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Effects of pulsed electric fields and preliminary vacuum drying on freezing assisted processes in potato tissue

Caiyun Liu^{1,2}, Nabil Grimi², Olivier Bals², Nikolai Lebovka^{2,3*}, Eugene Vorobiev²

¹*School of Medical Instrument and Food Engineering, University of Shanghai for Science and Technology, Shanghai 200093, P.R. China*

²*Sorbonne Universités, Université de Technologie de Compiègne, Laboratoire de Transformations Intégrées de la Matière Renouvelable, EA 4297, Centre de Recherches de Royallieu, BP 20529, 60205 Compiègne Cedex, France*

³*Institute of Biocolloidal Chemistry named after F. D. Ovcharenko, NAS of Ukraine, 42, blvr. Vernadskogo, Kyiv 03142, Ukraine*

Contact information about Corresponding Author:

Prof. N. Lebovka

Université de Technologie de Compiègne,

Laboratoire de Transformations Intégrées de la Matière Renouvelable, EA 4297, Centre
de Recherches de Royallieu, BP 20529, 60205 Compiègne Cedex, France

E-mail address: lebovka@gmail.com

*Corresponding author.

E-mail address: lebovka@gmail.com (Nikolai Lebovka).

ABSTRACT

The effects of pulsed electric field (PEF) treatment and preliminary vacuum drying (VD) on freezing assisted processes for the potato tissue were studied. The PEF treatment was done at 600 V/cm using the protocol to insure the high level of potato disintegration. The VD was done at sub-atmospheric pressure of $p=0.30$ bar. Such conditions allowed relatively fast dehydration accelerated by PEF treatment at low or moderate temperatures inside sample ($<50^{\circ}\text{C}$). Impacts of PEF and VD on freeze-thawing (FT) and freeze-drying (FD) processes were tested. The duration of the freezing and thawing processes noticeably increased with increasing of the moisture ratio. The PEF treatment also accelerated the FD and affected the final level of dehydration after prolonged FD for 24 h. It was demonstrated that application of VD and VD combined with FT deteriorated the rehydration, whereas VD combined with FD facilitated the rehydration of deeply dried potato tissue. The obtained regularities can be useful in future practical implementations of freezing assisted processes with fine control of deterioration of product quality and reduced operating and maintenance costs.

Keywords:

Pulsed electric fields

Vacuum drying

Freeze-thawing

Freeze-drying

Rehydration

Potato

Nomenclature

E	electric field strength, V/cm
m	mass of a sample, g
MR_f	final moisture ratio
MR_{FD}	moisture ratio in freeze drying
MR_v	moisture ratio in vacuum-drying
n	number of pulses
N	number of trains
t	time, s
t_f	time of frying, s
t_i	pulse duration, μ s
t_{PEF}	time of PEF treatment, s
T	temperature inside sample, $^{\circ}$ C
T_{VD}	temperature in vacuum chamber, $^{\circ}$ C
Δt	interval between pulses, ms
W_i	initial moisture content, db
W_f	moisture contents after frying, db

Abbreviations

db	dry basis (g water/g solid)
FD	freeze-drying
FT	freeze–thawing
PEF	pulsed electric fields
VD	vacuum drying
wb	wet basis (g water/g sample)

1. Introduction

The processing of foods at sub-zero temperatures is widely used to preserve products quality and avoid important deterioration of their original colour, flavour and texture (Zaritzky, 2006). To preserve a product quality and irreversible damages at cellular level one should avoid formation of large ice crystals inside the foods. The mechanisms of ice formation in cells and plant tissues were extensively discussed (Pearce, 2001; Reid, 1997). Freezing in foods can be significantly influenced by preliminary dehydration (dehydro-freezing) when using osmotic (Dermesonlouoglou et al., 2016; Shete et al., 2018) air-drying (Zhang et al., 2017), and vacuum-drying procedures (Reis, 2014). The semi-dried foods with reduced moisture content demonstrate extended shelf life and reduced tissue damage is observed in frozen products (James et al., 2014). Preliminary osmotic dehydration and further dehydration by air- and freeze-drying also allowed improving characteristics of dried products (Sette et al., 2016).

Different emerging techniques based on application of ultrasound, microwaves, radiofrequencies, pressure, high voltage electric fields and pulsed electric fields (PEF) were tested to assist food freezing (Cheng et al., 2017). In recent time the PEF treatment has attracted great attention for processing of foods with preservation of fresh like quality (Puértolas and Barba, 2016; Vorobiev and Lebovka, 2020). Particularly, the significant effects of PEF treatment on acceleration of mass transfer processes in food were reported (Semenoglou et al., 2020). Moreover, the PEF assisted processing is minimal as it allows removing the membrane barriers by electroporation mechanism (Tylewicz, 2020).

In general, processing of foods at sub-zero temperatures assisted by hybrid techniques that combine PEF treatment and partial dehydration of foods seems to be promising. In previous studies the effects of PEF on different processes at sub-zero temperatures have been extensively studied (Ben Ammar et al., 2010b; Dadan et al., 2020; Jalte et al., 2009; Parniakov et al., 2016a, 2016c, 2015). For example, the effects of PEF pre-treatment on the freezing, freeze-drying and rehydration behaviour of potato tissue were reported (Jalte et al., 2009). It was demonstrated that removing the membrane barriers accelerates diffusion exchange between extracellular and intracellular (cytoplasm solution) environments, which can critically affect the potato tissue structure and crystallization behaviour. For PEF treated materials the noticeable decreasing of freeze-drying time at sub-zero temperature was observed. Moreover, PEF treated and dried potato samples had more uniform shape, smaller shrinkage, less modified colour, and visually better quality. The similar effects of PEF treatment on freezing behaviour were reported for other types of vegetable tissues: onions, leafy vegetable (spinach), and vegetable stem (green beans) (Ammar et al., 2011, 2009). The effects of combined PEF treatment and osmotic dehydration (in

salted water) on potato structure, as well as on freezing and freeze-drying behaviours were also investigated (Ben Ammar et al., 2010a). The data evidenced that preliminary PEF or PEF + osmotic treatment resulted in a noticeable acceleration of freeze-drying kinetics and better product quality. The mechanisms of freezing/thawing of apple tissue assisted by PEF and osmotic treatment in glycerol solutions were studied (Parniakov et al., 2016a, 2016c, 2015). The freeze-thawing (FT) experiments revealed pronounced reducing of both freezing and thawing duration and strengthening of the apple texture for PEF treated samples. With optimal parameters of osmotic treatment, the apple texture after defrosting was comparable to that of fresh apples. The impacts of PEF and other non-thermal treatments on freezing progress and the quality of food were recently compared (Dadan et al., 2020).

Preliminary dehydration by vacuum-drying (VD) can be rather effective for assistance of products freezing (James et al., 2014; Reis, 2014). Effects of PEF on vacuum cooling, freezing and drying of apple tissue have been studied (Parniakov et al., 2016b). In this work the pressure in the chamber was maintained at $P=10$ mbar. At such condition the temperature of the sample rapidly decreased (in few minutes) below ≈ 0 °C, that corresponds to the start of a freezing. The dehydration of the sample was observed at sub-zero temperatures. For PEF treated samples, the more important decrease of the temperature was observed and the heat and mass transfer processes were noticeably accelerated. The PEF treatment allowed preservation of the shape of the dried samples and avoiding of shrinkage. Recently it was demonstrated that PEF treatment can significantly affect vacuum drying of potato tissue at sub-atmospheric pressure, $p=0.30$ bar (that corresponds to the boiling temperature of water ≈ 70 °C) (Liu et al., 2018). It allowed decreasing the drying time, and dehydration at low and moderate temperatures (below 60°C) inside samples. The benefits of drying of fruits and vegetables at low and moderate temperatures include possibility of preservation of food colorants (Shynkaryk et al., 2008) and obtaining high quality dried products (colour, nutrient content, taste, etc.) (Menon et al., 2020). It has been demonstrated that PEF treatment cause changes in potato cell viability, and leakage of ionic species (Oey et al., 2016). Moreover, PEF treatment significantly improved the VD of potato tissue and allowed avoiding of starch gelatinizing during the drying (Liu et al., 2018). The noticeable effects of PEF on texture and microstructure of dried potato tissue were also revealed.

In general, the potato was frequently used in previous works as model tissue for testing of different PEF effects (Vorobiev and Lebovka, 2020) and studies of PEF assisted freezing can be useful for developments of practical strategies for freezing of potato (Cheng et al., 2017). However, the combined effects of PEF treatment and partial dehydration by VD at moderate temperatures on freeze-thawing and freeze-drying behaviours of foods were never studied before.

This work is devoted to study the effects of treatment by PEF and preliminary VD on freezing assisted processes for potato tissue. The potato samples were initially PEF treated at conditions to insure the high level of tissue electroporation with large disintegration degree (Liu et al., 2019). Removing of membrane barriers by PEF allowed significant acceleration of drying. PEF treated samples were then dehydrated by VD at relatively high pressure of 0.3 bar and moderate temperatures inside samples below 50 °C. Partially dehydrated potato samples were tested using different freeze-thawing (FT) and freeze-drying (FD) procedures. Finally, The samples were analyzed by textural relaxation and rehydration tests.

2. Materials and methods

2.1. Materials

Commercial potatoes (*CAESAR*) were purchased in a local supermarket (Compiègne, France) and placed in a refrigerator at ≈ 7 °C. The studied samples were prepared in the form of disk ($d=25$ mm diameter and $h=5$ mm thickness). The cell structure of the parenchyma of potato tissue is not homogenous (Konstankiewicz et al., 2002) and the samples from the inner core were taken. The moisture content of samples was 80–82% that was determined by drying of samples at 105 °C in the convection oven (UL50, Memmert, Germany).

2.2. Preliminary and freezing procedures

The samples were preliminary PEF treated at conditions to insure the high level of tissue electroporation with large disintegration degree (Liu et al., 2019) and then dehydrated using VD (VD samples). The applied dehydration was performed at moderate temperatures inside samples (below 50 °C). Then freezing-thawing (FT) or freeze-drying (FD) procedures were applied (Fig. 1).

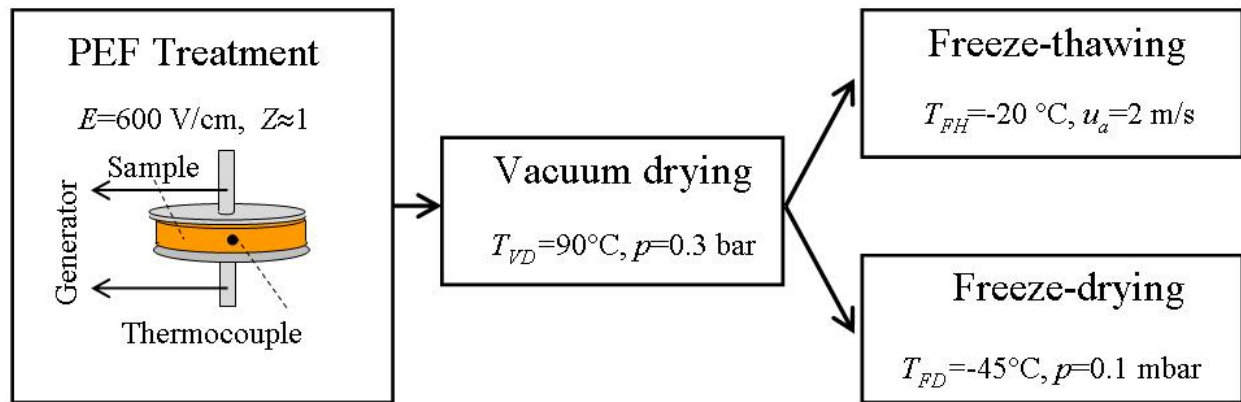


Fig. 1. - Treatment procedures applied to the potato tissue.

The combined VD and FT or VD and FD procedures are designated as VD + FT or VD + FD, respectively. The control samples without PEF treatment (untreated samples, U) and without VD were used to evaluate the individual effects of PEF or VD on freezing processes. The summary of the experimental conditions are presented in Table S1 (Supplementary materials).

2.2.1. PEF treatment

The PEF generator (1500V-20A, Service Electronique UTC, France) was used in experiments. The sample was placed between bottom and upper electrodes in the Teflon cylindrical tube and covered with fresh potato juice in order to reduce the sample degradation and to improve electrical contact between the electrodes and the sample. The electric field strength was $E=600$ V/cm and the monopolar pulses with duration of $t_i=100$ μ s, and distance between them of $\Delta t_i=10$ ms were used. The treatment was applied in the series of $N=10$ trains with pause between them of $\Delta t=10$ s. Each train consisted of $n=100$ pulses. The total PEF duration was $t_{PEF} = 100$ ms. The applied protocol allowed obtaining the high level of potato electroporation with disintegration index close to 1 ($Z \approx 1$) (Ben Ammar et al., 2011a; Boussetta et al., 2013).

2.2.2. Vacuum drying

The VD was done using vacuum oven (Cole-Parmer, 2.3 cuft, 120 VAC, USA) connected with a vacuum pump (Werie, Rietschle, RTV1, Germany). The VD was performed at temperature in the oven of $T_{VD}=90^\circ\text{C}$ and sub-atmospheric pressure of $p=0.30$ bar that corresponds to the boiling temperature of water $\approx 70^\circ\text{C}$. It allowed decreasing the drying time, and processing at relatively low temperatures inside the samples. Running mass of the sample, m , during the VD was recorded at 5 s intervals using digital balance (KERN, PCB-3, Germany). The moisture ratio of the sample during vacuum drying was calculated as

$$MR_v = (m - m_t) / (m_i - m_t) \quad (1)$$

where m , m_i and m_t are the actual, initial (before VD), and terminal (completely dried sample) masses of the sample, respectively.

The terminal mass of the sample, m_t , was determined using the drying for 24 h at 105°C in the convection oven (UL50, MEMMERT, Germany). The level of $MR_v=1$ corresponds to the samples without VD ($m=m_i$).

2.2.3. Freeze-thawing

In the FT experiments, the samples were frozen using the air-blast freezer (Sanyo, Gunma, Japan). The air velocity ($u_a=2$ m/s) was controlled by an electronic device VEAT 2.5 A (Airtechnic, Firminy, France). The temperature inside the freezer was -45°C . The temperature inside the geometrical center of the sample, T , was recorded at 1 s intervals using a Fuji electric systems thermocouple (PHL11B12-E10YV-F, Japan). Initial temperature of the samples before freezing was $20^{\circ}\text{C}\pm 1$. After the samples cooling up to the temperature of $T_{FH}\approx 20^{\circ}\text{C}$, they were thawed using the airflow at room temperature ($20^{\circ}\text{C}\pm 1$) and velocity of $u_a=2$ m/s. The duration of freezing, Δt_f , and thawing, Δt_t , were determined by approximating the linear parts of the temperature $T(t)$ dependencies during FT (see, Fig. S2 in Supplementary materials). The time of sample cooling up to the temperature -20°C , t_c , was also determined (Fig. S2).

2.2.4. Freeze-drying

In the FD experiments, the samples were initially frozen up to the temperature of $T_{FD}\approx -45^{\circ}\text{C}$ using the same air-blast freezer as in the freeze-thawing experiments. Then samples were loaded onto a pre-cooled plateau at -20°C placed in a pilot freeze-drier (Cryotec, France). The pressure in the chamber was maintained at $p=0.1$ mbar. The weight of the samples during freeze-drying was controlled using a balance (KERN, PCB-3, Germany) inserted inside freeze-drier. The preliminary control experiments with calibrated mass were performed to insure the precision of mass measurements. The moisture ratio of the sample during freeze-drying was calculated as

$$MR_f=(m-m_i)/(m_i-m_t) \quad (2)$$

where m , m_i and m_t are the actual, initial (after VD dehydration) and terminal (completely dried sample) masses of the sample, respectively. Note, that before FD dehydration, $MR_f=MR_v$.

2.3. Analyses

2.3.1. Force relaxation test

The force relaxation tests were done using a texture analyzer TA-XT plus (Rhéo, Champlan, France). Pre-loading with 15% deformation was applied to compensate the non-uniformity of the sample structure. The force was set at the level of 5 N, the speed of piston displacement was 1.0 mm/s and stress relaxation curves were recorded with 0.1s resolution during 100 s. The force relaxation curves $F(t)$ were measure for untreated and PEF-treated samples using VD and VD+FT procedures (see, Fig. S3 in Supplementary materials). The textural relaxation disintegration index was defined as (Castagnini et al., 2020; Vorobiev and Lebovka, 2020)

$$Z_i = (F_i - F) / (F_i - F_d) \quad (3)$$

where F , F_i and F_d are the relaxation forces of tested, intact, and FT samples determined at the relatively long relaxation time ($t=100$ s).

2.3.2. Rehydration

The dried samples were rehydrated in distilled water at 25°C. The agitation was applied using C-MAG HS 7 S000 (IKA, France). During the rehydration the samples were taken out of water, drained, gently blotted with adsorbent paper, and then weighted using the balance (KERN, PCB-3, Germany). The rehydration ratio was defined as:

$$R = m / m_i \quad (4)$$

where m_i is the initial mass of fresh sample before VD, and m is the mass of sample after rehydration. The value of $R=1$ corresponds to the complete rehydration of sample up the level of fresh tissue.

2.4. Statistical analysis

All experiments were replicated 5 times. Data are expressed as mean \pm standard deviation. Comparisons between means were conducted using statistical analysis of variance (ANOVA) in conjunction with Tukey's post-hoc test at a significance level of $p < 0.05$ using software SPSS Statistics 19.0. The error bars in all figures correspond to the standard deviations.

3. Results and discussion

3.1. Freeze-thawing

This part discusses the combined assistance of freeze-thawing with preliminary applications of PEF treatment and VD dehydration. Preliminary investigations have shown that PEF treatment resulted in noticeable acceleration of VD (see, Fig. S1, Supplementary materials). Moreover, the temperature inside samples, T , was lower for PEF treated samples as compare with untreated ones (Fig. S1). The effects were in correspondence with previously reported data (Liu et al., 2018). For VD experiments with moisture ratio MR_v within the range 0.2-1.0, the temperature inside samples never exceeded 50°C (Fig.S1). In all experiments the final moisture ratio was $MR_v=0.2$.

Figure 2 shows the temperature T at the geometrical center of the sample versus the time, t , during the FT of untreated (solid lines) and PEF-treated (dashed lines) samples with moisture ratio $MR_v= 1.0$ (Fig. 2a, non-dehydrated samples) and $MR_v= 0.5$ and $MR_v= 0.2$ (Fig. 2b, samples dehydrated by VD).

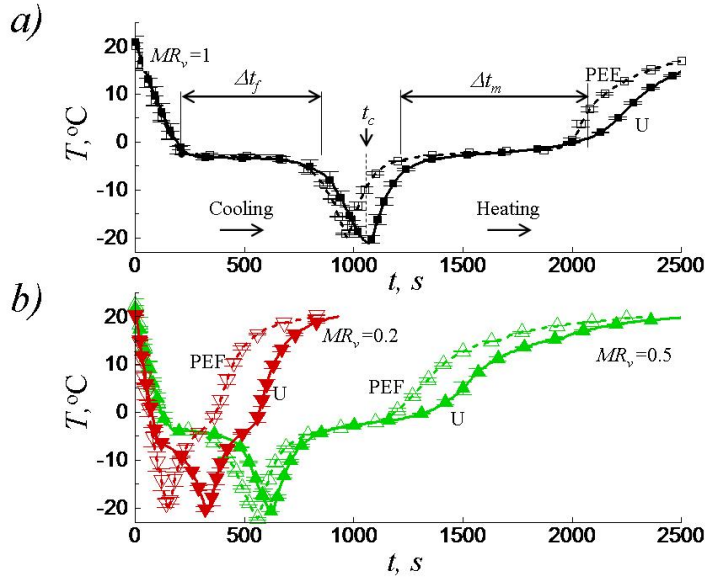


Fig. 2. - Temperature at the geometrical center of the sample, T , versus the time, t , during the FT for untreated (U, without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples with moisture ratio $MR_v= 1.0$ (a, non-dehydrated samples) and $MR_v= 0.5$ and $MR_v= 0.2$ (b, samples dehydrated by VD). Here, Δt_f and Δt_m are the duration of freezing and melting, respectively, and t_c , is the cooling time up to the temperature ≈ -20 °C.

Freezing process includes stages of the preliminary cooling, crystallization and final cooling (Zaritzky, 2006). In the crystallization stage the transformation of water into the ice occurred. During this stage, the temperature remains approximately constant. The thawing process also includes the similar stages of the preliminary heating, melting (with nearly constant temperature) and final heating. For non-dehydrated samples the untreated and PEF treated potatoes froze approximately at the same temperature $T_f \approx -3$ °C (Fig. 2a). Therefore, at $MR_v=1.0$, the PEF treatment practically unaffected the value of T_f . However, PEF treatment noticeably accelerated freezing processes. The obtained results were in full correspondence with previously reported data on effect of PEF treatment on freezing of potato (Jalte et al., 2009). The mechanism of the effect of PEF on crystallization has been recently discussed (Vorobiev and Lebovka, 2020). It includes creation of membrane residues that serve as fresh nucleation sites and removing of membrane barriers can accelerate the exchange between extracellular and intracellular (cytoplasm solution).

Moreover, the preliminary VD dehydration also significantly affected the FT curves (Fig. 2b). The decrease in value of MR_v resulted in significant decrease of the cooling time t_c . Moreover, below some critical level of MR_v (for example $MR_v \approx 0.2$ for PEF sample), the crystallization/melting stages were practically suppressed. The observed effects can reflect

morphological changes and proportions of water in different cellular environments (intracellular and intercellular spaces, and cell walls) in tissue during the preliminary dehydration (Khan et al., 2017).

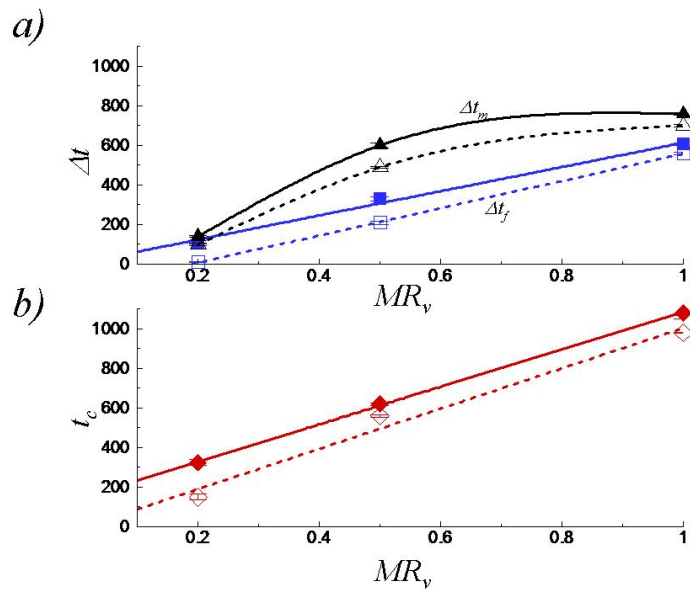


Fig. 3. - The freezing Δt_f , thawing Δt_t (a) and cooling time t_c (b) versus the VD moisture ratio, MR_v , for untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples obtained using VD+FT procedure. The lines are to guide the eye.

The duration of freezing Δt_f and melting Δt_t (Fig. 3a), as well as the cooling time t_c (Fig. 3b) noticeably increased with increasing of MR_v . At given MR_v , the PEF treatment resulted in decrease the values of Δt_f , Δt_t , and t_c . Typically, the VD dehydration requires high-energy consumption (Reis, 2014) and therefore, the combination of PEF treatment with VD can be effective tool for assistance of freezing.

Figure 4 shows the effect of FT processes on the textural relaxation disintegration index, Z_t , for untreated and PEF treated samples at different levels of VD moisture ratio, MR_v . For VD dehydrated samples without FT the texture of PEF untreated sample became significantly disintegrated with decreasing of increasing of MR_v , moreover, the $Z_t(MR_v)$ curve shown the distinct maximum at $MR_v \approx 0.5$. However, for PEF treated samples the changes in Z_t were rather insignificant in whole range of $MR_v = 0.2-1.0$. For combined VD dehydration procedure followed by FT (VD + FT procedure) the texture became stronger with decreasing of MR_v . It can be explained by the following argument. The preliminary VD can prevent formation of large crystals and reduce the damage of tissue. It resulted in improving the textural characteristics of the final tissue after the freezing-thawing procedure (James et al., 2014). However, in both cases

of VD without FT and VD followed by FT the textural changes for PEF treated samples were more significant than for untreated ones.

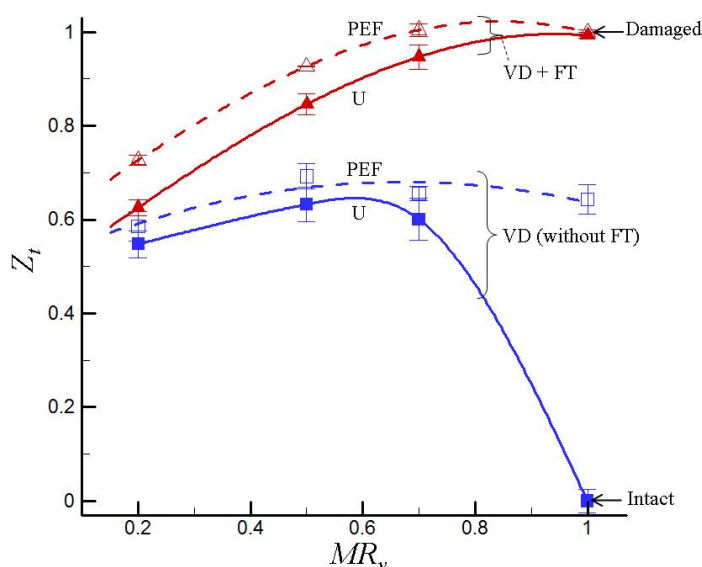


Fig. 4. - Textural relaxation disintegration index, Z_t , versus the VD moisture ratio, MR_v , for untreated (U, without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples obtained using VD and VD + FT procedures. The lines are to guide the eye.

3.2. Freeze-drying

In lyophilisation procedure, the sample was frozen before freeze-drying (FD). Then ice was sublimated directly into the vapour phase (at temperature below the melting point and sub-atmospheric pressure) (Bhatta, Stevanovic Janezic, & Ratti, 2020; Donsi, Ferrari, & Matteo, 2001; Ratti, 2008). The FD includes initial freezing, primary drying stage (sublimation), and secondary drying stage (desorption). In principle, FD allows better retention of morphological and biochemical properties of bioactive compounds, and better retention of structure of products. However, FD is a very time consuming and it is considered as the most expensive process owing to the high operating and maintenance costs (Liu et al., 2008).

Nowadays, the process intensification by additional treatment prior to freeze-drying is considered as key approach to overcome the limitations the FD technique. The preliminary combined treatment by PEF and VD dehydration allows regulation the water content inside product before FD.

Figure 5 shows the moisture ratio, MR_f , during the freeze-drying process versus the, t , (a) for untreated (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples at different moisture contents obtained after preliminary VD, $MR_v = 1.0$ and $=0.7$ (a) and

$MR_v=0.5$ and $=0.2$ (b). Both PEF treatment and dehydration by VD significantly affected the FD processes. The freeze-drying rate, V_f , (see Fig. S4 in Supplementary materials) continuously decreased with decreasing of MR_v and the constant rate periods ($V_f = -dMR_f/dt = \text{const}$) (Carrín and Crapiste, 2009) were not detected. The PEF treatment accelerated the FD process at different values of MR_v , but the most significant acceleration was observed at high initial moisture ratio $MR_v=1.0$ and $MR_v=0.7$ (Fig. 5a).

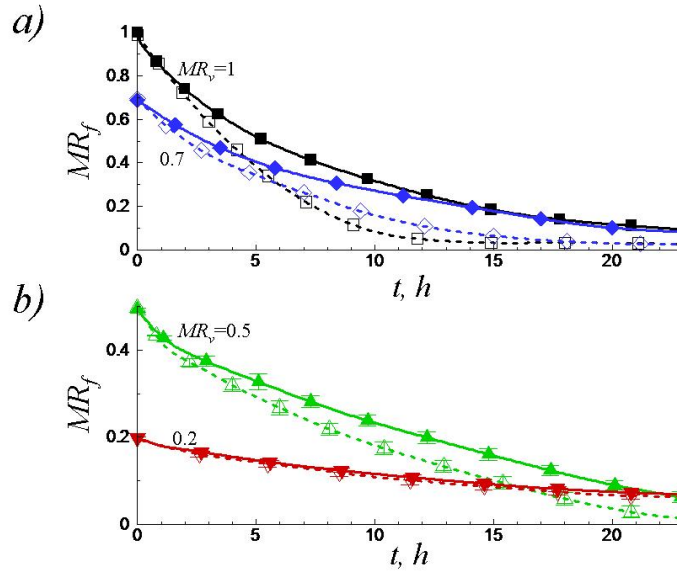


Fig. 5. - Moisture ratio, MR_f , during the freeze-drying process versus the time, t . The data are presented for untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples with different moisture content after preliminary VD, $MR_v=1.0$ and $=0.7$ (a) and $MR_v=0.5$ and $=0.2$ (b).

Below some critical moisture ratio of order of $MR_v \approx 0.1$ the second falling rate period with very slow drying rate $V_f < 10^{-2} \text{ h}^{-1}$ became apparent (Fig. S4). This stage corresponds to the drying of the bound water in an unfrozen state (Vega-Mercado et al., 2001).

Figure 6 presents the freeze-drying time, $t_{0.1}$, required to achieve the critical moisture ratio $MR_v=0.1$ at different moisture contents obtained after preliminary VD, MR_v , for untreated and PEF treated samples. Note, that both the PEF treatment and preliminary dehydration by VD significantly affected the value of $t_{0.1}$. The smallest value of $t_{0.1} \approx 9.5$ was observed for PEF treated sample without VD dehydration ($MR_v=1$). At relatively small level of VD dehydration ($MR_v \geq 0.5$) the increase in dehydration resulted in decrease of $t_{0.1}$ for untreated samples and the opposite tendency was observed for PEF treated samples (i.e., $t_{0.1}$ increased with decrease of MR_v).

The reason of such striking behavior is unclear. It can be speculated that preliminary VD dehydration of untreated and PEF treated tissue differently affects the spatial distributions of

residual water inside samples and influences the formation extracellular and intracellular ice crystals with different sublimation rates (Bhatta et al., 2020). Moreover, both the PEF treatment and preliminary dehydration by VD significantly affected the moisture contents of samples after prolonged FD for 24 h, MR_f (Fig. S5 in Supplementary material).

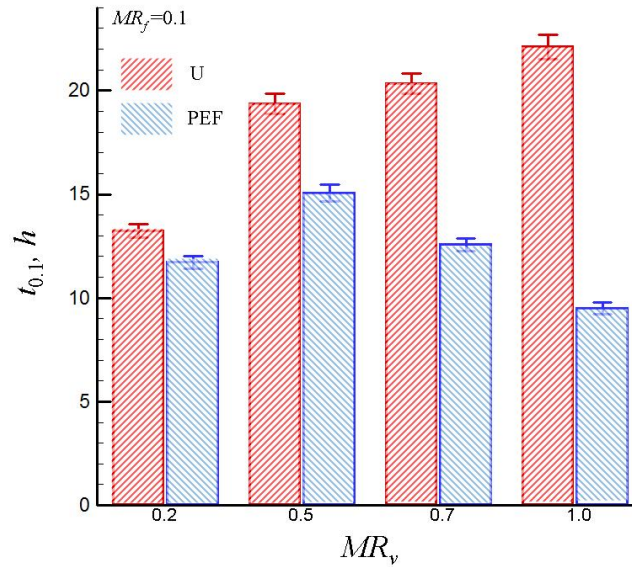


Fig. 6. - Freeze-drying time, $t_{0.1}$, required to achieve the critical moisture ratio $MR_f=0.1$ at different moisture contents obtained after preliminary VD, MR_v , for untreated (U, without PEF treatment) and PEF treated samples.

For example, at $MR_v=1.0$ (i.e., for absence of preliminary VD dehydration) the values of $MR_f \approx 0.095$ and $MR_f \approx 0.022$ were obtained for untreated and PEF treated samples, respectively. However, for strongly dehydrated samples (at $MR_v=0.2$) the final moisture ratios, MR_f , for untreated and PEF treated samples were nearly the same, $MR_f \approx 0.07$ (Fig. S4). Therefore, the highest level of dehydration ($MR_v=0.2$) can be obtained using only PEF-assisted FD without application of preliminary VD dehydration.

3.3. Rehydration capacity

Rehydration is aimed at the restoration of tissue property during the contact of dried material with water. The rehydration ratio, R , (Eq (4)) is important quality characteristic of the dried product (Xu et al., 2020). The kinetics rehydration of dried product can be approximately described using the Lucas–Washburn equation that predicts the linear increase of water uptake with increase of square root of time, \sqrt{t} (Saguy et al., 2005).

Figure 7 shows examples of rehydration kinetics of untreated (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary

dehydrated by VD ($MR_v=0.5$) and then the procedures of freeze-thawing (VD + FT) or freeze-drying for 24 h (VD + FD) were applied.

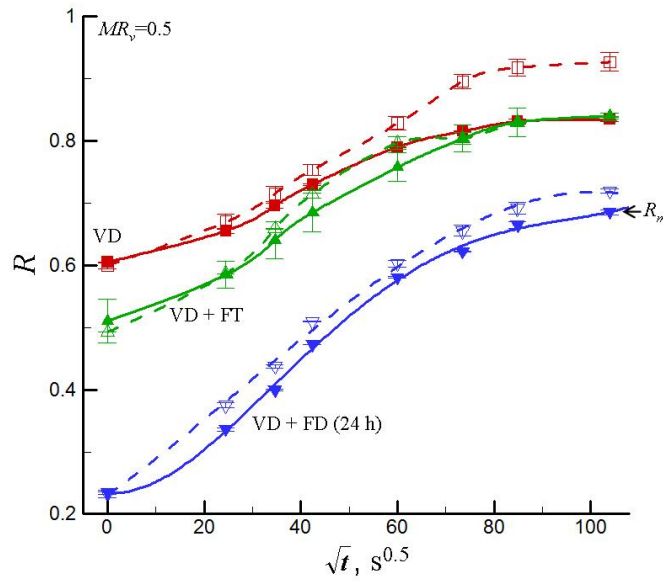


Fig. 7. - Examples of rehydration kinetics of untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD ($MR_v=0.5$) and then the procedures of freeze-thawing (VD + FT) or freeze-drying for 24 h (VD + FD) were applied. The saturation value R_m , measured at $t \approx 3$ h, approximately corresponds to the maximum rehydration capacity. The lines are to guide the eye.

The rehydration of the dried tissue initially involved a high water uptake rate followed by a decreased rate. The saturation value R_m , measured at $t \approx 3$ h, approximately corresponds to the maximum rehydration capacity. The similar $R(\sqrt{t})$ dependencies were also observed for other studied values of MR_v within the range between 0.2 and 1.0 (see Fig. S6a in Supplementary materials). For relatively long time of rehydration ($t > 3$ hours), the value of R saturated at the some maximum level of R_m (Fig. 7).

The value R_m can be used for characterization of the rehydration capacity (Xu et al., 2020). Figure 8 shows rehydration capacity, R_m , versus the VD moisture ratio, MR_v , for untreated (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples obtained using VD, VD+FT and VD+FD (24 h) procedures. For VD and VD + FT samples, the value of R_f increased with increasing of MR_v . and the opposite behaviour was observed for VD + FD (24 h) samples.

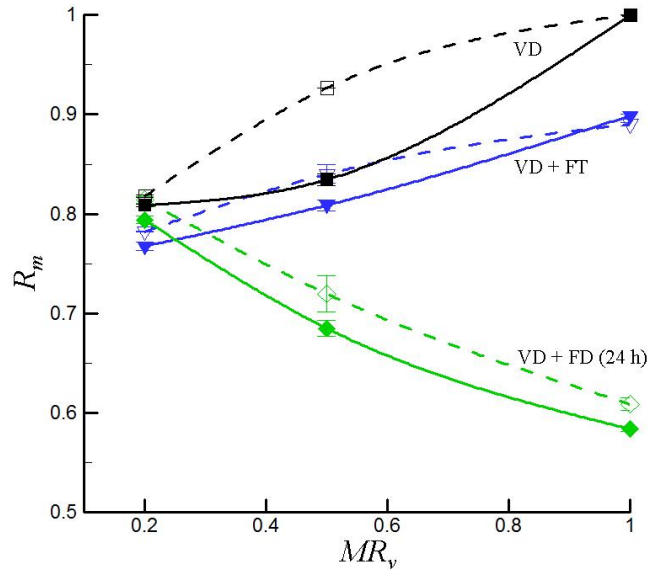


Fig. 8. - Maximum rehydration capacity, R_m , versus the moisture ratio after preliminary VD, MR_v , for untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. Here, the data for samples obtained after VD + FT and VD + FD (24 h) procedures are also presented. The lines are to guide the eye.

The deterioration of rehydration capacity for VD or VD combined with FT (VD + FT) procedures can reflect possible negative changes in shrinkage, porosity and hydrophilic properties of the potato tissue related with induced damages in the material (Krokida and Maroulis, 2000). The application of VD dehydration followed by freezing drying for 24 h in VD + FD (24 h) procedure produced the samples with rather low rehydration capacity as compared with that for VD and VD + FT procedures. Evidently, it reflected significantly smaller moisture contents and porosity in VD + FD (24 h) samples ($MR_f \approx 0.07-0.095$ and $MR_f \approx 0.022-0.07$ for untreated and PEF treated samples (see, Fig.S6b in Supplementary material). However, preliminary VD facilitated the rehydration capacity of VD + FD (24 h) samples and at $MR_v = 0.2$ approximately the same values of $R_m \approx 0.8$ were observed for VD and VD + FD samples (Fig. 8). Moreover, the PEF treatment facilitated rehydration capacity of potato tissue for all samples obtained using VD, VD + FT and VD + FD (24 h) procedures. Moreover, in all cases the PEF treatment enhanced the rehydration capacity. The obtained results evidenced the positive effect of combined PEF treatment and preliminary VD on the rehydration capacity of deeply freeze-dried samples with low level of moisture ratio ($MR_f = 0.02-0.07$, Fig. S6b in Supplementary part).

4. Conclusions

The effects of combined pulsed electric field (PEF) treatment and preliminary vacuum drying (VD) dehydration on freezing assisted processes (freeze-thawing (TH) or freeze-drying (FD) in potato tissue were investigated. The reasons for choosing of combination of PEF treatment and VD are the following. The PEF-induced electroporation can facilitate the heat and mass transfer processes and can improve the rate of VD (Vorobiev and Lebovka, 2020). The VD was done at relatively high pressure ($p=0.3$ bar) and it allowed fast dehydration at low or moderate temperatures inside sample without significant deterioration in product quality and undesirable changes in its porosity (Liu et al., 2018). Moreover, both the PEF treatment and VD can positively affect freezing processes (Vorobiev and Lebovka, 2020). The significant impact of the PEF treatment and preliminary VD on the freeze-thawing was revealed. Crystallization/melting stages can be practically suppressed for PEF treated and preliminary dehydrated samples with small water contents, $MR_v \approx 0.2$. The proposed combined PEF and VD treatment allowed noticeable acceleration of freezing and thawing processes.

The PEF treatment and preliminary VD also noticeable accelerated the FD process. The rehydration capacity for samples obtained using VD and VD + FT procedures increased with increasing of MR_v . However, the inverse behaviour was observed for samples obtained using VD + FD (24 h) procedures. Therefore, VD and VD combined with FT deteriorated rehydration capacity, whereas VD combined with FD can facilitate the rehydration of deeply dried potato tissue with low moisture content ($MR_f \approx 0.022-0.07$). The observed behaviour can reflect effects PEF treatment and preliminary VD on changes in shrinkage, porosity and hydrophilic properties of the potato tissue during the freezing processes. The obtained regularities can be useful in future practical implementations of freezing assisted processes with fine control of deterioration of product quality, better retention of product biochemical properties and reduced operating and maintenance costs.

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Appendix A. Supplementary data

Supplementary materials related to this article can be found, in the online version, at [doi:https://doi.org/xxx](https://doi.org/xxx).

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Figure captions

Fig. 1. - Treatment procedures applied to the potato tissue.

Fig. 2. - Temperature at the geometrical center of the sample, T , versus the time, t , during the FT for untreated (U, without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples with moisture ratio $MR_v = 1.0$ (a, non-dehydrated samples) and $MR_v = 0.5$ and $MR_v = 0.2$ (b, samples dehydrated by VD). Here, Δt_f and Δt_i are the duration of freezing and melting, respectively, and t_c , is the cooling time up to the temperature ≈ -20 °C.

Fig. 3. - The freezing Δt_f , thawing Δt_i (a) and cooling time t_c (b) versus the VD moisture ratio, MR_v , for untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples obtained using VD+FT procedure. The lines are to guide the eye.

Fig. 4. - Textural relaxation disintegration index, Z_t , versus the VD moisture ratio, MR_v , for untreated (U, without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples obtained using VD and VD + FT procedures. The lines are to guide the eye.

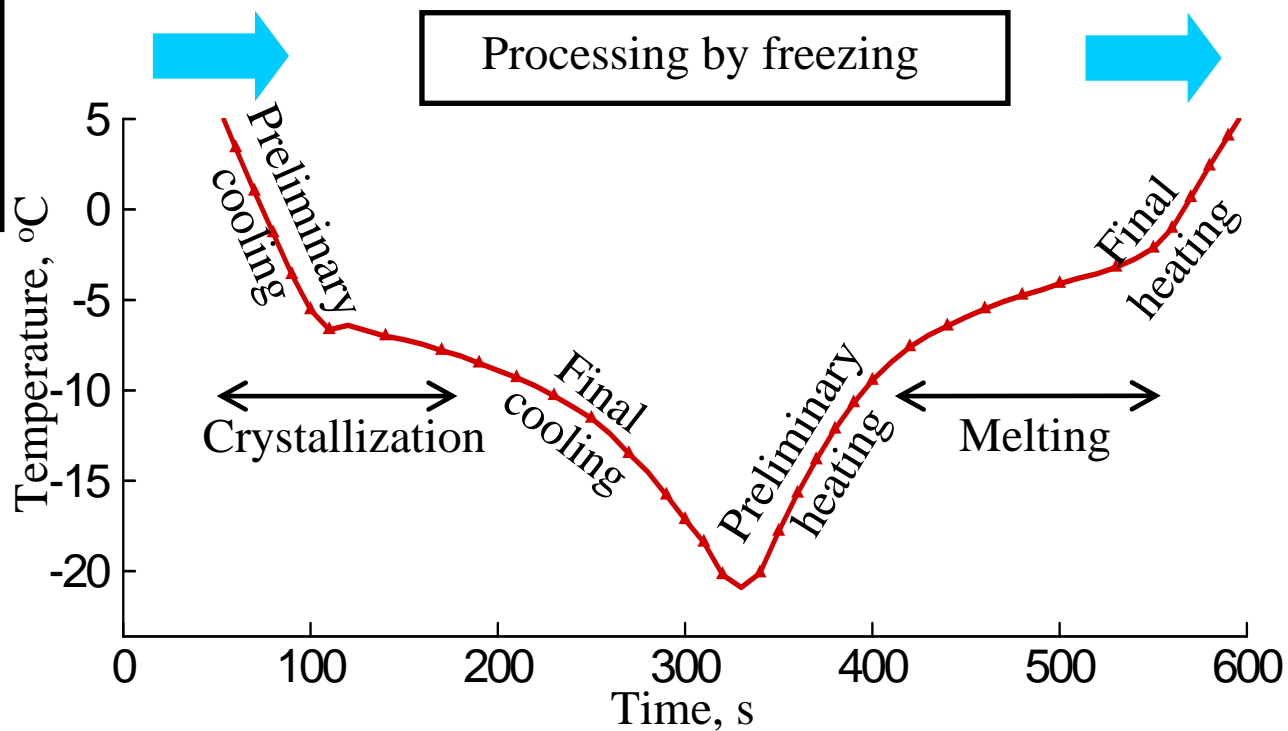
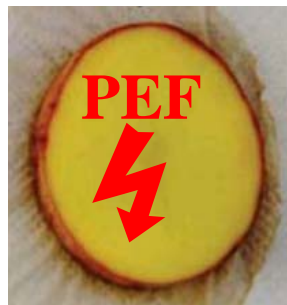
Fig. 5. - Moisture ratio, MR_f , during the freeze-drying process versus the time, t . The data are presented for untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples with different moisture content after preliminary VD, $MR_v = 1.0$ and $= 0.7$ (a) and $MR_v = 0.5$ and $= 0.2$ (b).

Fig. 6. - Freeze-drying time, $t_{0.1}$, required to achieve the critical moisture ratio $MR_f = 0.1$ at different moisture contents obtained after preliminary VD, MR_v , for untreated (U, without PEF treatment) and PEF treated samples.

Fig. 7. - Examples of rehydration kinetics of untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD ($MR_v = 0.5$) and then the procedures of freeze-thawing (VD + FT) or freeze-drying for 24 h (VD + FD) were applied. The saturation value R_m , measured at $t \approx 3$ h, approximately corresponds to the maximum rehydration capacity. The lines are to guide the eye.

Fig. 8. - Maximum rehydration capacity, R_m , versus the moisture ratio after preliminary VD, MR_v , for untreated (without PEF treatment, solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. Here, the data for samples obtained after VD + FT and VD + FD (24 h) procedures are also presented. The lines are to guide the eye.

Vacuum
dehydration
0.3 bar



Rehydration

