^{-1} (Table 1), a TPC higher by 5% was observed in the sample treated with the lower specific energy. The application of a higher energy input during a PEF treatment may degrade the phenolics due to the reactive oxygen species and free radical formation (Teissié et al. 1999).

Figure 3 shows the antioxidant activity of the obtained dried apples, which varied between 0.95–1.86 mg d.m. per mL and differed statistically ($P < 0.05$). For the fresh apple, the EC_{50} was equal to 1.35 ± 0.03 mg d.m. per mililiter. Thus, the raw material exhibited higher values of this index than the majority of the dried apples, which, at the same time, means a lower antioxidant activity. As mentioned above, browning products are formed during drying, which may have antioxidant effects, scavenging free radicals (Dadan et al. 2018). This could explain the better antioxidant activity of the dried apples than that of the fresh material. A negative correlation between the TPC and the EC_{50} was observed ($r = -0.98$), which is consistent with the results obtained by other authors (Wiktor et al. 2015; Sledz et al. 2017; Gąsecka et al. 2018). The higher the TPC and the lower the EC_{50}, the better the antioxidant properties of the dried apples. As in the case of the TPC, the antioxidant activity was lower in the samples pre-treated with the PEF (by 23–81%). Possibly, it happened due to the creation of reactive oxygen species and free radicals during the PEF pre-treatment (Wiktor et al. 2020). However, at the same time, the samples 40°C_1kJ·kg^{-1} (1.06 mg d.m. per mL) and 40°C_6kJ·kg^{-1} (1.11 mg d.m. per mL), which exhibited the highest TPC, had a statistically identical antioxidant activity as the sample 40°C_0kJ·kg^{-1} (1.13 mg d.m. per mL). It may indicate the optimal PEF pre-treatment and vacuum drying parameters for apples, in terms of the better preservation of bioactive compounds.

https://doi.org/10.17221/93/2021-RAE

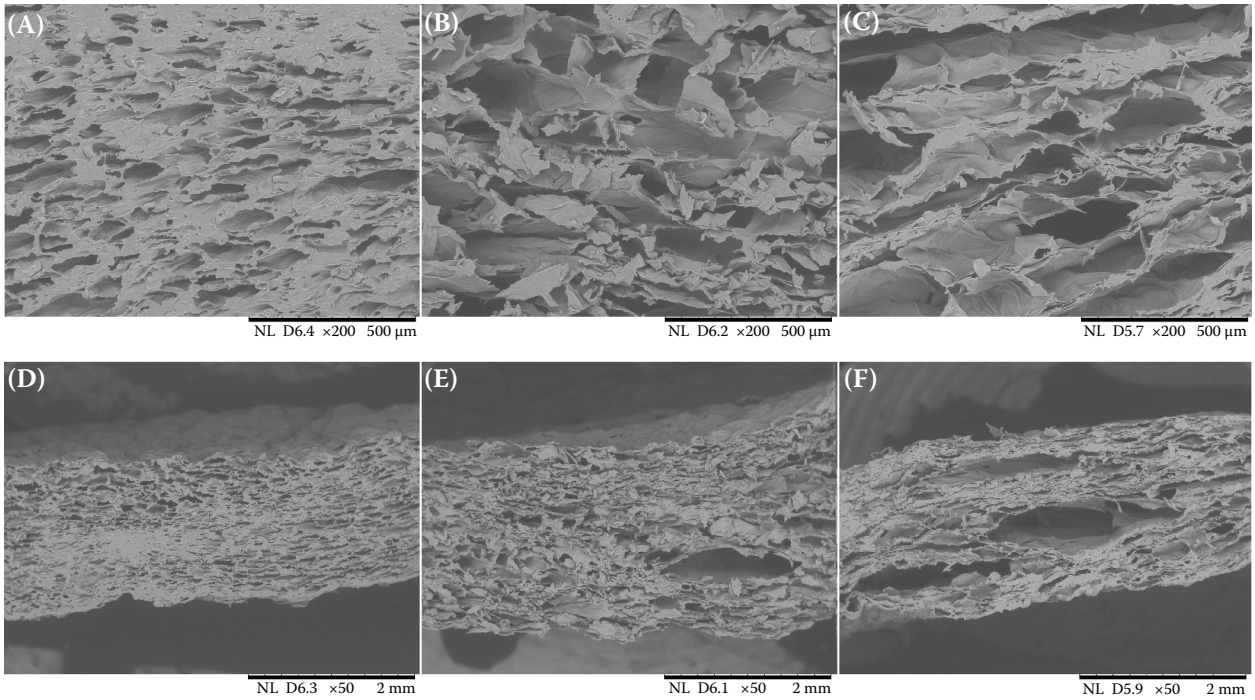

Figure 4. Scanning electron microscope (SEM) images of the vacuum dried untreated and PEF-treated apples

(A–C): magnification 200×; (D–F): magnification 50×; (A, D) – 55°C_0kJ·kg^{-1}; (B, E) – 55°C_1kJ·kg^{-1}; (C, F) – 55°C_6kJ·kg^{-1}

Microstructure. The SEM images of the untreated and PEF-pre-treated dried apples are presented in Figure 4. As is shown, the microstructure of the untreated sample was relatively dense and compact, with minor pores (Figure 4A and 4D). The electroporation caused by the application of the PEF modified the mechanical properties of the tissue (Lebovka et al. 2004b) which, after the water evaporation, contributed to the higher porosity (Figure 4A–C and 4E–F). Another explanation of the more porous structure might be the faster evaporation due to the cell membrane perforation. Due to the high evaporation rate, the water might form channels in the tissue that would increase the porosity of the dried material. Moreover, the higher the amount of supplied energy during the PEF treatment was, the more porous the structure of the dried apples was. These observations are consistent with the data in the study (Wiktor et al. 2016). Electroporation, by creating new or enlarging the already existing pores in the cell membrane of a particular tissue, increases that tissue's permeability (Wiktor et al. 2016). This is undoubtedly a desired effect from the perspective of the extraction process, where the purpose of using a PEF is the enhancement of the extraction rate and increasing the efficiency of this process (Lebovka et al. 2004b; Zhou et al. 2022). In the case of drying, the PEF is mainly applied to accelerate the water removal, but leakage of bioactive ingredients can occur during this type of pretreatment (Wiktor et al. 2020). The drying time of the samples 55°C_1kJ·kg^{-1} and 55°C_6kJ·kg^{-1} was shorter than that for sample 55°C_0kJ·kg^{-1} by 20% and 17%, respectively (Table 1). At the same time, these two samples treated with PEF before vacuum drying exhibited significantly ($P < 0.05$) lower antioxidant activity and TPC than the untreated sample, dried with the same parameters (Figures 2–3). As shown in Figure 4, the samples 55°C_1kJ·kg^{-1} and 55°C_6kJ·kg^{-1} were more porous than sample 55°C_0kJ·kg^{-1}. Thus, the increased porosity, and, hence, permeability, could also lead to leakage of antioxidant components.

CONCLUSION

The results obtained in this study demonstrate that a pulsed electric field can be effectively applied to improve the vacuum drying of apple tissues and to reduce the drying time even by 22% in comparison to the reference material. Due to electroporation, the structure of the material is ruptured, which leads to an increase in the mobility of water and facilitates its removal during drying. There was

https://doi.org/10.17221/93/2021-RAE

no linear relation found between the degree of cell damage and the reduction in the drying time after applying the PEF technology. Additionally, supplying energy at level higher than 1 kJ·kg^{-1} during the PEF pre-treatment did not lead to better results in the analyses of the vacuum-dried apples. This value may constitute the electroporation saturation threshold. PEF, a type of non-thermal pre-treatment, in general, led to decreases in the retention of the total phenolic content and in the antioxidant activity in comparison to the untreated dried materials. It may be associated with releasing enzymes or enzyme reactants from the treated tissue or forming reactive oxygen species and free radicals during the PEF pre-treatment. However, the proper combination of low drying temperature (40 °C) and mild energy input (1 kJ·kg^{-1}) may result in better antioxidant properties. The processing conditions should be selected depending on the final technological aim.

REFERENCES

Agrawal D.C., Menon V.J. (1992): Surface tension and evaporation: An empirical relation for water. Physical Review A, 46: 2166–2169.

Beigi M. (2016): Hot air drying of apple slices: Dehydration characteristics and quality assessment. Heat and Mass Transfer, 52: 1435–1442.

Beitel-White N., Lorenzo M.F., Zhao Y., Brock R.M., Coutermarsh-Ott S., Allen I.C., Manuchehrabadi N., Davalos R.V. (2021): Multi-tissue analysis on the impact of electroporation on electrical and thermal properties. IEEE Transactions on Biomedical Engineering, 68: 771–782.

Brand-Williams W., Cuvelier M.E., Berset C. (1995): Use of a free radical method to evaluate antioxidant activity. LWT – Food Science and Technology, 28: 25–30.

Dadan M., Rybak K., Wiktor A., Nowacka M., Zubernik J., Witrowa-Rajchert D. (2018): Selected chemical composition changes in microwave-convective dried parsley leaves affected by ultrasound and steaming pre-treatments – An optimization approach. Food Chemistry, 239: 242–251.

Delgado J.M.P.Q., da Silva M.V. (2014): Food dehydration: Fundamentals, modelling and applications. In: Delgado J., Barbosa de Lima A. (eds): Transport Phenomena and Drying of Solids and Particulate Materials, vol. 48. Cham, Springer: 69–94.

Deng J., Yang H., Capanoglu E., Cao H., Xiao J. (2018): Technological aspects and stability of polyphenols. In: Galanakis C.M. (ed.): Polyphenols: Properties, Recovery, and Applications. Amsterdam, Woodhead Publishing: 295–323.

Gąsecka M., Siwulski M., Mleczek M. (2018): Evaluation of bioactive compounds content and antioxidant properties of soil-growing and wood-growing edible mushrooms. Journal of Food Processing and Preservation, 42: e13386.

Grimi N., Mamouni F., Lebovka N., Vorobiev E., Vaxelaire J. (2010): Acoustic impulse response in apple tissues treated by pulsed electric field. Biosystems Engineering, 105: 266–272.

Lammerskitten A., Mykhailyk V., Wiktor A., Toepfl S., Nowacka M., Bialik M., Czyżewski J., Witrowa-Rajchert D., Parniakov O. (2019a): Impact of pulsed electric fields on physical properties of freeze-dried apple tissue. Innovative Food Science & Emerging Technologies, 57: 102211.

Lammerskitten A., Wiktor A., Siemer C., Toepfl S., Mykhailyk V., Gondek E., Rybak K., Witrowa-Rajchert D., Parniakov O. (2019b): The effects of pulsed electric fields on the quality parameters of freeze-dried apples. Journal of Food Engineering, 252: 36–43.

Lammerskitten A., Shorstkii I., Parniakov O., Mykhailyk V., Toepfl S., Rybak K., Dadan M., Nowacka M., Wiktor A. (2020): The effect of different methods of mango drying assisted by a pulsed electric field on chemical and physical properties. Journal of Food Processing and Preservation, 44: e14973.

Lebovka N.I., Praporscic I., Vorobiev E. (2004a): Combined treatment of apples by pulsed electric fields and by heating at moderate temperature. Journal of Food Engineering, 65: 211–217.

Lebovka N.I., Praporscic I., Vorobiev E. (2004b): Effect of moderate thermal and pulsed electric field treatments on textural properties of carrots, potatoes and apples. Innovative Food Science & Emerging Technologies, 5: 9–16.

Lebovka N.I., Shynkaryk N.V., Vorobiev E. (2007): Pulsed electric field enhanced drying of potato tissue. Journal of Food Engineering, 78: 606–613.

Liu C., Grimi N., Lebovka N., Vorobiev E. (2018): Effects of pulsed electric fields treatment on vacuum drying of potato tissue. LWT – Food Science and Technology, 95: 289–294.

Liu C., Grimi N., Lebovka N., Vorobiev E. (2019): Convective air, microwave, and combined drying of potato pre-treated by pulsed electric fields. Drying Technology, 37: 1704–1713.

Liu C., Pirozzi A., Ferrari G., Vorobiev E., Grimi N. (2020a): Effects of pulsed electric fields on vacuum drying and quality characteristics of dried carrot. Food and Bioprocess Technology, 13: 45–52.

Liu C., Pirozzi A., Ferrari G., Vorobiev E., Grimi N. (2020b): Impact of pulsed electric fields on vacuum drying kinetics and physicochemical properties of carrot. Food Research International, 137: 109658.

Llavata B., García-Pérez L.V., Simal S., Cárcel J.A. (2020): Innovative pre-treatments to enhance food drying: A current review. Current Opinion in Food Science, 35: 20–26.

https://doi.org/10.17221/93/2021-RAE

Mannozzi C., Cecchini J.P., Tylewicz U., Siroli L., Patrignani F., Lanciotti R., Rocculi P., Dalla Rosa M., Romani S. (2017): Study on the efficacy of edible coatings on quality of blueberry fruits during shelf-life. LWT – Food Science and Technology, 85: 440–444.

Martín-García B., Tylewicz U., Verardo V., Pasini F., Gómez-Caravaca A.M., Caboni M.F., Dalla Rosa M. (2020): Pulsed electric field (PEF) as pre-treatment to improve the phenolic compounds recovery from brewers' spent grains. Innovative Food Science & Emerging Technologies, 64: 102402.

Matys A., Wiktor A., Dadan M., Witrowa-Rajchert D. (2021): Influence of ultrasound and the conditions of convective drying with dehumidified air on the course of the process and selected properties of apple tissue. Foods, 10: 1840.

Nowacka M., Wiktor A., Anuszewska A., Dadan M., Rybak K., Witrowa-Rajchert D. (2019): The application of unconventional technologies as pulsed electric field, ultrasound and microwave-vacuum drying in the production of dried cranberry snacks. Ultrasonics Sonochemistry, 56: 1–13.

Ostermeier R., Parniakov O., Töpfl S., Jäger H. (2020): Applicability of pulsed electric field (PEF) pre-treatment for a convective two-step drying process. Foods, 9: 512.

Ostermeier R., Hill K., Dingis A., Töpfl S., Jäger H. (2021): Influence of pulsed electric field (PEF) and ultrasound treatment on the frying behavior and quality of potato chips. Innovative Food Science & Emerging Technologies, 67: 102553.

Parniakov O., Bals O., Lebovka N., Vorobiev E. (2016): Pulsed electric field assisted vacuum freeze-drying of apple tissue. Innovative Food Science & Emerging Technologies, 35: 52–57.

Piotrowski D., Lenart A., Borkowska O. (2007): Temperature changes during vacuum drying of defrosted and osmotically dehydrated strawberries. Polish Journal of Food and Nutrition Sciences, 57: 141–146.

Sacilik K., Elicin A.K. (2006): The thin layer drying characteristics of organic apple slices. Journal of Food Engineering, 73: 281–289.

Schultz E.L., Mazzuco M.M., Machado R.A.F., Bolzan A., Quadri M.B., Quadri M.G.N. (2007): Effect of pre-treatments on drying, density and shrinkage of apple slices. Journal of Food Engineering, 78: 1103–1110.

Shorstkii I., Sosnin M., Smetana S., Toepfl S., Parniakov O., Wiktor A. (2022): Correlation of the cell disintegration index with Luikov's heat and mass transfer parameters for drying of pulsed electric field (PEF) pretreated plant materials. Journal of Food Engineering, 316: 110822.

Singleton V.L., Orthofer R., Lamuela-Raventós R.M. (1999): Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. Methods in Enzymology, 299: 152–178.

Sledz M., Wiktor A., Nowacka M., Witrowa-Rajchert D. (2017): Drying kinetics, microstructure and antioxidant properties of basil treated by ultrasound. Journal of Food Process Engineering, 40: e12271.

Teissié J., Eynard N., Gabriel B., Rols M.P. (1999): Electropermeabilization of cell membranes. Advanced Drug Delivery Reviews, 35: 3–19.

Telfser A., Galindo F.G. (2019): Effect of reversible permeabilization in combination with different drying methods on the structure and sensorial quality of dried basil (*Ocimum basilicum* L.) leaves. LWT – Food Science and Technology, 99: 148–155.

Wiktor A., Iwaniuk M., Śledź M., Nowacka M., Chudoba T., Witrowa-Rajchert D. (2013): Drying kinetics of apple tissue treated by pulsed electric field. Drying technology, 31: 112–119.

Wiktor A., Sledz M., Nowacka M., Rybak K., Chudoba T., Lojkowski W., Witrowa-Rajchert D. (2015): The impact of pulsed electric field treatment on selected bioactive compound content and color of plant tissue. Innovative Food Science & Emerging Technologies, 30: 69–78.

Wiktor A., Nowacka M., Dadan M., Rybak K., Lojkowski W., Chudoba T., Witrowa-Rajchert D. (2016): The effect of pulsed electric field on drying kinetics, color, and microstructure of carrot. Drying Technology, 34: 1286–1296.

Wiktor A., Gondek E., Jakubczyk E., Dadan M., Nowacka M., Rybak K., Witrowa-Rajchert D. (2018): Acoustic and mechanical properties of carrot tissue treated by pulsed electric field, ultrasound and combination of both. Journal of Food Engineering, 238: 12–21.

Wiktor A., Pratap-Singh A., Parniakov O., Mykhailyk V., Mandal R., Witrowa-Rajchert D. (2020): PEF as an alternative tool to prevent thermolabile compound degradation during dehydration processes. In: Barba F., Parniakov O., Wiktor A. (eds): Pulsed Electric Fields to Obtain Healthier and Sustainable Food for Tomorrow. Waltham, Academic Press: 155–202.

Yu Y., Jin T.Z., Xiao G. (2017): Effects of pulsed electric fields pretreatment and drying method on drying characteristics and nutritive quality of blueberries. Journal of Food Processing and Preservation, 41: e13303.

Zhou J., Wang M., Berrada H., Zhu Z., Grimi N., Barba F.J. (2022): Pulsed electric fields (PEF), pressurized liquid extraction (PLE) and combined PEF+ PLE process evaluation: Effects on *Spirulina* microstructure, biomolecules recovery and Triple TOF-LC-MS-MS polyphenol composition. Innovative Food Science & Emerging Technologies, 77: 102989.

Received: December 12, 2022
Accepted: May 12, 2022
Published online: June 7, 2022