Food Research International 77 (2015) 773–798

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Current applications and new opportunities for the use of pulsed electric fields in food science and industry

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form 5 September 2015
Accepted 15 September 2015
Available online 18 September 2015

Keywords:
Pulsed electric fields
Bioactive compounds extraction
Drying
Freezing
Cold pasteurization
Reduction food contaminants

ABSTRACT

Several studies have demonstrated the feasibility of pulsed electric fields (PEF) for different applications in food industry. PEF technology is therefore a valuable tool that can improve functionality, extractability, and recovery of nutritionally valuable compounds as well as the bioavailability of micronutrients and components in a diverse variety of foods. Additionally, other studies have shown the potential of PEF treatments to reduce food processing contaminants and pesticides. This opens the doors to new PEF applications in the food industry. This review focused on some of the most renowned traditional and emerging PEF applications for improvement of osmotic dehydration, extraction by solvent diffusion, or by pressing, as well as drying and freezing processes. The impact of PEF on different products of biological origin including plant tissues, suspension of cells, by-products and wastes will be analyzed in detail. In addition, recent examples of PEF-assisted biorefinery application will be presented, and finally, the main aspects of PEF-assisted cold pasteurization of liquid foods will also be described.

1. Introduction

Pulsed electric fields (PEF) technology consists on an electrical treatment of short time (from several nanoseconds to several milliseconds) with pulse electric field strength from 100 to 300 V/cm to 20–80 kV/cm (Fincan & Dejmek, 2002; Koubaa et al., 2015; Vorobiev & Lebovka, 2008). At high electric fields (>20 kV/cm), it can constitute an alternative to traditional thermal processing to inactivate alterative and pathogenic microorganisms and quality related enzymes, with the advantage of retaining or minimally modifying sensorial, nutritional and health-promoting attributes of liquid food products (Sánchez-Vega, Elez-Martínez, & Martín-Belloso, 2014).

Under the effect of PEF at low electric fields, the biological membrane is electrically pierced and losses its semi-permeability temporarily or permanently (Barba, Grimi, & Vorobiev, 2014; Deng et al., 2014), which can allow the selective recovery of high-added value compounds from different matrices. In addition, PEF is a promising technology to improve drying and freezing processes.

This review is focused on describing some of the most important challenges and opportunities related to the potential applications of PEF-treatment in food science and industry and includes discussion of: i) phenomenon of electroporation, ii) impact of PEF on different products of biological origin (plant tissues, suspension of cells, by-products and wastes) and biorefinery applications, and iii) different modes of PEF-assisted processing (extraction by solvent diffusion or pressing, osmotic dehydration, drying, and freezing) and cold pasteurization of liquid foods (microbial inactivation, bioactive compounds stability and the potential reduction of food contaminants).

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http://dx.doi.org/10.1016/j.foodres.2015.09.015
0963-9969/

2. Phenomenon of electroporation

The first important steps in the application of PEF for the treatment of biological matrices were done about 50 years ago. In this line, some different groups observed that PEF treatment induced electrical breakdown of cell membranes, known as electroporation (Neumann & Rosenheck, 1972; Stampfli, 1958; Zimmermann, Pilwat, & Riemann, 1974, 1975, 1976; Zimmermann, Schulz, & Pilwat, 1973). This ability of PEF to induce cell electroporation was used for killing microorganisms (Hamilton & Sale, 1967; Sale & Hamilton, 1967). Later on, the different theories of membrane electroporation were worked out (Pakhomov, Miklavčič, & Markov, 2010; Pavlin, Kotnik, Miklavčič, Kramar, & Lebar, 2008; Weaver & Chizmadzhev, 1996) and the application of PEF to induce mechanical, hydrodynamic, osmotic and viscoelastic instabilities were demonstrated (Pakhomov et al., 2010; Weaver & Chizmadzhev, 1996), to develop other new processes.

Experimental works revealed that initiation of electroporation requires some threshold value of the potential difference across a membrane, that is the transmembrane potential, (u_{m}), typically, 0.5–1.5 V (Weaver & Chizmadzhev, 1996). The value of u_{m} depends upon the size and shape of the cells as well as the concentration of cells in suspension or structure and properties of plant tissue. For spherical cells the value of u_m is directly proportional to the size. Experimentally estimated threshold values of electric field strength, E_t, are of the order of 100–500 V/cm for cellular tissues with large cells ($\approx$30–60 μm) (Lebovka, Bazhal, & Vorobiev, 2000) and >3–10 kV/cm for small microbial cells ($\approx$1–10 μm) (Barbosa-Canovas & Altunakar, 2006). Depending on the PEF treatment conditions such as exposure time, (t_{PEF}), reversible electroporation with pore resealing (lasting from seconds to hours) and irreversible electroporation with complete damage of membrane can occur (Pavlin et al., 2008; Teissie, Golzio, & Rols, 2005).

3. Impact of PEF on different products of biological origin

The evaluation of electroporation efficiency in biological plant tissues or suspension of cells is a rather complicated task (Kanduser & Miklavčič, 2008). In general, it requires accounting for inhomogeneous distribution of the local electric fields, distribution of cell sizes and shapes, their state and local solute concentrations, local electrical conductivity, etc. (Canatella, Black, Bonnichsen, McKenna, & Prausnitz, 2004; Pucihar, Kotnik, et al., 2001, 2006, 2007). It was reported that the fraction of electroporated cells decreases with the increase of cell density (Kanduser & Miklavčič, 2008). However, the changes in the electrical conductivity due to electroporation process need to be taken into account (Ben Ammar, Lanoiselle, Lebovka, Van Hecke, & Vorobiev, 2011; Corovic et al., 2013). Fig. 1 demonstrates PEF typical effect on the structure of red beet tissue after aqueous extraction. It can be seen that the intact cells are intensively colored. However, PEF-treated cells with damaged membranes have pale colors and lose their vacuolar sap (Loginova et al., 2011a).

3.1. Plant tissues

In plant tissues, the threshold electric field strength (E_t) increases with the decrease in electrical conductivity constant $k = \sigma_d / \sigma_i$, where σ_d and σ_i are electrical conductivities of damaged and intact tissues, respectively (Ben Ammar et al., 2011). Electroporation efficiency of plant tissues can also be controlled by osmotic flow, moisture redistribution inside the tissue and resealing of cells (Lebovka et al, 2000; Bazhal & Vorobiev, 2000). The PEF-induced moisture redistribution is important in densely packed cell suspensions or cellular tissues, mainly due to the changes in the state of the neighboring cells that can influence the local conductivity. For instance, it is expected that the degree of electroporation increases with the decrease of the local conductivity (Pucihar et al., 2001). Moisture redistribution was justified by PEF-induced long-term changes in electrical conductivity (Angersbach, Heinz, & Knorr, 2000; Lebovka, Bazhal, & Vorobiev, 2001).

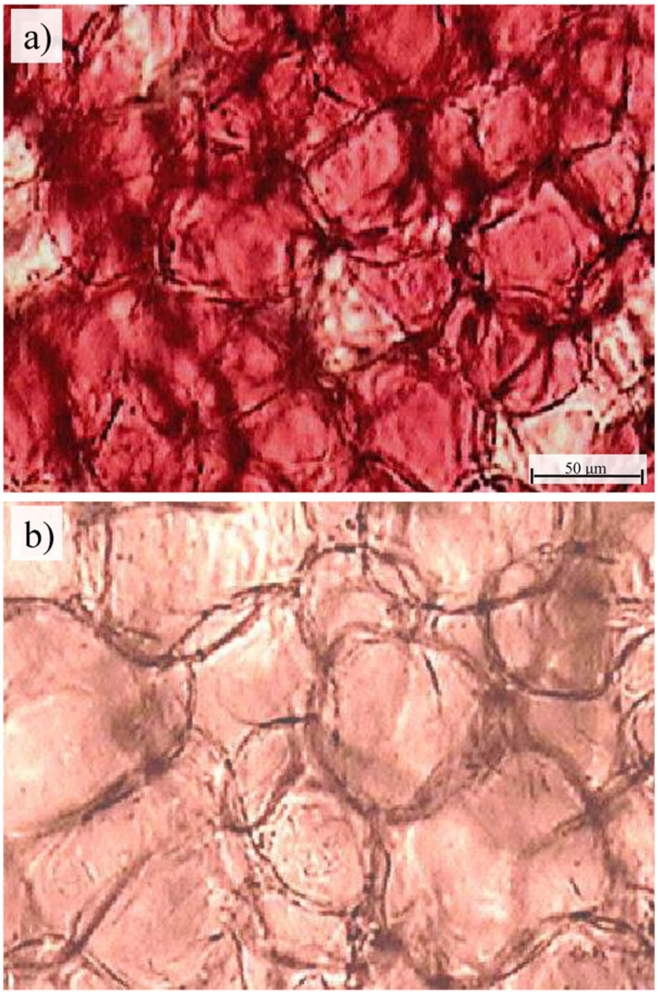

Fig. 1. Microscopic images of the red beet tissue after aqueous extraction: untreated (a) and PEF pre-treated (b).
With permission from Loginova et al. (2011a).

In practice, the electroporation efficiency depends upon details of pulse protocol (Raso & Heinz, 2006; Vorobiev & Lebovka, 2008). The electric field strength, E, and the total treatment time, t_{PEF}, are the main parameters that govern the efficiency of PEF-treatment. Ben Ammar (2011) evaluated the conductivity disintegration index, Z_c, versus the time of PEF treatment, t_{PEF}, for potato and orange. They found that higher electric field strengths lead to better tissue damage. However, at high electric fields, the electrical power consumption becomes essential and ohmic heating intensively occurs.

Note that the electric field strength concentrated on membrane, E_m, can be estimated as $E_m = u_m / d \approx ER / d$, where d is the membrane width ($\approx$5 nm). For food plant tissues, $R \sim 50$ μm, so, E_m can be estimated as $E_m \sim 10^4 E$, i.e., the electric field strength on a membrane can be rather high, $\approx 10^6$–10^7 V/cm and electroporation reflects the membrane instability stimulated by the application of a high electric field. Moderate PEF treatment with relatively low values of E ($\approx$20–100 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 the end of PEF treatment. This sort of electroporation is called as reversible.

At moderate PEF treatment, some of the cells lose their permeability, but other are able to be resealed, and the insulating properties of the cell membrane can be recovered within several seconds after pulse