Impact of pulsed electric fields on the physical properties of food plant materials

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Abstract

This work presents the recent investigations of the impact of pulsed electric fields (PEF) on the physical properties of food plant tissues. It is shown that tissues treated by PEF generally have compression characteristics intermediate between those of fresh and thermally treated tissues. It is shown that the liquid expression mechanisms inside of plant tissues denatured by PEF correspond to the mechanisms, described by the filtration/consolidation theory of compressible porous media. The mass transfer properties and diffusivity of food plant tissues modified by PEF are also studied. Some other physical properties of plant tissue modified by electroporation are also investigated.

Keywords

Pulsed electric fields, food plant tissues, electroporation, compression characteristics, mass transfer properties

1. Introduction

Application of pulsed electric field treatment (PEF) in processing of bio-, food or agricultural products becomes more and more popular [1–3]. PEF is considered as a non-thermal treatment of very short duration (from several nanoseconds to several milliseconds) with pulse amplitude from 100-300 V/cm to 10-50 kV/cm. Under the effect of PEF, the biological membrane gets electrically pierced (electroporated), it affects the permeability and barrier properties of cell membrane and accelerates the mass transfer processes. PEF application creates the flows of liquid and solutes between individual cells, inside of extracellular channels and outside of solid particles. The electroporation can also modify the mechanical and electro-physical properties of materials. The PEF-assisted techniques display unusual synergetic effects and possibility of processing at low temperatures. Moreover, PEF-treatment allows avoidance of undesirable changes in a biological material, which are typical for other techniques, such as thermal, chemical and enzymatic ones[4,5]. The supplementary advantage of PEF treatment for food applications is related with a possibility of microbial killing [1].

Though the practical implementation of electricity for treatment of different biological tissues (of prunes, apples, grapes and sugar beets) was started in 1950th [6], a lot of problems still exist in the field. The experimental works revealed that initiation of electroporation requires application of relatively high electric fields E≈100 V/cm for plant cells and E≈5-10 kV/cm for damage of microbial cells, and the effects are dependent on the treated material and details of pulse protocol [7]. Among numerous examples of PEF applications for intensification of separation, extraction, pressing, diffusion and drying may be mark out. However, the full details of the mechanisms of food plant material modification due to PEF application are not well understood yet and it restrains the fast implementation of PEF-assisted extraction techniques.

This contribution reviews the modern state of the art in the field of PEF-assisted processing of food plant materials, recent practical efforts, examples of applications for different food materials, and industrial perspective of PEF implementations.

2. Basic of electroporation, degree of disintegration and power consumption

Impact of PEF on food plant reflects losing of barrier functions by biomembranes. Electric field application provokes formation of pores inside the membrane and increases its permeability. Traditionally this phenomenon is called “electroporation”, “electropermeabilization” or “electroplasmolysis” (see reference [7] and references cited therein). Figure 1 demonstrates typical effect of PEF on the structure of red beet tissue after aqueous extraction. It can be seen that the intact cells are intensively colored and PEF-treated cells with damaged membranes have pale colors and lose their vacuolar sap [8].
Efficient electroporation requires some threshold value of transmembrane potential, \( u_m \), typically, \( 0.5-1.5 \text{V} \). Depending on conditions of treatment, the value of \( u_m \) and PEF exposure time \( t_{PEF} \), a temporary (reversible) or irreversible loss of barrier function can occur. For a spherical cell in the external field, the induced transmembrane potential \( u_m \) is a function of cell radius \( R \), field strength \( E \) and position of the observation point on the surface of membrane:

\[
    u_m = 1.5 REf \cos \theta (1 - \exp(-t / \tau_c))
\]  

(1)

Here, \( \theta \) is the angle between the external field \( E \) and radius-vector \( r \), \( f \) is the electroporation factor that is dependent on geometry and electrophysical properties of cells and \( \tau_c \) (\( \approx 1-10 \mu \text{s} \)) is the time constant reflecting charging of capacities \( C \) in the membranes.

\[ Z_c = (\sigma - \sigma_i) / (\sigma_d - \sigma_i), \]  

(2)

where \( \sigma \) is the electrical conductivity value measured at low frequency (\( \approx 1 \text{kHz} \)) and indexes ‘i’ and ‘d’ refer to the conductivities of intact and totally damaged tissue, respectively.

This equation gives \( Z=0 \) for the intact tissue and \( Z=1 \) for the totally disintegrated material. The useful parameter of quantization of electroporation efficiency of PEF treatment at the given value of \( E \) is the characteristic damage time \( \tau \), which is defined as the time necessary for half-damage of material (i.e. \( Z=0.5 \)).

In practice, the electroporation efficiency depends upon details of pulse protocol [2,3]. The electric field strength \( E \) and the total time of treatment \( t_{PEF} \) are the principal parameters that govern the efficiency of PEF-treatment. Figure 2 presents examples of conductivity disintegration index \( Z_c \) versus the time of PEF treatment \( t_{PEF} \) for potato and orange [9]. In general, the higher electric field strength leads to better damage. However, at high electric fields, the electrical power consumption becomes essential and ohmic heating intensively develops. For food plant tissues, an important damage of rather large food tissue cells (\( R=30-50 \mu \text{m} \)) can be observed at \( E = 200-1000 \text{V/cm} \) and treatment time within \( 10^{-4}-10^{-1} \text{s} \) [7], and for small microbial cells (\( R=1-10 \mu \text{m} \)), larger field (\( E = 20-50 \text{kV/cm} \)) and smaller treatment time (\( 10^{-5}-10^{-3} \text{s} \)) are required [1].

Note that the electric field strength concentrated on membrane can be estimated as \( E_m = u_m / d = ER / d \), where \( d \) is the membrane width (\( \approx 5 \text{nm} \)). For food plant tissues, \( R=50 \mu \text{m} \) so, \( E_m \) can be estimated as \( E_m \approx 10^4 \text{E} \), i.e., the electric field strength on a membrane can be rather high, \( \approx 10^6-10^7 \text{V/cm} \) and electroporation reflects the membrane instability stimulated by application of a high field.

Moderate PEF treatment with relatively low values of \( E \) (\( \approx 20-100 \text{V/cm} \)) also can cause electroporation to some extent. In this case, the resealing processes can be quick enough to repair the membranes immediately after PEF treatment termination. This sort of electroporation is called as reversible. At moderate PEF treatment, some of the cells lose their permeability, but other are able to reseal, and insulating properties of the cell membrane can be recovered within several seconds after pulse termination. PEF application can invoke also a strong metabolic response in tissue [10]. High-intensity PEF treatment causes an irreversible damage of the cell membrane. Long-
term changes in tissue electrical conductivity after PEF treatment application can also be related to osmotic flow and moisture redistribution inside the sample [11]. The electroporation efficiency is also dependent on different pulse parameters, presented in Fig. 2. The experimental data clearly demonstrate the influence of pulse duration $t_i$ (10-1000 µs) on the efficiency of PEF-treatment [6]. Longer pulses were found to be more effective, and their effect was particularly pronounced at room temperature and moderate electric fields ($E=100-300$ V/cm). Bipolar pulses seem to be more advantageous, as far as they cause additional stress in the membrane structure, allow avoiding of the asymmetry of membrane damage in the cell and offer minimum energy consumption, with reduced deposition of solids on the electrodes and smaller food electrolysis. Moreover, a complex protocol with adjustable long pause between the trains allows fine regulation of the disintegration of tissue without noticeable temperature elevation during the PEF treatment.

![Figure 2: Conductivity disintegration index $Z_c$ versus the time of PEF treatment $t_{PEF}$ for potato ($\sigma_d/\sigma_i=14.3$) and orange ($\sigma_d/\sigma_i=1.3$) [9].](image)

In spite of the fact that PEF-treatment of different food plant tissues was studied in many previous works, the correlations between electroporation efficiency and properties of tissues are not well understood yet. Figure 3 presents examples of characteristic damage time $\tau$ versus electric field strength $E$ for different fruit and vegetable tissues [9]. These materials demonstrate remarkable differences in electroporation efficiency. In part, it can be explained by differences in size of the cells, because Eq.(1) predicts that larger cells get damaged before the smaller ones. In general, this correlation was supported by the observed experimental data [9]. The correlations between electroporation efficiency and electrical conductivity contrast $k=\sigma_d/\sigma_i$ (here, $\sigma_d$ and $\sigma_i$ are electrical conductivities of completely damaged and intact tissues, respectively) were experimentally observed and reasonably explained on the base of electroporation theory.

![Figure 3: Characteristic damage time $\tau$ versus electric field strength $E$ for different fruit and vegetable tissues [9].](image)

In general, the electroporation effect does not require high power consumption, and it stipulates the industrial attractiveness of PEF-treatment. However, the problem of choice of the proper pulse protocol parameters (e.g. values of electric field strength $E$ and pulse duration $t_i$), required for minimal power consumption, is still disputable. The power consumption $Q$ (mass density of the energy input) can be estimated using the equation

$$Q = E^2 \int_0^\infty \sigma(t,T) dt / \rho ,$$

where $\rho$ is the material density.

Note that during the PEF treatment the value of $\sigma$ can be a rather complex function of time $t$ and temperature. The theory predicts that the power consumption, required for effective electroporation of food plant material, may be roughly estimated as $Q\sim \sigma_d E^2 t/\rho$. Experiments and theory evidences that the function $Q(E)$ has a minimum at some optimum electric field strength $E_o$. Increase of $E$ above $E_o$ can result in progressive increase of the power consumption without no increment to the conductivity disintegration index $Z$. For vegetable and fruit tissues (apple, potato, cucumber, aubergine, pear, banana and carrot), the typical values of $E_o$ were within 200-700 V/cm and PEF treatment times, required for effective damage, $t_{PEF}$ were within 1000 µs-0.1 s [3,6]. The estimated power consumptions $Q$ for PEF-treated tissues were found to be rather low and typically lying within 1-15 kJ/kg. So, from...
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the standpoint of power consumption, the PEF method is practically ideal for production of damaged plant tissues as compared to other methods of treatment like mechanical (20–40 kJ/kg), enzymatic (60–100 kJ/kg), and heating or freezing/thawing (> 100 kJ/kg).

2. PEF effect on compression characteristics of food tissues

Control of compression characteristics of fruits and vegetables tissues is very important for optimization of industrial mechanical operations such as solid/liquid expression, cutting, peeling etc.… Detailed textural investigations (stress–deformation and relaxation tests) have shown that tissues (carrot, potato and apples) were losing a part of their textural strength after PEF treatment, and both the elasticity modulus and the fracture stress decreased with increase of the damage degree [12] [13] [14]. The differences in the pressure-displacement curves P-ε for PEF-treated and untreated tissues were usually observed. The PEF effects on compression and solid-liquid expression from different vegetable tissues were also extensively studied. The compression-to-failure and stress–relaxation measurements of the apple, carrot and potato tissues, treated by PEF with different time of treatment \( t_{PEF} \), were presented in [12]. After PEF treatment with rather high intensity and long duration (\( E = 1.1 \) kV/cm, \( t_{PEF} = 0.1s \)) the tissues were partially loosing their initial strength. However, changes both in the elasticity modulus \( G_m \) and the fracture stress \( PF \) were significantly smaller than changes observed for the freeze-thawed and thermally \( (T=45^\circ C, 2h) \) pretreated tissues. So, the tissue structure seems to be less affected by the PEF treatment as compared to the freeze-thawing or heating and the tissues treated by PEF generally have compression characteristics intermediate between those of fresh and thermally treated tissues. This conclusion was later confirmed by the textural studies of sugar beet tissue treated by PEF [13]. The PEF-treatment accelerated also the stress relaxation of tissues and tissues treated by strong PEF usually demonstrated slower relaxation as compared with freeze-thawed tissues (Figure 4).

Effects of PEF treatment on textural and compressive properties of potato were also studied in details [12,14,15]. It was shown that relatively strong PEF treatment resulted in decrease of the stiffness of potato to levels similar to those of hyper-osmotically treated samples. The uniaxial force textural investigations (stress–deformation and relaxation tests with unconfined potato samples) have shown that the tissue was losing a part of its textural strength after PEF treatment, and both the elasticity modulus and the fracture stress decreased with increase of the damage degree [12].

![Figure 4: Examples of the stress relaxation curves for the untreated, PEF-treated and freeze-thawed apple tissue [12].](image1.png)

![Figure 5. Solid/liquid expression data for Muscadelle grapes represented with the help of Eq.(4)](image2.png)

These data were confirmed by textural and solid–liquid expression investigations of PEF-treated potato tissues [15]. It was also shown that only PEF treatment application was not sufficiently effective for complete elimination of the textural strength, however, mild thermal pre-treatment at 45-55°C allowed to increase PEF efficiency [12]. The three-dimensional textural investigations (of confined potato samples) with applied pressure varying within 0.5–4 MPa have shown that fracture pressure was approximately the same for both PEF-treated and untreated specimens, but PEF-treated tissues displayed higher stiffness in comparison to untreated ones [14]. In 3d-compression
experiments, the critical pressure $P_m$, at which the time of the pressure-induced cell rupture should be of the same order of magnitude as the time of fluid expression from the damaged cells, was estimated as $P_m \approx 6$ MPa. Moreover, the fracture pressure $P_f$, estimated from these experiments, was approximately the same for untreated and PEF-treated samples of potato, $P_f \approx 4.5 \pm 0.4$ MPa and it was noticeably larger than the fracture pressure $P_f \approx 1.5$–1.6 MPa under uniaxial compression. The model of PEF assisted solid/liquid expression of agro-food materials was developed on the base of filtration-consolidation theory [12]. The following simplified equation was proposed for description of time dependence of the mass of extracted juice:

$$t/m = v_0^{-1} + t/m_\infty$$

where $v_0$ represents the initial rate of juice flow at the beginning of the expression, and $m_\infty$ represents the hypothetical maximal mass of juice, which could be extracted at indefinite pressing duration. This model was successfully applied for description of the experimental data of expression from Muscadelle grapes. Figure 5 presents the experimental results for non-treated and PEF pretreated grapes using Eq. (4). This linearized presentation allowed good fitting of the experimental expression data for non-treated and PEF pretreated grapes and estimation of $m_\infty$ values.

3. PEF effect on mass transfer properties and diffusivity of food plant tissues

Acceleration of mass transfer is very important in industrial mechanical operations. In raw food plants, the valuable compounds are initially enclosed in cells, which have to be damaged for facilitation of the intracellular matter recovery. Conventional cell damage techniques, such as fine mechanical fragmentation, thermal, chemical and enzymatic treatments, lead to more severe disintegration of the tissue components, including cell walls and cell membranes. The PEF treatment, which is less destructive than conventional methods, can be used for more selective extraction of cell components. E.g., the extraction technology is a power-consuming hot water technique in sugar industry. It involves diffusion of sugar from the sliced cossettes of sugar beet at 70-75°C. A relatively high temperature is required for tissue denaturation by heat. At high temperature, cell components other than sugar, such as pectin, pass into juice during extraction, thus affecting the juice purity, and formation of some colorants like melanoidins is promoted by thermal diffusion. It results in necessity of application of a rather complex multi-staged process (preliming, liming, 1st and 2nd carbonation, several filtrations, and sulfitation) and high lime discharge. Recent experiments have shown that the diffusion process in the sugar extraction technology can be radically intensified by electric field treatment. The strong dependence of the sugar beet damage efficiency versus temperature and pulse protocol parameters was recently demonstrated [13]. For instance, the effective diffusion coefficients $D_{ef}$ were nearly the same for sugar diffusion from untreated sugar beet slices at 60°C and from those PEF-treated at 30°C ($E = 400$ V/cm, $t_{PEF} = 0.1$ s). The purest juice was obtained after cold diffusion. However, even after the thermal diffusion at 70°C, the juice purity was higher for slices pretreated by PEF than for untreated slices [8]. The sugar beet pulp could be well exhausted by a cold or mild thermal extraction of cossettes treated by PEF, and the pulp obtained by cold extraction of PEF-treated cossettes had dryness >30%, which was noticeably higher than dryness of the pulp obtained by conventional hot water extraction technique [8]. The estimated energy surplus for cold extraction with temperature reduction from 70°C to 30°C (i.e. by $\Delta T = 40$ °C) was $\approx 46.7$ kW.h/t, which was noticeably higher than the power consumption required for PEF treatment, $\approx5.4$ kW.h/t. It was concluded [8] that this power consumption can be even reduced by further optimization of PEF parameters and minimization of the liquid to solid ratio during PEF treatment.

The similar effects of accelerated mass transfer after PEF treatment were observed also for red beets, carrots, apples, grapes, peppers, fennel, chicory, alfalfa, red cabbage and many other fruit and vegetable tissues. E.g., the benefits of PEF application for enhancement of the soluble matter (sucrose, proteins and inulin) extraction from chicory were recently demonstrated [8]. It was shown that PEF treatment with the field strength 100–600 V/cm noticeably accelerated diffusion even at low temperatures within 20–40 °C. Proposed technique appears to be promising for future industrial applications of “cold” soluble matter extraction from chicory roots. PEF treatment application can be particularly useful for thermally sensible bioproducts such as red beet (Beta vulgaris L.). This culture is widely used for industrial production of natural water-soluble betalain pigments. They are rather sensible to temperature, and it complicates extraction process and reduces the yield of colorants. PEF treatment at 400-600 V/cm and ambient temperature enabled increase of the yield of high quality colorant [8] and allowed acceleration of drying of the red beet tissue [13]. PEF treatment accelerated the osmotic dehydration of carrot and increased the effective diffusion coefficients of water and soluble matter, as well as the Brix-values [12]. Moreover, the possibility of
selective PEF assisted extraction of water soluble components (soluble sugars) and production of a “sugar-free” concentrate rich in vitamins and carotenoids, which can be used as an additive in diet foods, was demonstrated [14].

4. Conclusions
PEF treatment application to food plant material became very popular. This method can serve as an effective tool for improvement of traditional processing in food industry. PEF can be successfully applied to the majority of fruit and vegetable tissues without deterioration of colour, flavour, vitamin C and other important nutrients of foods. Besides, the PEF treatment has minimal cost in the energetic sense and is non-thermal, i.e. it may be applied to the thermally sensible products. It encourages continuous research and industrial works aimed at development of such non-conventional operations in food processing.

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