Pulsed-Electric-Fields-Induced Effects in Plant Tissues: Fundamental Aspects and Perspectives of Applications

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Abstract The purpose of this contribution is to review the existing approaches to pulsed electric field (PEF) application as a tool for enhancing the processing of plant tissues. The PEF-treatment as a nonthermal method, which allows to preserve the natural quality, color, and vitamin constituents of food products. The numerous laboratory attempts to modernize the optimal PEF application protocols still lack universality. The problem is inherently multidisciplinary and integrates different biological, electrophysical, and chemical processes. The fundamental aspects of electroporation in application to plant tissues, electrically induced damage, optimal power consumption, synergetic effect of combined PEF-thermal treatment, and influence of pulse protocol parameters are presented and critically discussed. The experimental data on PEF-induced acceleration in expression, diffusion, and drying processes are also analyzed.

1 Introduction

During the last decade, the pulsed electric field (PEF)-treatment was found to be useful for enhancing the pressing, drying, extraction, and diffusion processes (Barsotti and Cheftel 1998; Angersbach et al. 2000; Vorobiev et al. 2005; Vorobiev and Lebovka 2006). The PEF-treatment has also found application as a minimally invasive method for processing of plant tissues, allowing to avoid many undesirable changes in products, pigments, vitamins, and flavoring agents, which are typical for other pre-treatment techniques, including thermal, chemical and enzymatic ones. Moreover, the PEF-treatment is also promising for purposes of microbial inactivation (Barbosa-Canovas and Vega-Mercado 1996; Toepfl et al. 2007).

The PEF-treatment at moderate electric field strength $E = 500$–1000 V/cm and treatment time within $10^{-4}-10^{-2}$ s allows to damage tissue effectively without any significant temperature increase (Fincan and Dejmek 2002; Lebovka et al.

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2002). Efficiency of the PEF-induced damage can be appreciably enhanced by additional thermal treatment (Lebovka et al. 2005a; Lebovka et al. 2007a; Shynkaryk 2007).

A moderate electric field (MEF)-treatment by low-gradient electric fields (<100 V/cm) can also induce tissue damage. The advantages of MEF application have been already discussed in the early works. The MEF-induced enhancement was demonstrated for juice extraction and diffusion (Flaumenbaum 1949; Zagorulko 1958; Katrokha and Kupchik 1984; Gulyi et al. 1994) and for processing of vegetable raw materials, meat, and fish (Kogan 1968; Matov and Reshetko 1968; Rogov and Gorbatov 1974). Recently, also, efficiency of the MEF-induced damage with respect to different materials was demonstrated (Wang and Sastry 2002; Lebovka et al. 2005b). The research efforts were aimed on optimization of the protocols accounting the increase of the product temperature and energy consumption (Praporscic et al. 2006). It was shown that MEF-treatment allows to enhance extraction, expressing, and drying processes for different food materials (Wang and Sastry 2002; Zhong and Lima 2003).

This chapter discusses recent advantages of the PEF-treatment application in processing of plant tissues.

2 Electric Field Effects in Plant Tissues

Electric fields (PEF or AC) produce a current through the biological tissue and may result in damage of membranes and volumetric ohmic heating. As a result, a number of different phenomena, such as intracellular liquid release, diffusion of solutes, and membrane resealing processes, develop inside the cellular structure after their treatment. Specific effects like electro-osmotic flow and electrolysis phenomena can be also important.

2.1 Origin of Electropermeabilization

The unique property of PEF application is related to selective damage of the biological membranes. An external electric field E induces a transmembrane potential u_m on a membrane. When the transmembrane potential exceeds some threshold value (typically about 0.2–1.0 V), electric field cause a temporary loss of semipermeability by the cell membranes (electropermeabilization) or their damage.

The exact mechanism of permeabilization is not precisely understood yet, but it is accepted that electroporation consists of different stages including (Teissié et al. 1999; Teissie et al. 2005; Krassowska and Filev 2007):

(1) charging and polarization of the membranes (charging time of ≈ 1 μs);
(2) temporal destabilization and creation of pores (reported as occurring on time scales of 10 ns (Tarek 2005));

(3) expansion of pore radii and aggregation of different pores (in a time range of 100 μs);
(4) resealing of pores and memory effects (lasting from seconds to hours).

Proposed theories account for pore formation (electroporation), and for electromechanical, electrohydrodynamical, viscous-elastic, electrothermal, and electroosmotic instabilities (Ho and Mittal 1996; Weaver and Chizmadzhev 1996; Chen et al. 2006). Sufficiently strong PEF exposure (high electric fields and long time of treatment) leads to formation of large pores, deformation of membranes, and cell lysis (Pliquett et al. 2007). The other possibilities of cell lysis may be explained by chemical imbalances resulting from the enhanced transmembrane transport (Dimitrov and Sowers 1990) and Joule overheating of the membrane surface (Lebovka et al. 2000b). Reversibility of electroporation is closely related to the pulse protocol, i.e. electric field strength, shape of pulses, pulse duration, and intervals between pulses (Canatella et al. 2001). The PEF application can results in transient or stable electroporation.

2.1.1 Transmembrane Potential

For a single spherical cell, the transmembrane potential depends on the angle θ between the external field E direction and the radius vector r on the membrane surface (Schwan 1957):

$$u_m = 1.5RE\cos\theta(1 - \exp(-t/t_c))f. \tag{1}$$

Here, R is the cell radius, and the time dependence reflects the membrane capacitance charging processes.

The time constant t_c is defined as (Pauly and Schwan 1959)

$$t_c = t_c^m/(1 + a), \tag{2}$$

where $t_c^m = Ch/\sigma_m$, C is the specific capacitance of membrane, h is its thickness, and $a = (h\sigma_i/R\sigma_m)/(1+\sigma_i/\sigma_o)$. Here, σ_m, σ_e, and σ_i refer to conductivities of the membrane, extracellular medium, and cytoplasm, respectively.

The typical values of $C = 10^{-2}$ F/m^2, $h = 5$nm and $\sigma_m = 3{\cdot}10^{-7}$ S/m (Kotnik et al. 1998) give $t_c^m = 1.7 \cdot 10^{-4}s$.

The general expression for f is rather complex (Kotnik et al. 1998), but in the case of $h\sigma_i/R\sigma_m >> 1$ (for physiological conditions, $\sigma_i \approx 3{\cdot}10^{-1}$ S/m, and $R = 100$ μm, $h\,\sigma_i/R\,\sigma_m \approx 50$) it can be simplified to:

$$f = 1 - 1/a. \tag{3}$$

The steady conditions realized when the pulse duration t_p is long as compared with the time required to charge up the membrane capacitance. The value of u_m is proportional to the cell radius R. The highest drop of potential occurs at the cell

poles, and decreases to 0 at $\theta = \pm\pi/2$. So, the larger cells get damaged before the smaller ones, and the damage probability is maximum at the cell poles. The width of a membrane h (≈ 5 nm) is very small as compared with a plant cell radius R (≈ 100 μm). The electric field strength concentrated at the membrane can be estimated as $E_m = u_m/h \approx ER/h \sim 2 \cdot 10^4 E$.

In soft plant tissues the cells are rather large R (≈ 100 μm) as compared with microbial cells (≈ 1–10 μm) and induced transmembrane potentials, as well as membrane charging phenomena, can be greatly influenced by the cell radius and σ_e/σ_i. ratio. An undamaged biological tissue is usually a low-conductivity medium, so, it satisfies the inequality $\sigma_e/\sigma_i << 1$. But it can be assumed that σ_e/σ_i value increases with increase of the PEF-induced damage, and $\sigma_e/\sigma_i \approx 1$ in the limit of high tissue disintegration. Figure 1 presents dependences of t_c, f versus σ_e/σ_i (a) calculated for different values of cell radius R. For small cells ($R = 1$ μm), the value of f is close to 1 and the value of t_c is less than 1 μs. For larger cells like those in cellular tissues, with $R \approx 100$ μm, the value of f deviates from 1 and t_c increases noticeably at small σ_e/σ_i values. The scheme at the top of the figure demonstrates that charging of large membrane cells can be greatly influenced by the ratio of σ_e/σ_i.

If a cell is nonspherical, the transmembrane potential u_m becomes more complex function of the cell size and geometry, direction of external field and location on the membrane surface. In steady conditions, the transmembrane potential u_m in some

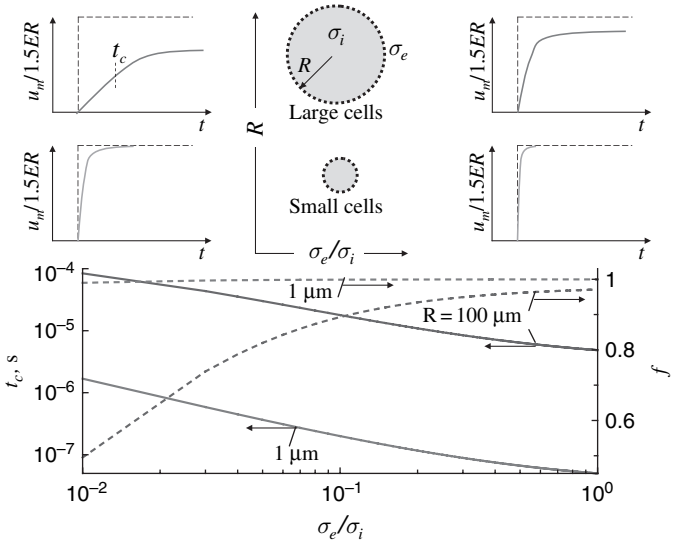

Fig. 1 Dependences of parameters t_c and f in Equation (1) versus ratio of the extracellular medium and cytoplasm electrical conductivities σ_e/σ_i for different values of cell radius R. The calculations were done using $\sigma_i = 3 \cdot 10^{-1}$ S/m (physiological medium). The scheme at the top of the figure demonstrates differences in charging of membranes for small and large cells and for different values of σ_e/σ_i. ratio

point on the membrane surface $r(x,y,z)$ may be calculated from the following generalized Schwan equation (Fricke 1953):

$$u_m = \sum_{i=x,y,z} r_i E_i/(1 - L_i). \tag{4}$$

Here, L_i are the depolarizing factors defined by the cell aspect ratio a (Landau et al. 1984). For a spherical cell $L_x = L_y = L_z = 1/3$, for a long cylinder $L_x = L_y \approx 0.5$, $L_z \approx 0$, and for a thin disk $L_x = L_y \approx 0$, $L_z \approx 1$. This approximation works for the membranes with negligibly small conductance and its application was extensively discussed in literature (Bernhardt and Pauly 1973; Zimmermann et al. 1974; Kotnik and Miklavcic 2000; Gimsa and Wachner 2001).

2.1.2 Stability of Membranes and Cells

In electroporation theory, the lifetime τ_m of a membrane can be estimated as (Weaver and Chizmadzhev 1996):

$$\tau_m = \tau_\infty \exp W/kT(1 + (u_m/u_o)^2), \tag{5}$$

where W is the membrane damage activation energy, τ_∞ is a parameter, $k = 1.381 \cdot 10^{-23}$ J/K is the Boltzmann constant, T is the absolute temperature, and u_o is a parameter characterizing the electroporation response of the membrane.

For lipid membranes, the following estimations of parameters were obtained experimentally: $W \approx 270$ kJ/mol, $u_0 \approx 0.17$ V, and $\tau_\infty \approx 3.7.10^{-7} s$ (Lebedeva 1987); however, these values depend on the structure and composition of membranes in plant cells. For example, for membranes in sugar beet cells the values of $W \approx$ 166 kJ/mol and $\tau_\infty \approx 10^{-23}$ s were obtained experimentally (Lebovka et al. 2007a).

The mean lifetime of a spherical cell τ_c may be estimated by averaging of τ_m^{-1} over the cell surface. (Lebovka et al. 2002; Lebovka and Vorobiev 2004)

$$\tau_c^{-1} = \int_0^\pi \tau_m^{-1} d \cos\theta/2, \tag{6}$$

where τ_m is determined by Equations (1) and (5).

The lifetime τ_c of a spheroid depends also on its orientation in the external field (Lebovka and Vorobiev 2007). For example, the lifetime of a prolate spheroid is minimum for its orientation along the external field E ($\theta = 0^\circ$) and maximum for its perpendicular ($\theta = 90^\circ$) orientation (Fig. 2).

This result is an accordance with maximum of the transmembrane potential and electropermeabilization for cells oriented by their longest axes in parallel to the external electric field, which was reported for different ellipsoidal microorganisms (Valic et al. 2003; Toepfl et al. 2007; Agarwal et al. 2007).

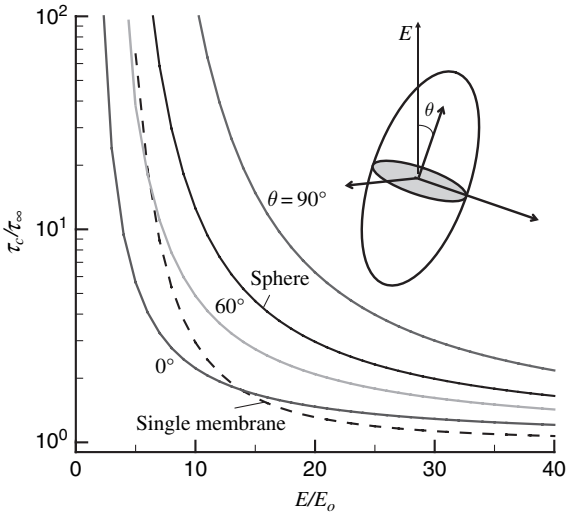

Fig. 2 Lifetime τ_c of a prolate spheroid versus field strength E at different angles θ between electric field direction and axis of spheroid. Here, $E_o = 2u_o/3R$, R is the radius of a sphere with the same volume as spheroid, $a = 10$ is the aspect ratio, and dashed line corresponds to the lifetime of a single membrane (in this case $E/E_o = u_m/u_o$). Numerical calculations were done (Lebovka and Vorobiev 2007) using parameters estimated for lipid membranes (Lebedeva 1987)

2.2 Electrically Induced Damage in the Cellular Tissues

In cell suspensions and in biological tissues, electroporation is a complex function of cell orientation and distribution of cell sizes and may be influenced by aggregation of cells, their arrangement, local cell density and solute concentration, and distribution of local electric field (Canatella et al. 2004; Pucihar et al. 2007; Pavlin et al. 2007). Moreover, an external field can affect orientation (Lebovka and Vorobiev 2007) and aggregation of cells (Toepfl 2006) in suspensions. Redistribution of the local fields inside a biological tissue is possible also during the PEF-treatment (Lebovka et al. 2000a; Lebovka et al. 2001).

2.2.1 Estimation of the Damage Degree

The damage degree P can be defined as the ratio of the damaged cells and the total number of cells. The direct estimation of the damage degree can be done through microscopic observation of the PEF-treated tissue (Fincan and Dejmek 2002), but this procedure is not simple and it is ambiguous.

It is possible to estimate the damage degree from diffusion coefficient measurements in the PEF-treated biological materials (Jemai and Vorobiev 2001; Lebovka et al. 2007b)

$$P \approx (D - D_i)/(D_d - D_i), \tag{7}$$

where D is the measured apparent diffusion coefficient and the subscripts i and d refer to the values for intact and totally destroyed material, respectively.

The apparent diffusion coefficient can be determined from solute extraction or convective drying experiments. Unfortunately, diffusion techniques are indirect and invasive for biological objects, and they may impact the structure of the tissue. Moreover, validity of Equation (5) approximation is still controversial (Vorobiev et al. 2005; Lebovka et al. 2007b).

A conventional method of damage degree P estimation is based on electrical conductivity measurements. The local electrical conductivity is elevated near the damaged cells, and averaged electrical conductivity increases as the damage degree grows. The conductivity disintegration index Z can be defined as (Rogov and Gorbatov 1974):

$$Z = (\sigma - \sigma_i)/(\sigma_d - \sigma_i), \tag{8}$$

where σ is the electrical conductivity value measured at low frequency (1–5 kHz) and indexes i and d refer to the conductivities of intact and totally destroyed cellular system, respectively. This equation gives $Z = 0$ for the intact tissue and $Z = 1$ for the totally disintegrated material.

This method is useful for tissues and colloidal biosuspensions (Lebovka et al. 2000a; Vorobiev and Lebovka 2006; El Zakhem et al. 2006a, 2006b). But it requires determination of σ_d from supplementary measurements for maximally damaged material after freeze-thawing or strong PEF-treatment with high strength electric field and long duration of PEF-treatment (Lebovka et al. 2007a).

Another method is based on electrical conductivity measurements at low (≈ 1 kHz) and high (3–50 MHz) frequencies (Angersbach et al. 2002):

$$Z = (k\sigma^o - \sigma_i^o)/(\sigma_i^\infty - \sigma_i^o), \tag{9}$$

where $k = \sigma_i^\infty/\sigma^\infty$ and the indexes o and ∞ refer to the low and high conductivity limits, respectively.

Unfortunately, there exist no exact relation between disintegration index Z and damage degree P, though it may be reasonably approximated by empirical Archie's equation (Archie 1942):

$$Z \approx P^m, \tag{10}$$

where exponent m falls within the range of 1.8–2.5 for biological tissues, such as apple, carrot and potato (Lebovka et al. 2002).

2.2.2 Evolution of Damage and Transient Effects

Examples of the time dependence of the conductivity disintegration index Z are presented schematically in Fig. 3. It is useful to introduce the characteristic damage

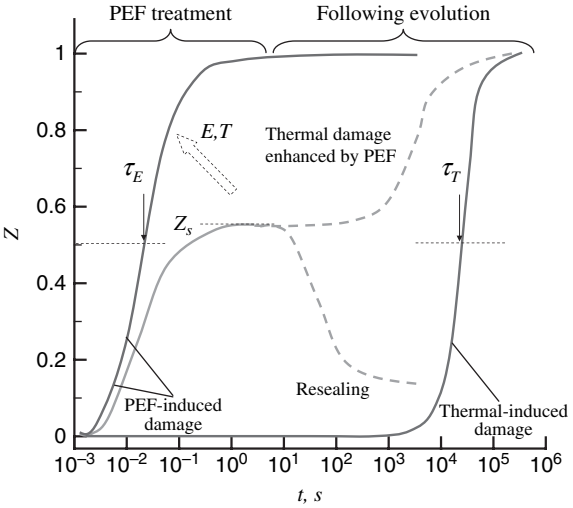

Fig. 3 Evolution of the conductivity disintegration index Z under the PEF and thermal treatment. Here, τ_E and τ_T are the electric and thermal characteristic damage times, respectively, Z_s is the level of disintegration index saturation

time τ defined as a time needed for attaining a half of the maximal damage ($Z \approx 1/2$) (Bazhal et al. 2003).

The damage evolution in tissue can be approximated by the following transition function (Bazhal et al. 2003):

$$Z = \left[1 + (\tau/t)^{\kappa}\right]^{-1}, \tag{11}$$

where k is an empirical exponent. For damage caused by PEF-treatment, time t corresponds to the total time of PEF-treatment: $t = t_{PEF} = nt_{\mathrm{p}}$, where n is the number of pulses and t_p is the pulse duration. It follows from Equation (11) that $Z = 1/2$ at $t = \tau$ so, the definition of the characteristic damage time τ is evident.

The thermally induced damage requires a long time and is accelerated by the temperature T increase. The PEF-induced damage depends on the treatment protocol and its rate grows with increase of the electric field strength E and temperature T (Lebovka et al. 2005a, 2005b).

At moderate electric fields ($E < 300$ V/cm) and room temperature, disintegration index Z may reach plateau at long PEF-treatment. It was experimentally observed that the saturation level Z_s increased with increase of both E (Lebovka et al. 2001) and T (Lebovka et al. 2007a). For example, the maximal disintegration index Z_s was of the order of 0.75 at $E = 100$ V/cm for sugar beet tissue (Lebovka et al. 2007a).

The saturation behavior possibly reflects existence of a complex structure and wide spread of the cell geometries and sizes. At higher fields, $E > 500$ V/cm, the saturation behavior was not observed for tissues with relatively homogeneous structures (potatoes, apples, etc.), and it was possible to attain the maximal disintegration

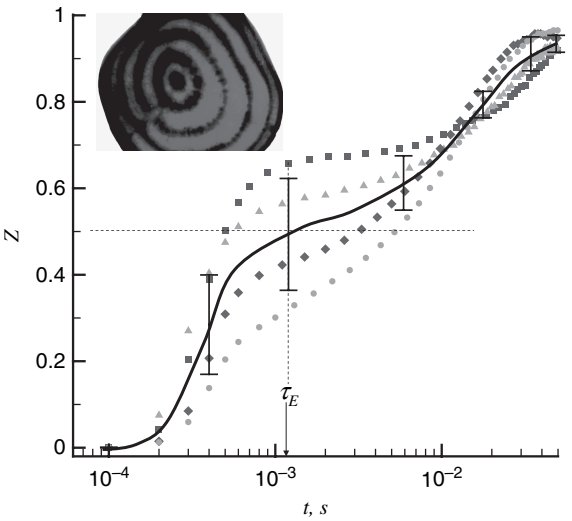

Fig. 4 Evolution of the conductivity disintegration index Z under the PEF-treatment at electric field strength $E = 400$ V/cm, pulse duration $t_i = 10$ μs, pulse repetition time $\Delta t = 200$ μs. Symbols are for data of four different experiments, solid line corresponds to the mean values, and error bars are the standard deviation

($Z_s \approx 1$) for these materials. But inhomogeneous materials, such as the red beetroot tissues, for example, can display a step-like behavior of the conductivity disintegration index Z even at higher fields (Fig. 4). These steps evidently reflect existence of different domains in the red beetroot tissues and the presence of the cell survivability distribution (Shynkaryk et al. 2008; Shynkaryk 2007).

If PEF stops at the saturation level (Fig. 3), the scenario of the further evolution can be different. At small level of disintegration, the cells can partially reseal (Knorr et al. 2001). But higher level of disintegration usually results in further increase of Z after a relatively long time (Lebovka et al. 2001; Angersbach et al. 2002) and acceleration of the thermally induced damage as shown in Fig. 3. The nature of the PEF-induced transient effects is not fully understood yet and requires more thorough study in the future.

2.3 Optimal Energy Consumption

Characteristic damage time τ depends on the tissue type (Lebovka et al. 2002), which can be explained by cell size differences, membranes nature and constitution, and tissue porosity. Characteristic damage time in the limit of very high fields τ_∞ reflects resistance of material to the PEF-treatment (Fig. 5a). The higher is the value of τ_∞, more treatment time is needed to destroy material. For example, the value of τ_∞ decreases in the following order: banana → apple → carrot (Bazhal 2001; Bazhal et al. 2003).

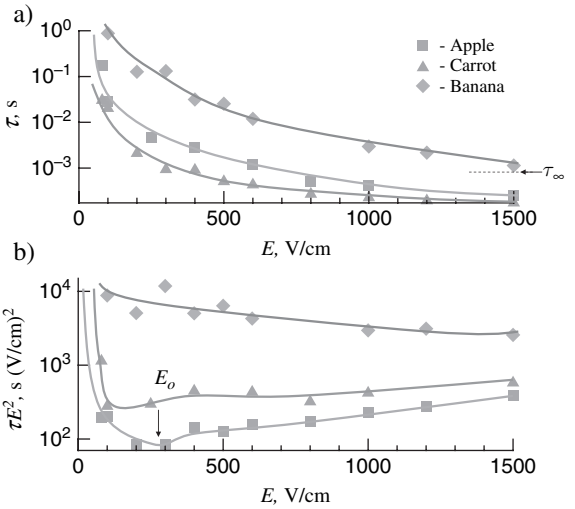

Fig. 5 Characteristic damage time τ (**a**) and product τE^2(**b**) versus electric field intensity E for apple, carrot and potato. The PEF-treatment was done at $T = 20°C$ (Bazhal 2001; Bazhal et al. 2003)

High disintegration of tissue requires sufficient power consumption, associated with PEF-treatment. The volume density of the energy input Q during the PEF-treatment is equal to

$$Q = \int_0^t \sigma(t) E^2 dt, \tag{12}$$

where the electrical conductivity of tissue σ increases with time t owing to damage.

The energy consumption Q is roughly proportional to the product τE^2 (Lebovka et al. 2002). As $\tau(E)$ decreases with increase of the electric field strength E, the product τE^2 goes through a minimum (Fig. 5b). The optimum value of E_o at minimum power consumption corresponds to the minimum of the product τE^2.

The further increase of E results in progressive increase of the energy consumption, but gives no additional increase in the conductivity disintegration index Z. For vegetable and fruit tissues, the typical values of E_o lie in the range of $E = 200$–500 V/cm (Bazhal et al. 2003).

2.4 Synergetics of PEF and Thermal Treatments

Separate application of the PEF processing at a moderate electric field strength ($E<100$ V/cm) and at a room temperature, or of the thermal processing at a moderate temperature ($T<50°C$) without any electric field, require a long time of (PEF or thermal) treatment, and high energy consumption as a consequence. The

simultaneous PEF and thermal treatment exerts a synergetic effect on the tissue damage (Lebovka et al. 2005a, 2005b, 2007a).

This effect can reflect structural transitions, which are possible inside membranes at elevated temperatures. The tissue membranes consist of different lipids and other species, and their phase transitions are possible within the temperature interval of 20–55°C (Exerova and Nikolova 1992; Mouritsen and Jørgensen 1997). In the vicinity of phase transition softening of the membranes occurs, pores arise more easily, and electroporation can be stimulated at smaller fields. A noticeable drop of the breakdown transmembrane voltage was experimentally observed near the temperature of thermal softening of a single membrane ($\approx$50°C) (Zimmermann 1986).

In cellular tissues, the characteristic damage time was dropping by many orders of magnitude (Fig. 6) with increase of temperature T or electric field strength E (Lebovka et al. 2007a). Relations between the characteristic damage time τ and electric field strength E, or temperature T, may be rather complex. The experimental data for potato tissue were fitted successfully by the following equation (Lebovka et al. 2005a):

$$\tau_m = \tau_\infty \exp W/kT(1 + (E/E_o)^2), \tag{13}$$

where τ_∞, W, and E_0 are adjustable empirical parameters.

Note that that this equation is mathematically simple and resembles Equation (5) in its form. It has no any fundamental justification based on the mechanisms of electroporation processes in tissues.

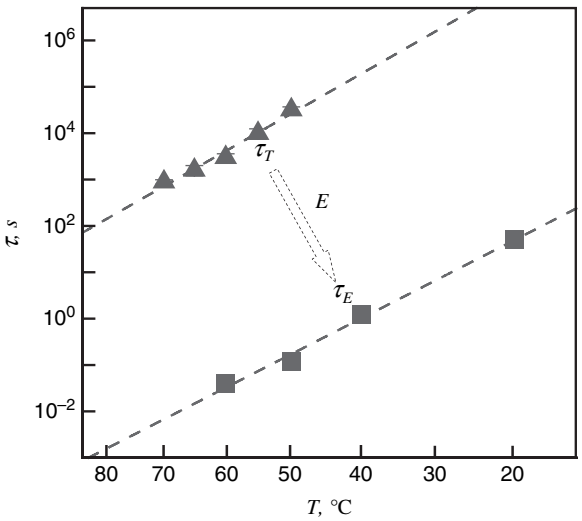

Fig. 6 Temperature dependencies of electric τ_E and thermal τ_T characteristic damage times for sugarbeet tissue. The PEF-treatment was done at $E = 100$ V/cm (Lebovka et al. 2007a)

2.5 Electroporation during Ohmic Heating

When the current flows through the tissue, the ohmic heating develops. It causes a temperature rise, which can be estimated using the following differential equation:

$$dT/dt = \sigma E^2/\rho C. \tag{14}$$

Here, ρ is the density and C is the specific heat capacity of tissue; also, adiabatic regime implying very small thermal exchange with environment is assumed.

Direct application of Equation (14) for estimation of the temperature $T(t)$ evolution in tissues is not simple, because the time t function of electrical conductivity σ is unknown.

The linear temperature dependencies are typical for electrical conductivity of both damaged and intact tissues (Fig. 7a):

$$\sigma = \sigma_o(1 + \alpha(T - T_o)/(1 + \alpha T_o)), \tag{15}$$

where σ_o is the electrical conductivity at the reference temperature T_o, and α is the temperature coefficient of the electrical conductivity.

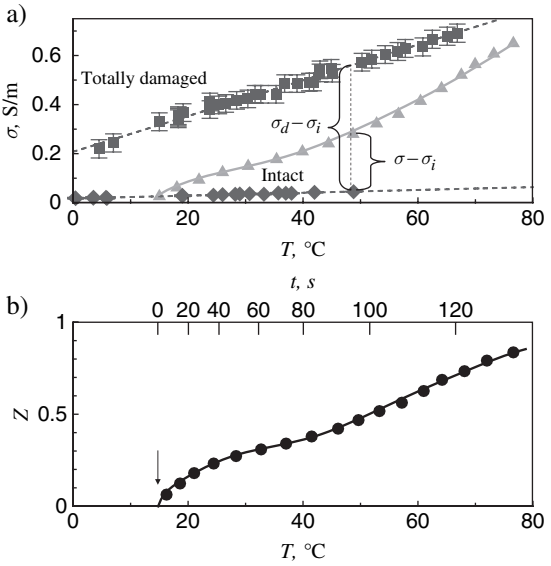

Fig. 7 Temperature dependence of electrical conductivity $\sigma(a)$ and conductivity disintegration index $Z(b)$ of an ohmically treated sugarbeet tissue at $E = 60$ V/cm. Dashed lines in (**a**) show the temperature dependency of conductivities (σ_d and σ_i) in the totally damaged and intact tissues, respectively. Upper axis in (**b**) corresponds to the time of treatment t

As an example, for sugarbeet tissue, $\sigma_{o,i} = 0.018 \pm 0.004$ S/m, $\alpha_i = 0.036 \pm 0.007/^{\circ}$C for the intact and $\sigma_{o,d} = 0.21 \pm 0.\ 05$ S/m, $\alpha_d = 0.035 \pm 0.003^{\circ}$C for the maximally disintegrated tissue (Lebovka et al. 2007a).

When electrical conductivity is a linear function of temperature, the integration of Equation (14) results in

$$T = T_o + (\exp(\sigma_o E^2 t / C\rho) - 1)/\alpha, \tag{16}$$

Changes in the tissue structure, electrically induced during its ohmic heating, can be essential (Wang and Sastry 2002). The ohmic heating at electric fields E of the order of 20–80 V/cm induces changes of electroporation nature, as it was observed for potato and apple tissues (Lebovka et al. 2005a, 2005b). So, electrical conductivity may be a complex nonlinear function of time, temperature, electric field strength and damage degree.

The direct monitoring of electroporation changes can be done by experimental measurements of the conductivity evolution during the ohmic heating (Fig. 7a). The conductivity disintegration index can be estimated from Equation (8) using experimentally measured temperature dependencies of the conductivities of intact σ_i and totally damaged σ_d tissues. This procedure is schematically demonstrated in Fig. 7b for sugar beet tissue (Lebovka et al. 2007a)

It seems to be very promising to select a pulse protocol suitable for the PEF-treatment at a moderate electric field and to apply simultaneously the ohmic heating for the same product.

2.6 Damage as a Function of Pulse Protocol

Experiments show that application of electrical pulses can exert several different effects on the cell membrane, which depend on various pulse parameters; such as amplitude, shape, duration t_p, number of repeats n, and intervals between pulses Δt (Canatella et al. 2001). Also, the relevant parameters are treatment temperature and initial ionic strength. Criteria of optimal protocol selection are not precisely understood yet.

2.6.1 Electric Field Strength and Total Treatment Time

Sale and Hamilton (1967) defined the applied electric fiend strength E and the total treatment time t_{PEF} ($t_{PEF} = nt_i$) as the main relevant parameters determining efficiency of the PEF damage. The higher electric field strength leads to better damage efficiency (Canatella et al. 2001; Toepfl et al. 2007), but as it was noticed in Section 2.3, the optimal values of the electric field strength for many vegetable and fruit tissues are within $E = 300$–500 V/cm. The time dependence of the disintegration degree may reach plateau at long times of the PEF-treatment by smaller electric fields. Also, the electrical power consumption noticeably increases at a moderate electric field in the range of $E < 100$ V/cm (Lebovka et al. 2007b). The damage

efficiency clearly correlates also with the total time of treatment t_{PEF} (Lebovka et al. 2000a), but it is evident that main processing parameters E and t_{PEF} do not completely account for the experimentally observed behavior related to PEF-induced effects.

2.6.2 Waveforms

The pulse shapes commonly used in PEF generators are exponential decay and square wave. Furthermore, pulse shapes may be either monopolar or bipolar. The square-wave generators are more expensive and require more complex equipment than the exponential decay generators. But square wave generators have better energy performance and demonstrate higher disintegrating efficiency in experiments with microcells inactivation (Zhang et al. 1994).

Bipolar pulses are more advantageous than monopolar ones. Successive monopolar pulses can produce high concentration of the space charge near electrodes due to migration of ions and living cells. Bipolar pulses cause additional stress in the membrane structure and enhance damage efficiency. It was also reported that bipolar pulses offer minimum energy consumption, with reduced deposition of solids on the electrodes and decreased food electrolysis (Chang 1989; Qin et al. 1994; Wouters and Smelt 1997).

2.6.3 Intervals Between Pulses

An interval between pulses Δt was shown to effect the PEF disintegration efficiency of the apple tissue (Lebovka et al. 2001). The protocol with $\Delta t = 60$ s displayed accelerated kinetics of disintegration in comparison with that of $\Delta t = 10^{-2}$ s for the fixed total treatment time t_{PEF}. It was unexpected, because the resealing processes can mask electropermeabilization at long time intervals between pulses. The obtained results can be explained accounting for PEF acceleration of the moisture diffusion transfer processes inside the cellular structure. Influence of the pulse delaying time on the inactivation of *E. coli* was reported (Evrendilek and Zhang 2005), but explanation of the observed results is still ambiguous. The further experiments are needed to clarify the effect of interval between pulses on the disintegration efficiency.

2.6.4 Pulse Duration

Literature lacks sufficient information regarding the effect of pulse duration on the PEF-induced disintegration of tissues at the fixed total treatment time. Existing works discuss mainly the effects of pulse duration in the PEF inactivation experiments with different microorganisms (Martin-Belloso et al. 1997; Wouters et al. 1999; Raso et al. 2000; Mañas et al. 2000; Aronsson et al. 2001; Abram et al. 2003; Sampedro et al. 2007).

Some authors have demonstrated that inactivation was more efficient at higher pulse width at invariable quantity of the applied energy (Martín-Belloso et al. 1997;

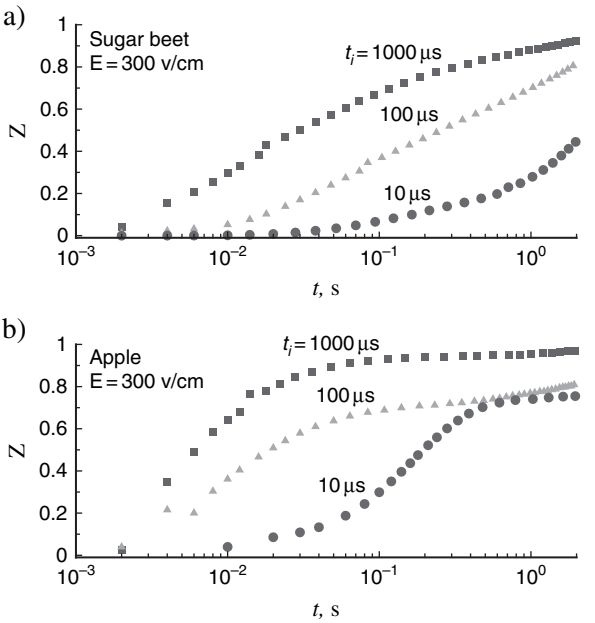

Fig. 8 Electrical disintegration index Z of sugar beet (**a**) and apple (**b**) tissues versus PEF-treatment time t_{PEF} at different pulse durations $t_i = 10$, 100, 1000 μs. The PEF-treatment was done at $T = 20^{\circ}$C, $E = 300$ V/cm, and $\Delta t = 100$ μs (De Vito et al. 2008)

Abram et al. 2003), but others observed little effect of the pulse width on inactivation (Raso et al. 2000; Mañas et al. 2000; Sampedro et al. 2007). The effect of pulse width seems to vary depending on electric field strength; still, the obtained results are controversial (Wouters et al. 1999; Aronsson et al. 2001).

Note that theory predicts deceleration of the membrane charging processes for large cells and for extracellular medium with low electrical conductivity (Kotnik et al. 1998). The membrane charging time t_c may be rather large, $t_c \approx 10^{-5}-10^{-4}$ s, for cellular tissues with large cells (Fig. 1). An efficient PEF-treatment requires long pulse duration t_i as compared with membrane charging time t_c in order to reach the maximum transmembrane voltage. At larger values of t_c the longer pulses will be required for attaining the desired voltage amplitude. So, we can expect higher PEF efficiency for longer pulse width t_i at invariable total treatment time and other conditions. Experiments clearly showed the effect of pulse duration t_i (10–1000 μs) on the efficiency of the PEF-treatment of sugar beet (Fig. 8a) and apple (Fig. 8b) tissues. Longer pulses were more effective, and their effect was particularly pronounced at room temperature and moderate electric fields ($E = 100$–300 V/cm) (De Vito et al. 2008). But general relationships between the PEF-treatment protocols, type and quality of soft tissues, process parameters (temperature, geometry and size of samples, etc.), and the resulting degree of material disintegration are not completely clear and require more thorough study in the future.

3 PEF-Enhanced Expression, Diffusion, and Drying

3.1 Solid–Liquid Expression from Food Plants

Extraction by pressing, called also solid–liquid expression is widely used in production of sugar, wine, fruit and vegetable juices (Schwartzberg 1997). Different equipment like screw presses, belt presses, hydraulic presses, or filter-presses, are employed for expression of juices from the raw food materials. The cellular juice is initially enclosed in cells, which have to be ruptured for the expression.

Pressing at a moderate pressure is usually insufficient for the effective rupture of cells. Different pretreatment operations (fine grinding of raw material, heating, and enzyme maceration) assure the cell rupture and intracellular liquid release to facilitate pressing. However, intensive mechanical, thermal, or enzymatic treatment causes plant tissue degradation and juice pollution. A multistage juice clarification is then needed (Albagnac et al. 2002, Van der Poel et al. 1998).

The PEF application as a pretreatment operation before pressing and combination of PEF with pressing allows to increase significantly the juice yield and to obtain products of higher quality (Eshtiaghi and Knorr 1999; Bazhal 2001; Bazhal et al. 2001; Bouzrara 2001; Bouzrara and Vorobiev 2000, 2001, 2003; Jemai and Vorobiev 2002, 2006; Lebovka et al. 2003; Praporscic 2005; Praporscic et al. 2005; Chalermchatand and Dejmek, 2005; Toepfl 2006).

3.1.1 Example of a Laboratory Device for the Combined Pressing and PEF-Treatment

The laboratory device developed in the University of Technology of Compiegne (UTC) (Fig. 9) permits both pretreatment and intermediate treatment by PEF. The treatment cell has a polypropylene frame with a cylindrical cavity compartment (20 mm thick, 56 mm in diameter), which should be initially filled with gratings and then closed from both sides by steel covers. A mobile electrode is attached to the elastic rubber diaphragm. A stationary wire gauze electrode is installed between the filter cloth and the layer of gratings. Both electrodes are connected to the PEF generator, which can provide the monopolar or bipolar pulses of near-rectangular shape. The pulse duration t_i can be varied within the interval of 10–1000 μs, and the pulse repetition time Δt can be varied within the interval of 1–100 ms. Pulse protocols (E, t_i, Δt, number of pulses n) and all the output data (current, voltage, electrical resistance and actual mass of extracted juice) are collected using a data logger and a special software. The pressure of compressed air is applied to the layer of gratings through the mobile electrode and elastic diaphragm.

3.1.2 Kinetics of Solid–Liquid Expression and Quality of Juices

Eshtiaghi and Knorr (1999), Bouzrara (2001), Bouzrara and Vorobiev (2000, 2001, 2003), Jemai and Vorobiev (2002, 2006), Praporscic et al. (2005) studied the effects

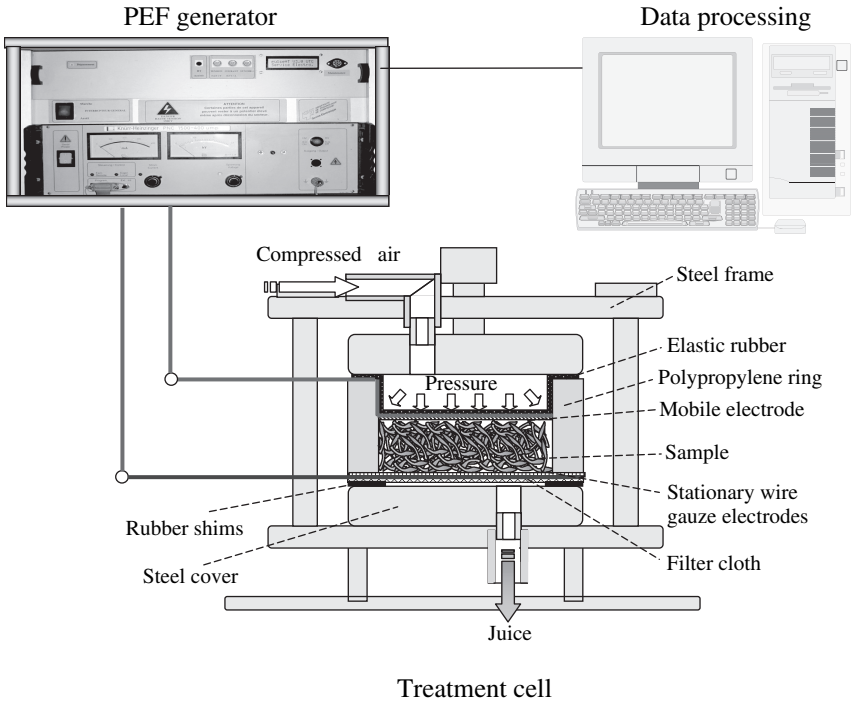

Fig. 9 Experimental setup

of PEF-pretreatment and intermediate treatment on the efficiency of sugar beet pressing.

Bouzrara and Vorobiev (2001) have studied the pressing of slices obtained by grating a sugar beet root on a 6 mm grater. After initial pressurization of gratings inside the treatment chamber (Fig. 9), the juice yield was about 19.1% at 5 bars. Application of the PEF (500 pulses, pulse duration of 100 μs, pulse frequency 100 Hz) markedly enhanced the juice yield, which rises to 43%, 68%, and 79% respectively for voltage gradients of 215 V/cm, 300 V/cm, and 427 V/cm. Initial pressurization of slices serves to assure a good electrical contact between them. Moreover, during pressurization some quantity of released cellular juice is expressed from the treatment chamber. As a result, the quantity of solid–liquid mixture remained in the treatment chamber and to be treated by PEF decreases. Therefore, the intermediate PEF-treatment leads to minimization of the electrical energy consumption. Taking into account the juice yield evolution as a function of both intensity of the PEF and pulse number, Bouzrara and Vorobiev (2001) have demonstrated that the energy input needed for effective intermediate PEF-treatment of the pressurized sugar beet gratings was just 0.6–1 W-hour/kg of raw material. The PEF-pretreatment of coarse gratings unsaturated by the released juice was inhomogeneous and less efficient (Bouzrara and Vorobiev 2000, 2001; Praporscic et al. 2005). In addition to PEF parameters, other factors, such as compressive pressure

(studied in the range of 0.5–10 bars) and size of sugar beet gratings (studied widths: 1.5, 3, 4, 5, 6 and 7 mm, length 5 mm and thickness 1.5 mm) have been reported to have significant effects on efficiency of the expression process (Bouzrara and Vorobiev 2000, 2001; Bouzrara 2001).

Bazhal and Vorobiev (2000) have demonstrated improvement of the juice extraction from Golden Delicious apple slices by solid–liquid expression with an intermediate PEF-treatment. The slices were obtained by grating an apple on a 6-mm grater. The laboratory filter press cell was similar to that presented in Fig. 9. When pressure was varied from 1 to 30 bars, the juice yield after the first pressing increased from 28% to 61%. The maximum juice yield was attained at the energy input of 3 kJ/kg of raw material.

Bouzrara (2001) studied the solid/liquid expression of the carrot gratings at their intermediate PEF-treatment with voltage gradients of $E = 180$, 225, 270 and 360 V/cm, $t_i = 100$ μs and frequency $f = 100$ Hz. The overall treatment time t_{PEF} was 5 s. The carrot slices were grated on a 6 mm grater and pressed at 5 bars. An intermediate PEF-treatment permitted to increase the juice yield from 25.6% to 38.3% at 180 V/cm and to 72.4% at 360 V/cm. A threshold of the juice yield was noted for the energy input about of 1.5 Wh/kg of raw material.

Efficacy of the PEF-treatment was also demonstrated for expression of juices from spinach (Bouzrara 2001), haricots, topinambours and red cabbages (Vorobiev et al. 2002), potatoes and onions (Vorobiev et al. 2004), artichokes (Marchal et al. 2004), and grapes (Praporscic et al. 2007a).

The plant tissue conditioning by mild heating at 45–50°C leads to its softening and influences textural properties of foods (apples, carrots, potatoes). Lebovka et al. (2004a, 2004b) has demonstrated that such conditioning enhances expression kinetics. Both thermal and PEF-pretreatments of plant tissue result in increase of the juice yield during its further expression. A combination of these methods clearly demonstrates the synergetic effect (Vorobiev and Lebovka 2006). Ohmic heating (OH) additionally to thermal effect is believed to induce electopermeabilization of the cell membranes (Wang and Sastry 2002). Praporscic et al. (2005, 2006) have compared the effects of moderate OH and PEF-treatments on kinetics of the juice expression from sugar beet gratings. These authors also explored the combined action of the said two treatments. OH accelerates expression kinetics even at mild temperatures (30–50°C). However, only at higher temperature of OH (60°C), the yield of the expressed juice was comparable to that obtained with PEF. A synergetic effect is remarked when the sugar beet tissue was conditioned by OH with further PEF-treatment (Praporscic et al. 2005). However, while the energy consumed by PEF was low (1–5 kW-hour/t of raw material), the OH applied at 40°C during 10 min consumed nearly 40 kW-hour/t of the raw material (Praporscic et al. 2005).

An important advantage of the PEF-treatment is acceleration of the juice expression from coarse particles. It has been demonstrated (Praporscic et al. 2005) that quantity of juice expressed from small ($1.5 \times 1 \times 35$ mm), middle ($6 \times 1.5 \times 35$ mm) and coarse ($7 \times 3 \times 35$ mm) sugar beet gratings differs less importantly with the PEF-treatment than without it. It means that the size of particles subjected to juice expression can be increased with the PEF-treatment without any noticeable impact

on the juice yield. The impact of the particle size on the quantity of expressed sugar juice becomes nearly negligible after conditioning of the tissue by mild heating followed by PEF-treatment (Praporscic et al. 2005).

The abovementioned studies were mainly focused on the impact of PEF on the juice yield enhancement, and only few of them investigated the qualitative characteristics of the expressed juices (Bouzrara and Vorobiev 2001, 2003; Vorobiev et al. 2005, Toepfl 2006).

Bouzrara and Vorobiev (2001) compared the physicochemical characteristics of the expressed cold sugar beet juices: after the first pressing (before PEF application) and after the intermediate PEF-treatment followed by second pressing. The second pressing juice after the PEF application was less colored and had higher sugar concentration than the first pressing juice.

Later on, Jemai and Vorobiev (2006) confirmed that cold juices expressed from sugar beet gratings after the intermediate PEF-treatment (second pressing juice) have higher purity values (95∼98%) as compared to that after the first pressing (90∼93%). Additionally, the quantity of pectin was noticeably lower in the second pressing juice, which facilitates its following purification. The color of the second pressing juice was systematically 3–4 times lower than the color of the first pressing juice and factory juices. Moreover, sugar crystals, obtained after evaporation and crystallization of the PEF-treated juices, were less colored that sugar crystals obtained from the factory juice. The pulp obtained after the PEF-treatment and juice expression contained 3–5 times more α-amino nitrogen and 2–3 times more sodium and potassium compared to sugar factory pulp (Jemai and Vorobiev 2006). These results showing significant amelioration of the qualitative juice characteristics open new interesting perspectives of a cold PEF-enhanced expression from the sugar beets.

Praporscic et al. (2007b) has studied evolution of the quantitative (juice yield) and qualitative (absorbance, °Brix) characteristics of juices obtained by expression from apple ($7 \times 3 \times 30$ mm) and carrot ($1.5 \times 2 \times 30$ mm) slices prepared using the food cutting equipment CL 50 (Robot-Coupe S.N.C., France). The arrows show the time of PEF application (Fig. 10).

As it can be expected, the PEF application results in more pronounced additional expression of juice. The absorbance and °Brix, presented in Fig. 10, are instantaneous values characterizing small portions of the expressed juice at a given mean time of expression t. These portions were collected in different containers, which were changed every 60 s during the first 1200 s of pressing and every 600 s during the remaining period. The PEF application results in considerable decrease of absorbance immediately after the electrical treatment. Note that the absorbance can increase slightly after $t > 3–5 \cdot 10^3$ s. This behavior seems to reflect the effects of color degradation at long time. The juice °Brix value of untreated slices is nearly constant or decreases with expression time increase. The PEF-treatment always results in substantial increase of the juice °Brix value immediately after the electrical treatment. A rather complex behavior of both absorbance and °Brix values reflects a balance between the input and output of juice inside a sample and changes in filtration properties of the press-cake formed from slices during expression. It is not

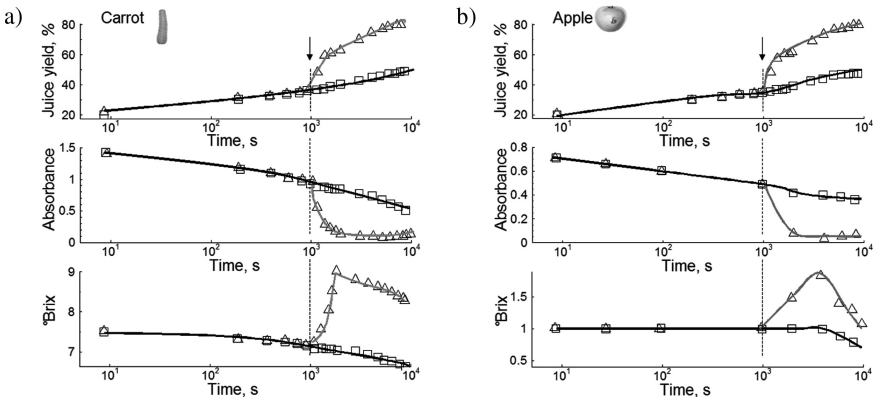

Fig. 10 Juice yield, absorbance, and °Brix kinetic curves for carrot (**a**) and apple (**b**) gratings with intermediate PEF-treatment

surprising that concentration of the solid particles and colored substances in a juice may decrease during the juice filtration through more compacted press-cake. Visually, the expressed juice becomes more transparent and less cloudy during pressing. It can be speculated that °Brix increase after the PEF-treatment (Fig. 10) is related to the release of the intracellular content as a result of the damage of cells.

Recently, Praporscic et al. (2007a) investigated quantitative (juice yield) and qualitative (absorbance and turbidity) characteristics of juices obtained during expression of white grapes (Muscadelle, Sauvignon, and Semillon). The experiments were carried out at expression pressure of 5 bars using laboratory compression chamber equipped with a PEF-treatment system (Fig. 9). The PEF with field strength $E = 750$ V/cm and the total treatment duration $t_{PEF} = 0.3$ s was applied. The total expression time was 45 min. Similar to apple and carrot samples, the intermediate PEF application resulted in substantial increase of the juice yield and decrease of the juice absorbance and turbidity. Figure 11 shows data on the final yield Y_f, absorbance A_f, and turbidity T_f of the juices obtained with the PEF-pretreatment (left columns) and without PEF-treatment (right columns). The PEF-treatment results in increase of the final juice yield Y_f up to 73–78% as compared to $Y_f \approx 49$–54% for the untreated grapes; that is, PEF-pretreatment increases the juice yield, approximately, by 25%. A rather noticeable decrease of absorbance A_f and turbidity T_f was observed for all the studied white grape varieties as a result of the PEF-treatment. In PEF-pretreatment experiments, the juice absorbance A_f and turbidity T_f were lower, but the electrical energy consumption was higher than for the intermediate PEF-treatment (Praporscic et al. 2007a).

If the valuable components (aromas, colorants, etc.) should be extracted from the food plants, washing, and water diffusion operations are frequently used as supplementary to pressing. The serious limitations of these technologies are related to a necessity to use large quantities of water (the ratio of $r =$ (mass of water)/(mass of slices) should be larger than 3, as a rule) and long time of washing (more than several

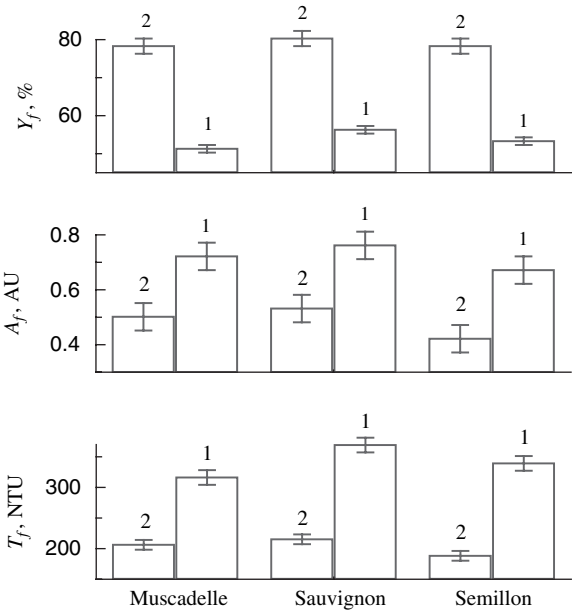

Fig. 11 Different final characteristics of the expressed juices (juice yield Y_f (%), absorbance A_f and turbidity T_f (NTU)) (1) without PEF and (2) with PEF-pretreatment

hours) (Albagnac et al. 2002). Grimi et al. (2007) studied the PEF-induced effects in juice extraction from the carrot slices using different combinations of pressing and washing operations. The carrot was chosen as a representative vegetable material, which contains both water-soluble (mainly soluble sugars) and non-water-soluble (carotenoids) components. The different cutting degrees varying from mash-like slices S_1 ($0.078 \times 0.078 \times 2$ mm) and S_2 ($0.15 \times 0.15 \times 2$ mm) to millimeter-sized slices S_3 ($1.5 \times 1 \times 20$ mm) and S_4 ($7 \times 2 \times 30$ mm) were used for finding a relationship between the juice characteristics and applied mode of extraction. Extraction included the PEF-pretreatment followed by the washing–pressing (PEF–W–P mode) or pressing–washing–pressing (PEF–P–W–P mode), and intermediate PEF-treatment after washing during pressing (W–P–PEF mode). The same PEF intensity (500 V/cm) was used in all the experiments. All the PEF-treatments were applied as follows: $n_t = 2$ trains of $n = 100$ rectangular pulses, each one lasting $t_i = 100$ μs, with pulse repetition time $\Delta t = 100$ ms. A pause of $t_p = 2$ s separated the trains.

This PEF protocol permitted to reach a higher degree of the electrical disintegration index without any substantial temperature increase (it was less than 2°C). The experiments were carried out at expression pressure of 5 bars using a laboratory compression chamber equipped with a PEF-treatment system (Fig. 9). The total extraction time (pressing + washing) was approximately 1 hour. Figure 12 compares the evolution of the solution °Brix values for PEF–washing–pressing (PEF–W–P), washing–pressing–PEF (W–P–PEF), and PEF–pressing–washing–pressing (PEF–P–W–P) modes of extraction from large slices S_4 at $r = 1$. The data shows that

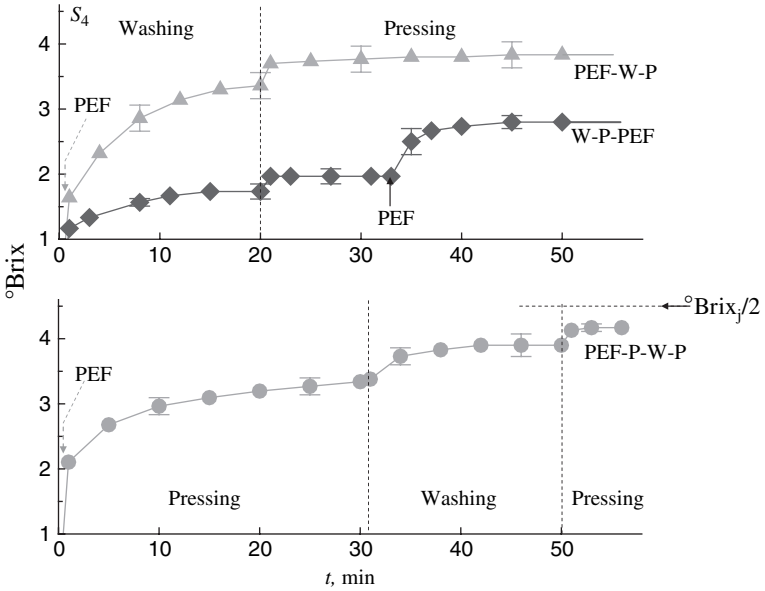

Fig. 12 °Brix of solution versus time for PEF–washing–pressing (PEF–W–P (▲)), washing–pressing–PEF (W–P–PEF (♦)) and PEF–pressing–washing–pressing (PEF–P–W–P (●)) modes of extraction. The slices were of size S_4, and the mass of slices was equal to the mass of water ($r = 1$). Symbols show the experimental data and lines are drawn for the guidance of eye. Arrows show the time of the PEF-treatment. The error bars represent the standard data deviations

PEF–P–W–P mode of extraction is most efficient and allows to obtain extracts with high final °Brix values, which are comparable with °Brix values of the diluted juice solutions.

Turbidity of solutions extracted from the PEF-pretreated large slices S_4 was 400–450 NTU, which is significantly lower than turbidity of solutions extracted from fine slices S_1 (1600–1700 NTU). It reflects a low content of the submicron particles in solutions. But PEF-pretreatment requires higher energy consumption as compared with the PEF intermediate treatment (W–P–PEF mode). For the specific case of the carrot, where carotenoids are practically insoluble in water, it can be assumed that their content in the juice is proportional to the level of solid particles in solution. This conclusion was supported by spectrophotometrical data for the juice extracts in cyclohexane (Grimi et al. 2007).

Both washing–pressing (PEF–W–P) and pressing–washing–pressing (PEF–P–W–P) procedures show approximately the same ability for concentration of carotenoids inside the press-cake, though the second procedure releases the water-soluble component inside the juice more efficiently. The considered example of PEF application to extraction from large slices of carrot evidences that it is possible to produce from the press-cake a ‘sugar-free’ concentrate rich in vitamins and carotenoids, which can be used as an additive in diet foods.

Figure 13 shows the photo of pilot filter press CHOQUENET adapted for the pressing-washing operations combined with PEF-treatment. This filter-press is installed in the University of Technology of Compiegne (UTC). Another pilot equipment—the screw press developed in UTC for the combined pressing and PEF-treatment operations—is presented in Fig. 14.

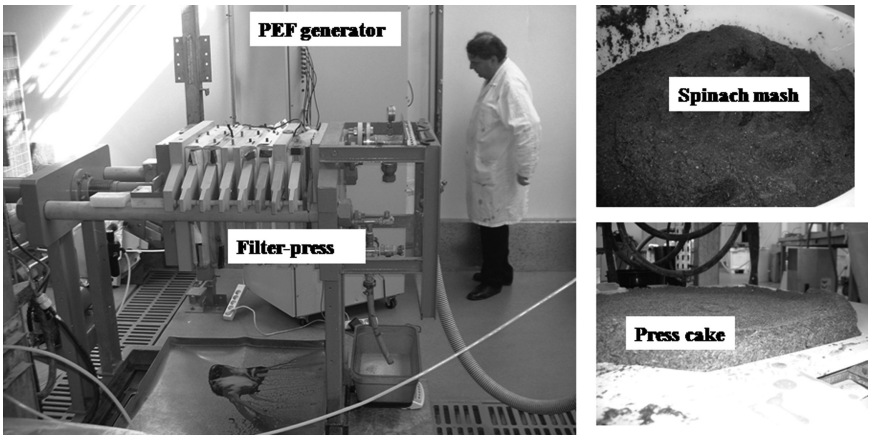

Fig. 13 The pilot filter press CHOQUENET adapted for the pressing–washing operations combined with PEF-treatment

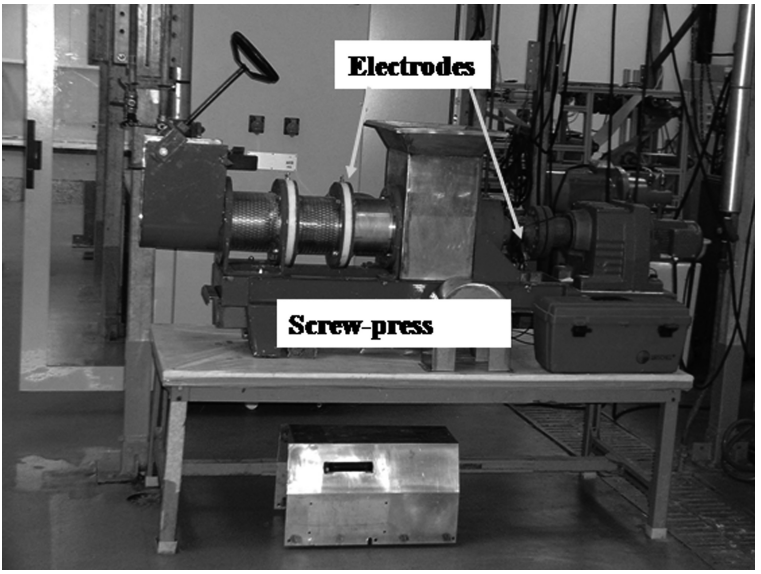

Fig. 14 The pilot screw press developed in UTC for the combined pressing and PEF-treatment operations

3.2 Aqueous Extraction of Solutes from Food Plants

Solvent extraction from the food plants is an important unit operation in different industrial applications (extraction of sugar, vegetable oils, natural colorants, aromas, and other valuable cell components) (Schwartzberg and Chao 1982). The modern chemical philosophy, known as green chemistry, seeks to avoid the use of dangerous and polluting solvents and encourages the use of eco-friendly solvents like water. However, the plant cells remain undamaged contacting with cold or warm water. Just water heated at least to 65–70°C destroys the cell membranes and permits the soluble matter diffusion from interior of cells. For example, the thermal treatment of beet tissue at 70–74°C is used for sugar diffusion in industrial sugar processing. Unfortunately, such elevated temperatures result in overheating of the cell walls leading to their continuous alteration and to release of polluting substances affecting the purity of juices. Overheating changes the inner chemical structure of cell walls through hydrolytic degradation reactions. For instance, the amount of pectin passing into the juice increases sharply with temperature rise, which complicates considerably the sugar juice purification (Van der Poel et al. 1998).

The PEF-treatment is a suitable alternative for achievement of a nonthermal membrane breakdown permitting cold (warm) aqueous diffusion of valuable plant substances. Recently, several studies dealing with the PEF effect on solute extraction from the food plant tissue were performed (Jemai and Vorobiev 2002, 2003; Fincan et al. 2004; El-Belghiti and Vorobiev 2004, 2005a, 2005b; El-Belghiti 2005; El-Belghiti et al. 2005; Corrales et al. 2008).

3.2.1 Diffusion Kinetics and Qualitative Characteristics of Extracts

Jemai and Vorobiev (2002) compared kinetics of diffusion from the apple discs (Golden delicious) after their thermal denaturation (75°C, 2 min) and after PEF-treatment at different field intensities ($E = 100$–500 V/cm) and treatment duration (1000 monopolaires rectangular pulses of 50 μs, 100 μs, and 200 μs). A detectable enhancement of the diffusion kinetics starts at the field intensities of 100–150 V/cm. For thermally treated samples, the temperature variation of the diffusion coefficient D is of Arrhenius type with two diffusion regimes: (i) without thermal pre-treatment ($E_a \sim 28$ kJ/mol) and (ii) after thermal denaturation ($E_a \sim 13$ kJ/mol). Only one regime with intermediate activation energy ($E_a \sim 20$ kJ/mol) was observed for electrically treated samples.

El-Belghiti and Vorobiev (2005b) investigated the influence of the energy provided by PEF (0–55 kJ/kg) on kinetics of extraction from the carrot slices obtained by grating carrot in a 6 mm grater (1.5 mm thick coarse slices) or in a 2 mm grater (0.5 mm thick fine slices). Diffusion of slices occurred to a limited volume of stirred surrounding water (liquid-to-solid mass ratio $r = 2$) kept at different moderate temperatures (18–35°C). In the absence of PEF-pretreatment, only 45% of solute was obtained from the coarse slices after 8 h of extraction at 18°C. On increase of energy provided by the PEF-pretreatment, the quantity of the extracted solute increased accordingly (up to 90–93%), until the energy threshold (9 kJ/kg)

was attained. No further enhancement of the solute yield was observed above this threshold. The energy input of 9 kJ/kg (attained at $E = 550$ V/cm, t_i = 100 μs and $n = 1000$ pulses) was considered as optimal and was maintained to optimize the diffusion parameters (duration, temperature, and stirring velocity). The results showed that fine and coarse slices had almost the same extraction kinetics after the PEF-treatment. That confirms attractiveness of PEF-treatment especially for the coarse particles.

El-Belghiti and Vorobiev (2005b) El-Belghiti et al. (2005) have studied the influence of the PEF intensity and duration on the static and centrifugal aqueous extraction from coarse sugar beet slices (1.5 mm in thickness) obtained on a 6 mm grater. There was observed a static diffusion of treated and untreated slices to a limited volume of well-stirred surrounding water (liquid to solid mass ratio $r = 3$) kept at different moderate temperatures (25–50°C). The yield of solute was significantly increased with PEF-treatment: it was about 40% for untreated slices and attained 93% after the PEF-treatment ($E = 670$ V/cm, $t_{PEF} =$ 0.025 s, energy input 5–6 kJ/kg) and 2 hours of extraction at ambient temperature. Majority of the cellular membranes were probably permeabilized at these levels of PEF intensity and duration. Further increase of the PEF intensity up to 800 V/cm was not effective. The temperature elevation to 50°C permitted to accelerate diffusion kinetics and to obtain 93% of solutes after the 40 min of extraction. Centrifugal diffusion of slices was done with the same liquid to solid mass ratio $r = 3$ and under different centrifugal accelerations (150–9660 g), and temperatures (18–35°C). The extraction kinetics was much faster in the centrifugal field. For instance, the yield of solute after the PEF-treatment reached 97% after 60 min of extraction even at the low centrifugal acceleration (14 g) and at the temperature of 25°C. There was observed existence of an acceleration threshold (150 g) beyond which no further enhancement of extraction occurred. At this centrifugal acceleration, the solute concentration of 97% was reached after 25 min of aqueous extraction at 25°C and just after 15 min of aqueous extraction at 35°C.

Industrial diffusion of sugar from the sugar beets is carried out at the elevated temperatures of 70–74°C with beet tissue preheating at 80–90°C (Van der Poel et al. 1998). Lebovka et al. (2007a) compared kinetics of thermal diffusion and diffusion coefficients for untreated and PEF-treated sugar beet slices. The PEF generator provided the trains of bipolar pulses of near-rectangular shape. Bipolar mode of the PEF-treatment allows to avoid asymmetry of electroporation at the poles of the cells. An individual train consisted of n pulses with pulse duration t_i and pulse repetition time Δt. There was a pause of $\Delta t_\mathrm{t} = 30$ s after each train. Owing to the long intertrain pause, the ohmic temperature elevation ΔT during one train application was rather small ($\Delta T \approx 1$°C). Therefore, the system relaxed to the initial temperature during the intertrain period and the PEF-treatment was done practically under isothermal conditions. The total time of electrical treatment during the PEF experiments was calculated as $t_t = nNt_i$, where N is the number of trains. The maximally damaged sugar beet tissues ($Z \approx 1$) were obtained at $E = 400$ V/cm and $t_t = 0.1$ s.

Diffusion of the electrically treated and untreated slices (1.5 mm × 10 mm × 10 mm) occurred to a limited volume of well-stirred surrounding water (liquid to

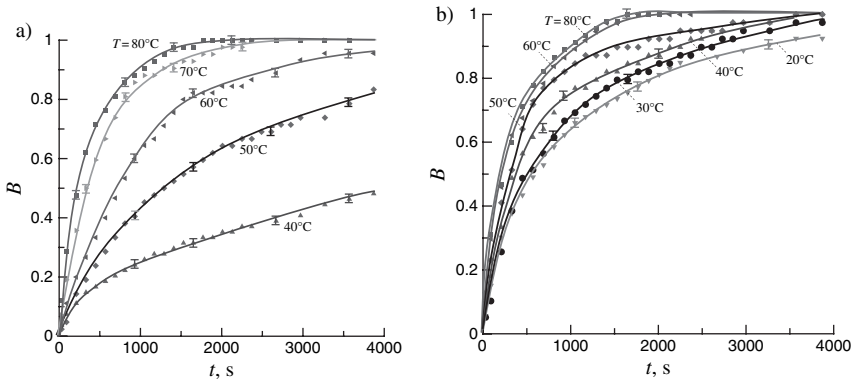

Fig. 15 The normalized Brix of the sugarbeet juice B versus extraction time t for the untreated (**a**) and PEF-pretreated (**b**) slices at different temperatures. The PEF pretreatment was done at the electric field strength $E = 400$ V/cm. Error bars are the standard deviation

solid mass ratio $r = 3$) kept at different temperatures (20–80°C). Figure 15 shows data of extraction kinetics at different temperatures ($T = 30$–80°C) presented as B versus time t, where B is the normalized °Brix of the sugar beet juice defined as

$$B = \frac{^{\circ}\text{Brix} - ^{\circ}\text{Brix}_{\text{i}}}{^{\circ}\text{Brix}_{\text{f}} - ^{\circ}\text{Brix}_{\text{i}}} \tag{17}$$

Here, $^{\circ}\text{Brix}_{\text{i}}$ and $^{\circ}\text{Brix}_{\text{f}}$ are the initial and the final soluble matter content, respectively. Both temperature increase and PEF-pretreatment accelerated the extraction kinetics (Fig. 15a, b).

For purposes of simplicity, Lebovka et al. (2007a) had assumed that the slices were thin slabs of a uniform thickness, and the Fick's second law solution (Crank 1975) was used for estimation of the effective sugar diffusion coefficient D_{eff} in a sugar beet:

$$B = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4h^2}\right) \tag{18}$$

where $h \approx 1.5$ mm is the thickness of a slab. The first five leading terms of Equation (4) were taken into account for D_{eff} estimation.

The Arrhenius plots of D_{eff} are presented in Fig. 16 for untreated and PEF-pretreated sugar beet slices. At 70°C, the values of D_{eff} were nearly the same for both untreated and PEF-pretreated slices (1–1.5·10^{-9} m^2/s). The activation energy for the PEF-treated slices was $W_{E,D} = 21 \pm 2$ kJ mol^{-1}, which is close to the activation energy of sugar in the aqueous solutions, $W_D \approx 22$ kJ/mol (Lysjanskii 1973). The activation energy was noticeably higher, $W_{T,D} = 75 \pm 5$ kJ/mol, for the untreated

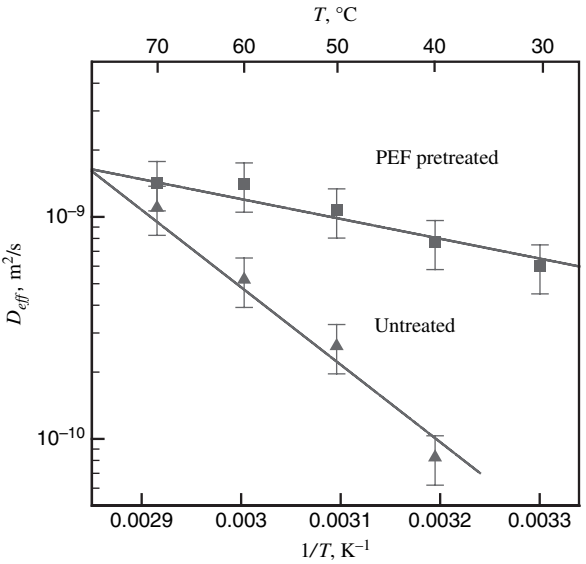

Fig. 16 The Arrenius plots of the effective diffusion coefficient Deff for untreated and PEF-pretreated sugar beet slices. Error bars are the standard deviation

slices, which possibly reflects interrelations of the restricted diffusion and thermally induced damage effects in the untreated sugar beet tissue.

As can be seen from Fig. 16, sugar diffusivity inside the PEF treated tissue remains rather high even at moderate temperatures. For instance, the value of D_{eff} is nearly the same for the PEF treated tissue at 50°C and for the untreated tissue at 70°C. It opens new possibilities for energy saving in the sugar beet production. Another interesting effect of the PEF-treatment is the higher juice purity (Lebovka et al. 2007a). The purest juice is obtained after the cold diffusion (Fig. 17). However, even after the thermal diffusion at 70°C, juice purity was higher for slices pretreated by PEF than for untreated slices.

Recently, El-Belghiti et al. (2008) studied the PEF-enhanced extraction from thin and coarse fennel gratings of seven different sizes in order to obtain extracts, which can be used as natural food preservatives (antioxidants). The finest gratings GR1 and GR2 were obtained by crushing using Urschel crusher (Urschel Laboratories Inc., Valparaiso, USA). The coarse gratings GR3–GR7 were obtained by cutting using the slicer CL 50 (Robot-Coupe SNC, France).

Different moderate pulsed electric field intensities $E = 0$–600 V/cm and number of pulses $N = 0$–850 was used to electropermeabilize the cell membranes and to accelerate the following extraction. Figure 18 presents kinetics of extraction from untreated (a) and PEF-treated (b) fennel gratings of different sizes. As can be seen from Fig. 18a, extraction kinetics from the finest gratings GR1 and GR2 was very rapid even without PEF-treatment and the final solute yield reached 98% after just 30 min of extraction. This indicates that almost all the cells were broken

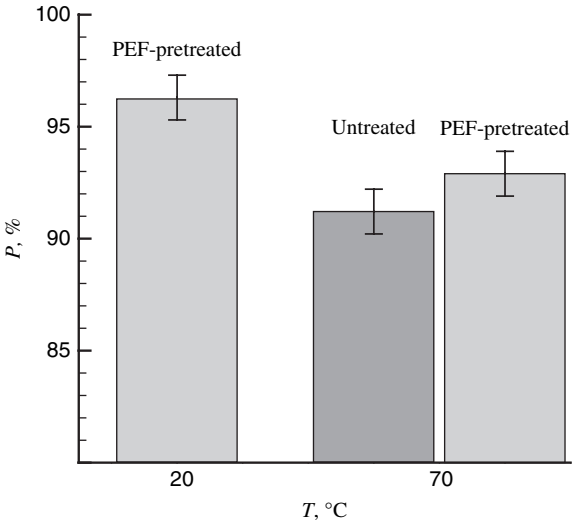

Fig. 17 Purity of the diffusion solutions at different temperatures for the untreated and PEF-pretreated slices

mechanically during the crushing. The PEF application did not accelerate the extraction kinetics for such gratings. However, extraction of the coarse grating was considerably improved after the optimal PEF-treatment, and the final solute yield of 98% was attained even for largest gratings GR6 and GR7 (Fig. 18b).

The optimal PEF-treatment was different for the gratings of different sizes. Generally, with increase of the gratings size from GR3 to GR7, the optimal PEF intensity increased from 300 to 600 V/cm and the optimal number of pulses increased from 200 to 900. This leaded to the increase of the PEF energy input from 2 kJ/kg to 3 kJ/kg for the smallest gratings GR3 to about 40 kJ/kg for the largest gratings GR7.

Expectedly, turbidity of the extracts obtained from coarse gratings was significantly lower than one obtained from thinner gratings. It was higher than 400 NTU for the gratings GR1 and lower than 50 NTU for the gratings GR7. Similarly, absorbance of the coarse gratings was lower than absorbance of the fine gratings. The PEF-treatment application somewhat decreased the turbidity and absorbance of gratings of the same size. Evidently, it is preferable to apply the PEF-treatment for solutes diffusion from coarse fennel gratings (GR3–GR7). Alternatively, extraction from coarse gratings can be assured by the hot water. That is why El-Belghiti et al. (2008) compared water diffusion from the coarse fennel gratings (GR5) treated by PEF and damaged thermally at 60–90°C. While kinetics of extraction from the coarse gratings was significantly accelerated due to thermal denaturation of the fennel tissue, the qualitative characteristics of extract were worse than after the PEF-treatment (Fig. 19). With the increase of heating temperature, the degradation

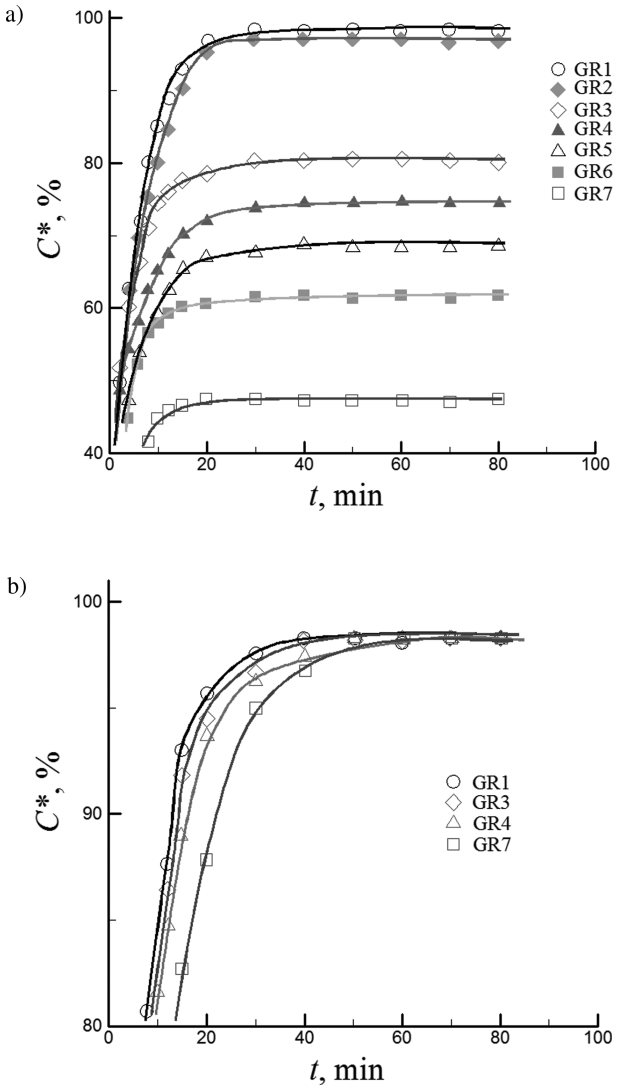

Fig. 18 Extraction kinetics $c^*(t)$ from untreated (**a**) and optimally PEF-treated (**b**) fennel gratings, where c^* is the ratio c/c_∞, c being the actual solutes concentration in solution and c_∞ being the equilibrium solute concentrations. The sizes of gratings: GR1 ($0.1 \times 0.4 \times 6$ mm), GR2 ($0.2 \times 0.8 \times 12$ mm), GR3 ($0.5 \times 1.9 \times (25–50)$ mm), GR4 ($0.75 \times 1.5 \times (30–50)$ mm), GR5 ($1.2 \times 2.6 \times (30–60)$ mm), GR6 ($1.6 \times 3.5 \times (25–75)$ mm) and GR7 ($1.8 \times 6 \times (30–60)$ mm). The optimal parameters of the PEF treatment: GR3 – $E = 300$ V/cm, $N = 200$; GR4 – $E = 350$ V/cm, $N = 350$; GR7 – $E = 600$ V/cm, $N = 900$

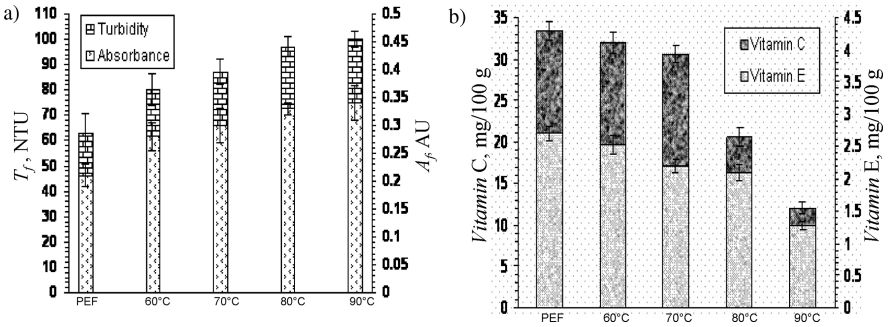

Fig. 19 Turbidity and absorbance (**a**) and concentration of vitamins (**b**) in extracts obtained after the PEF and thermal extraction from coarse gratings GR_5

of cell structure and intracellular components is more pronounced. A repercussion is observed on the extract characteristics (Fig. 19).

Another disadvantage of thermal extraction is a high energy consumption exceeding considerably the energy consumed by PEF-treatment. For instance, the energy consumption for the thermal extraction from fennel gratings GR5 at 60–90°C was approximately 500–650 kJ/kg, while it was just 15 kJ/kg for the same gratings treated by PEF

3.3 Osmotic Dehydration with PEF

Osmotic dehydration (OD) naturally occurs in the foods, such as fruits and vegetables, placed in a hypertonic sugar or salt solution presenting a high osmotic pressure and a low water activity. Diffusion phenomenon takes place with two simultaneous countercurrent flows: a water flow from the food to the outer solution and a simultaneous flow of solute from the solution to the food. These mechanisms lead to water loss (*WL*) and solid gain (*SG*) in the food. The OD process occurs at mild temperatures (up to 50°C) and requires less energy compared to drying. Therefore, it improves the product color and flavor retention. However, the cellular membrane exerts a high resistance to transfers, thus slowing down the OD rate. Recently, the PEF has been successfully applied for enhancing OD of different food plants, such as apples, carrots, mangos, and red bell peppers (Ade-Amowaye et al. 2001, 2002; Amami et al.2006; Amami et al. 2007a, 2007b).

Figure 20a and 20b show the influence of the electric field intensity E on the water loss $WL(g/g) = (W_0 - W)/S_0$ and solid gain $SG(g/g) = (S - S_0)/S_0$ for an apple sample placed in a sucrose solutions (44.5, 55 and 65 Brix) at ambient temperature (Amami et al. 2006). W_0 and W are, respectively, the initial and actual weight of moisture in the sample; S_0 and S are, respectively, the initial and actual weight of dry matter in the sample. Increase of the electric field intensity E up to

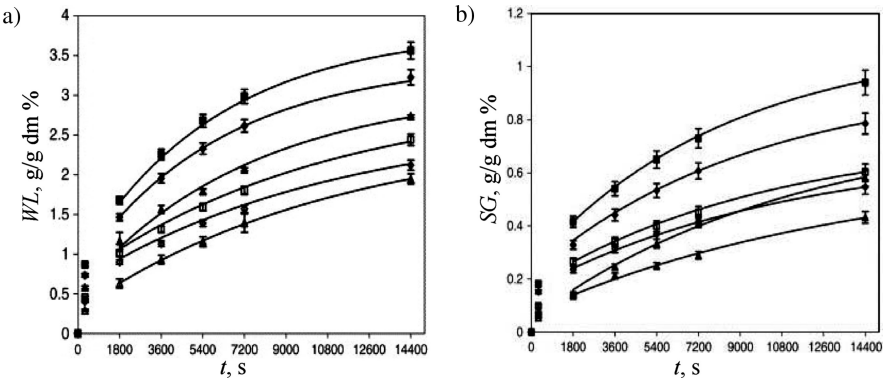

Fig. 20 Water loss (**a**) and solid gain (**b**) as functions of time for the OD of apple disk at room temperature in solutions of different concentration: *squares*, 65 $Brix_0$; *diamonds*, 55 $Brix_0$; *triangles*, 44.5 $Brix_0$. *Open symbols*: without treatment, *full symbols*: with PEF-treatment (0.9 kV/cm, 750 pulses of 100 μs each), line corresponds to predictions of the Fick's diffusion model

0.9 kV/cm and the number of rectangular pulses (pulse duration $t_i = 0.1$ ms) up to $n = 1000$, resulted in improvement of both *WL* and *SG*.

The energy consumption at the above PEF parameters was 21 kJ/kg. Reduction of n to 750 pulses (total duration of PEF application $t_{PEF} = t_i \cdot n = 10^{-4} \cdot 750 = 0.075$ s) just reduced slightly *WL* and *SG*, but minimized the energy consumption to 12 kJ/kg. The *WL* increase (∼50%), observed in Fig. 20 for experiments with PEF-treatment, was more impressive than that of *SG* (∼6%). Such a low value of *SG*, obtained for PEF-pretreated samples, might offer an advantage for the OD process in some applications requiring simultaneously high *WL* assorted to minimum solute uptake. Another example of a reduced solid gain in comparison to water loss was indicated for bell pepper (Ade-Amowaye et al. 2002). It is already known that PEF-treatment damages mainly the cell membranes; while other structural changes, induced in plant tissue by PEF, remain limited. Therefore, penetration of solids inside the tissue during OD may be retarded or blocked because of the structure resistance, which remains almost unchanged. However, the OD mechanism consecutive to PEF-treatment is not yet well elucidated. Some other examples of PEF-treatment prior to OD were also recently addressed (Teijo et al. 2002). Mango pieces treated with PEF (2.67 kV/cm, 100 pulses of 0.84 ms) were immersed in a 50°Brix sucrose solution at 40°C for 5 hour. The PEF effect on *WL* was not significant, but *SG* was slightly increased (from ≈ 0.63 g/g to ≈ 0.82 g/g) (Teijo et al. 2002). Recently, Amami et al. (2007a, 2007b) have demonstrated that the combined effect of PEF, centrifugal field and salts could enhance *WL* from the carrot tissue. Addition of salt during the static and centrifugal OD resulted in *WL* and *SG* increases; however, the *WL/SG* ratio remained approximately the same during the static OD. The combination of PEF with salt enhanced additionally both *WL* and *SG*. The application of centrifugal field during OD enhanced *WL* but reduced *SG*. Therefore, the *WL/SG* ratio was increased in the centrifugal field; however salt addition decreased this

ratio. If gain of solids is also the goal of OD (confectionary additives, for example), the static OD may be better than centrifugal OD, which is especially interesting in the case of desirable limitation of the solid uptake (dietetic products).

3.4 Drying of Food Plants

Removing of moisture from the food materials allows to minimize microbial activity and undesirable chemical reactions (Barbosa-Canovas and Vega-Mercado 1996). But commonly used hot-air drying or freeze-drying techniques are limited by high energy consumption and long drying times. Moreover, drying at elevated temperatures can produce undesirable changes in pigments, vitamins and flavoring agents (Aguilera et al. 2003). In general, the drying processes consume an appreciable part of the total energy used in food industry, and so it is very important to develop the new hybrid drying technologies for energy saving and preserving of food quality (Chou and Chua 2001).

Different pre-treatment drying techniques, such as microwave heating (Beaudry et al. 2003), ohmic heating (Salengke and Sastry 2005; Zhong and Lima 2003), electrohydrodynamic drying (Bajgai and Hashinaga 2001; Cao et al. 2004; Li et al. 2005), and drying by chemical reagents or osmotic pre-treatment (Chua et al. 2004), were reported.

Recently, the PEF-treatment at high and moderate fields have been proposed for enhancement of the drying processes (Ade-Omowaye et al. 2003; Toepfl 2006; Lebovka et al. 2006; Lebovka et al. 2007b; Shynkaryk 2007). The PEF-treatment seems to be a promising non-thermal method that provides interesting advantages for enhancement of drying of the thermally sensitive food materials.

3.4.1 Drying Kinetics and Moisture Diffusion Affected by PEF Cell Disintegration

Electrically assisted drying is characterized by decrease of processing time, temperature, and energy consumption. Electrically induced disintegration of the plant cells facilitates diffusivity of the moisture and can enhance drying. Figure 21 demonstrates the effects of PEF-treatment on potato tissue drying at 50°C in a convective dryer (Lebovka et al. 2007b). Here, the drying curves are presented as ω versus time *t,* where the dimensionless moisture ratio ω is determined as

$$\omega = (M(t) - M_e)/(M_o - M_e), \tag{19}$$

where M is the moisture content in a sample, and the subscripts o and e refer to the initial and equilibrium (final) moisture content, respectively.

The drying rate passes through the maximum near $\omega \approx 1$, when the excess surface moisture is removed, and then it decreases with decrease of ω (insert in Fig. 21). The drying process proceeds at the falling rate and no period of constant drying rate is observed. The constant rate-drying period usually reflects the presence of

a continuous layer of free water that covers the surface (Zhang et al. 1997). The absence of the constant rate stage indicated importance of internal mass transfer processes and can be also explained by the shrinkage factor (May and Perré 2002).

The drying time was affected considerably by the drying temperature and freeze-thawing or PEF-pretreatment (Lebovka et al. 2007b). The higher the total treatment time of the PEF-treated potato tissue, the more rapid was the drying process (Fig. 21). The PEF-treatment of material releases moisture from the damaged cells and enhances the transport processes, which results in increase of the drying rate.

The drying rate can be characterized by the effective moisture diffusion coefficient D_{eff} determined through solution of the Fick's second law (Crank 1975):

$$\omega = 8/\pi^2 \sum_{i=0}^{\infty} (2i+1)^{-2} \exp\left(-(2i+1)^2 \pi^2 D_{eff}\, t/4h_s^2\right). \tag{20}$$

This equation is valid for an infinite slab with thickness h_s.

The diffusion coefficient D_{eff} was estimated from the least square fitting of this series expansion to the experimental drying curves (Lebovka et al. 2007b). The diffusion coefficient D_{eff} increased with increase of the damage degree P and was a non-linear function of the conductivity disintegration index Z (Fig. 22). In approximation of the parallel model of diffusion (Saravacos and Raouzeos 1984), the diffusion coefficient can be presented as (Lebovka et al. 2007b)

$$D_{eff} = P D^d_{eff} + (1-P) D^i_{eff} = Z^{1/m} D^d_{eff} + (1 - Z^{1/m}) D^i_{eff} \tag{21}$$

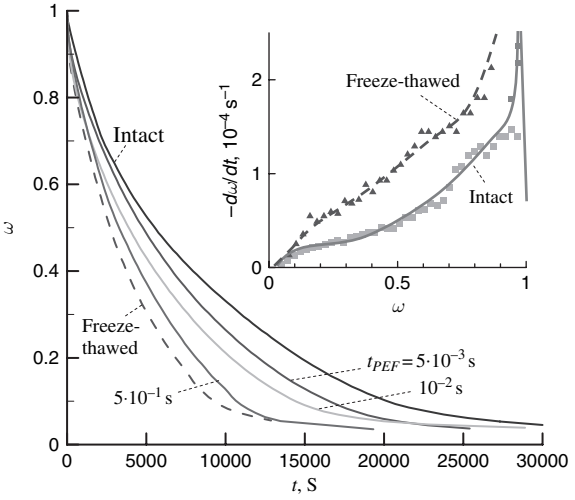

Fig. 21 The moisture ratio ω versus drying time t for intact, PEF-treated and freeze-thawed (*dashed line*) potato tissues at 50°C drying temperature. Insert shows drying rate curves as $d\omega/dt$ versus ω. The volumetric flow rate was 6 m^3/hour.The PEF-pre-treatment was done at room temperature, $T = 25$°C, electric field strength $E = 400$ V/cm, pulse duration $t_i = 10^{-3}$ s, pulse repetition time $\Delta t = 10^{-2}$ s, and different treatment time t_{PEF}, shown at the figure

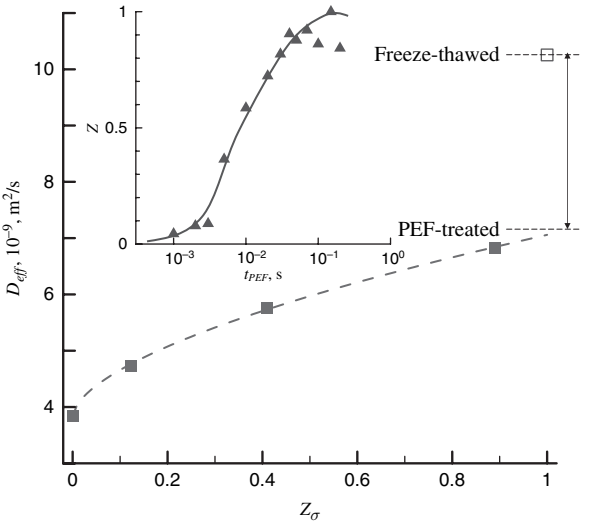

Fig. 22 Effective diffusion coefficient D_{eff} versus conductivity disintegration index Z for PEF pre-treated potato tissues. Insert shows conductivity disintegration index Z versus total treatment time t_{PEF}. The volumetric flow rate was 6 m^3/hour, the drying temperature was 50°C. The PEF-pretreatment was done at a room temperature, $T = 25$°C, electric field strength $E = 400$ V/cm, pulse duration $t_{\text{i}} = 10^{-3}$ s, pulse repetition time $\Delta t = 10^{-}$. The open square show the data for tissue pre-treated by freeze-thawing

where D^i_{eff}, D^d_{eff} are diffusion coefficients of the intact and totally PEF-damaged tissues, respectively. Here, Archie's equation (Equation (10)) relating P and Z was used.

The Archie's exponent m of 1.68 ± 0.04 was estimated by the least square fitting of the experimental data to Equation (21). This result was consistent with other estimations of m values for different biological tissues (Lebovka et al. 2002).

The drying rate and diffusion coefficient D_{eff}, observed for the freeze-thawed tissue, exceed noticeably the same parameters for the totally PEF-damaged tissue with $Z \approx 1$ (Fig. 22). It reflects differences in the structures of the freeze-thawed and PEF-damaged potato, as it was demonstrated by the textural studies (Lebovka et al. 2004a). It is known that drying processes can be noticeably influenced by the structure, density, and porosity of materials (May and Perré 2002).

Very similar accelerating effect of AC-treatment on convective air-drying was also observed at a moderate electric field strength ($\leq$100 V/cm) (Lebovka et al. 2006). The experimental results evidence essential influence of the electric field strength E and the total electric energy input W on the drying rate. The effective moisture diffusivity increases with E and W increase.

Figure 23 presents effective diffusion coefficient D_{eff} of moisture for intact, AC-treated and freeze-thawed potato tissues at two different drying temperatures (30 and 50°C). At air drying temperature 50°C, the effective diffusion coefficient D_{eff} of moisture for AC-treated potato tissue was still lower ($D_{eff} \approx 0.71 \cdot 10^{-8}$ m^2/c)

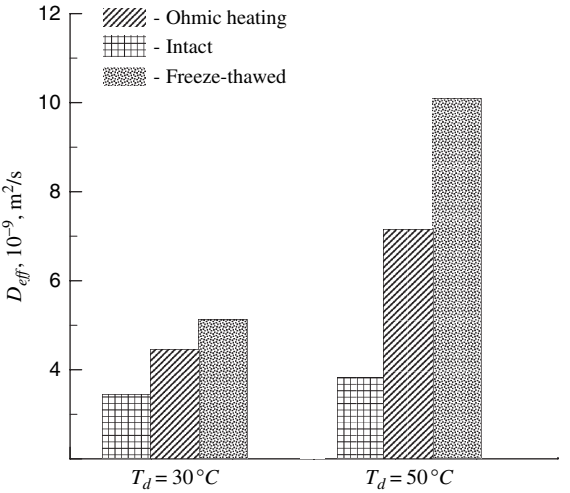

Fig. 23 Moisture effective diffusion coefficient D_{eff} for intact and AC- and freeze-thawing pretreated potato tissues. Here, T_d is the drying temperature. The volumetric flow rate was 6 m^3/hour. The ohmic heating pre-treatment was done using AC at starting room temperature $T = 25°C$, and electric field strength $E = 100$ V/cm; the samples were heated to the temperature of about 50°C, the total electric energy input was $W \approx 100$ kJ/kg and disintegration index was $Z \approx 0.7$

than that of the freeze-thawed pretreated potato ($D_{eff} \approx 1.0 \cdot 10^{-8}$ m^2/c), even at the highest degree of destruction $Z \approx 0.7$. At a low air drying temperature ($T = 30°C$), the AC treatment allowed to increase the moisture diffusivity to a level noticeably higher than that observed for an intact tissue at drying temperature 50°C.

Though the highest drying rate was always observed for the freeze-thawing pretreatment, this process is rather energy consuming and requires ≈ 280 kJ/kg (Toepfl and Knorr 2006). Thermal drying at the elevated temperatures is also energy consuming and it can cause undesirable changes in the product quality. The AC pretreatment allows to decrease the drying temperature, approximately, by 20°C for potato tissue, and this method seems to be promising for enhancing the air drying processes for this product.

Similar effects in drying behavior were also observed for the red beetroot tissues (Shynkaryk et al. 2008; Shynkaryk 2007). The PEF or freeze-thawing pre-treatment allowed to increase noticeably the moisture diffusivity (for the same drying temperature T_d), or to decrease the drying temperature, approximately, by 20–25°C (for the same level of diffusivity D_{eff}).

The activation energies W of moisture diffusion in intact, PEF- and freeze-thawing pretreated red beetroot, potato and apples tissues are presented in Table 1 (Lebovka et al. 2007b; Shynkaryk et al. 2008; Shynkaryk 2007). Differences between activation energies seem to reflect variety of structures of the untreated and pretreated tissues. However, direct correlations between the mode of treatment (PEF or freeze-thawing) and values of W were not observed for different materials.

Table 1 The activation energies of moisture diffusion W (kJ mol^{-1}) for intact, PEF- and freeze-thawing pretreated tissues. The drying temperatures T_d was within 30–90°C (Lebovka et al. 2007b; Shynkaryk et al. 2007)

		Pretreated by	
Dried products	Untreated	PEF ($Z \approx 1.0$)	Freeze-thawing ($Z \approx 1.0$)
Red beetroots (Unknown variety)	20.2 ± 2.3	19.2 ± 0.3	17.6 ± 1.3
Potatoes (Agata)	21 ± 1	20 ± 2	27 ± 4
Apples (Golden)	25.2 ± 1.8	18.6 ± 1.8	20 ± 3

3.4.2 Temperature Evolution

The temperature factor is very important for degradable food materials, where the undesirable changes in pigments, vitamins and flavoring agents are possible (Aguilera et al. 2003). Preserving regimes of drying are essential for preparation of such products as red beetroots, apples, currants and grapes. Moreover, changes of porosity and texture on the external surface of material taking place at elevated temperatures can restrict diffusivity and the moisture cannot escape.

Figure 24 shows examples of temperature evolution inside red beetroot versus moisture ratio ω for the untreated and pretreated red beetroot samples at different drying temperatures T_d (Shynkaryk et al. 2007; Shynkaryk 2007). The untreated samples exhibit higher temperature T than PEF- and freeze-thawed pretreated samples with the same moisture content ω. Stability of water-soluble betalaines, contained by red beetroot, is strongly affected by water activity and temperature,

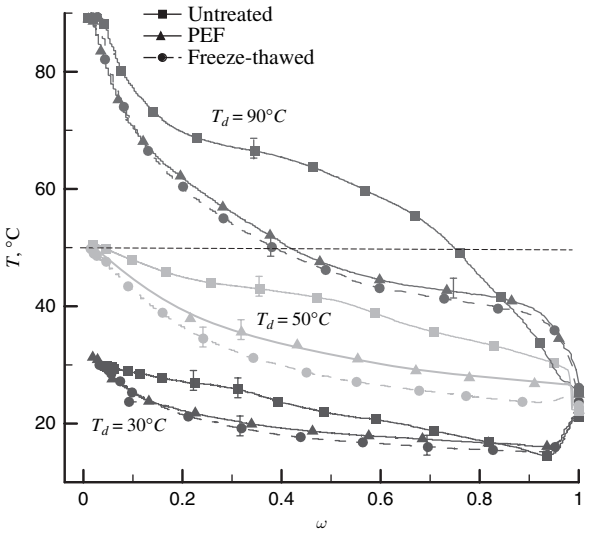

Fig. 24 Temperature in the centre of a red beetroot sample T versus moisture ratio ω for the untreated and PEF and freeze-thawing pretreated tissues at different temperatures of convective air T_d. The lines are drawn for the guidance of the eye and error bars are the standard deviations

and elevated temperatures (>50°C) accelerate degradation of this pigments (Saguy et al. 1978).

Preserving regime of drying is very important for red beetroot for preparation of the product rich in red-purple pigments, and degradation can be expected to diminish at smaller drying temperature and smaller moisture content inside the pre-treated tissues. The moisture content at 50°C ω_{50} remains rather low (<0.4) even when drying temperature $T_d = 90$ for the pretreated tissues, but the values of ω_{50} are noticeably higher for the untreated tissues. Moreover, the obtained spectral data (Shynkaryk et al. 2007; Shynkaryk 2007), demonstrate that PEF-pretreatment is beneficial for drying regimes, as far as it preserves colorants. Although the PEF-pretreatment results in higher tissue shrinkage, as well as in higher time of rehydration, a difference in textural properties of the rehydrated samples with and without PEF-treatment is not essential. So, the observed behavior reflects a possibility of a colorant-safe drying for the pretreated samples, and PEF-assisted drying seems to be promising for enhancing industrial air drying processes.

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