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Better damage of chicory tissue by combined electroporation and ohmic heating for solute extraction

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A B S T R A C T

Damage of chicory tissue by combined electroporation and ohmic heating is studied for better solute extraction. Moderate (400–1000 V/cm) and high (10,000 V/cm) PEF treatments were applied varying pause duration between the trains of individual pulses. Ohmic heating was induced with increase of the number of trains N. Temperature dependence of tissue damage degree Z is evaluated for the different PEF intensities. With higher ohmic heating, chicory tissue is faster and better damaged. Electric field strengths of 600–800 V/cm combined with ohmic heating permit to enhance noticeably the solute extraction from chicory tissue. The solute diffusivity D for the different PEF treatments, is nearly the same for same values of Z. Chicory tissue treated to the same damage degree (Z = 0.8–1.0) using different PEF conditions (800, 1000 and 10,000 V/cm) has nearly the same diffusivity.

Combined electroporation/ohmic heating pretreatment by moderate PEF (400–1000 V/cm) presents an interesting alterative for the treatment of high product throughputs (e.g. in the case of inulin production from chicory).

Keywords: Chicory; Inulin; Pulsed electric fields; Electroporation; Ohmic heating; Extraction

1. Introduction

Chicory is widely used for the production of inulin which is important food ingredient (Baert, 1997; Park et al., 2007). Inulin is used as a fiber ingredient to improve taste and texture, as fat replacer in dairy industry to produce low-fat dairy products, and as sugar replacer in chocolate to reduce sugar content (Franck and De Leenheer, 2005). However, industrial extraction of inulin from chicory roots requires high temperature (70–80 °C) (Toneli et al., 2008) and long duration (~1.5 h). This leads to cell tissue alteration and impurities release into the inulin juice resulting in a complicated juice purification (Franck, 2006). Thus, investigation of alternative inulin extraction methods is meaningful for energy-saving and technology simplifying.

Pulsed electric fields (PEF) has been proposed as an effective method of non-thermal membrane damage of food plants (Bazhal et al., 2003; Fincan et al., 2004; Vorobiev and Lebovka, 2008a, 2010; Barati et al., 2011; Donsi et al., 2011; Moubarik et al., 2011; Janositz et al., 2011; Toepfl, 2011; Puértolas et al., 2013). Advantages of PEF treatment in terms of promoting extraction process from sugar beet and chicory roots were recently reported (Eshtiaghi and Knorr, 2002; Bouzrara and Vorobiev, 2003; Jemai and Vorobiev, 2003; El Belghiti and Vorobiev, 2004; Lebovka et al., 2007; Loginova et al., 2010, 2011; Maskooki and Eshtiaghi, 2012; Zhu et al., 2012, 2013). In the study of Loginova et al. (2010), the positive effect of PEF treatment for inulin extraction from chicory was evidenced at the laboratory scale with a batch extraction chamber. However, when the moderate PEF of 400–600 V/cm was applied at ambient temperature, the solute diffusivity in the chicory tissue was slower comparatively to the one in the sugar beet tissue (Loginova et al., 2010). Zhu et al. (2012) used a pilot PEF generator and a semi-continuous counter-count extractor in their

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Nomenclature

B	normalized soluble matter content
C	capacity of the capacitor (F)
D	diffusion coefficient (m^2/s)
E	electric field strengths (V/cm)
I	electrical current (A)
m	mass (kg)
n	number of pulses in one train
N	number of trains
P	energy of one electric pulse (J)
Q	specific energy (kJ/kg)
t	time (s)
T	temperature (°C)
t_i	pulse duration (s)
Δt	distance between two pulses (s)
Δt_t	pause between individual trains (s)
t_{PEF}	electrical treatment time (s)
U	voltage (V)
Z	electrical conductivity disintegration index
σ	electrical conductivity (S/m)

Subscripts

i	initial
f	final
D	diffusion

Abbreviation

PEF	pulsed electric field

study. These authors confirmed a rather slow inulin diffusivity in the chicory tissue after the PEF treatment ($E = 400–600$ V/cm) at ambient temperature. It may be speculated that in studies of Loginova et al. (2010) and Zhu et al. (2012) PEF intensities were insufficient for the important cell damage of chicory tissue.

Both intensive electroporation by high PEF treatment and tissue softening by preheating may contribute to the better cell damage and enhance the following solute extraction (inulin, sucrose, polyphenol and colorant). In this work we investigate the different PEF treatment conditions and treatment temperatures for more important cell damage of chicory tissue and for the enhancement of solute extraction from chicory. For the simultaneous electroporation and ohmic heating of chicory tissue, we apply the PEF treatment with short pause between impulses.

2. Materials and methods

2.1. Materials

Chicory roots, which consists of $24.9 \pm 0.2\%$ solid matter, provided by COSUCRA-Belgium, was used for the investigation. The cylinder-shaped samples, which were 20 mm in diameter and 4–10 mm in height, were prepared for PEF treatment. Freeze-thawed sample was prepared at −18 °C for 24 h, then a thawing of sample was done at ambient temperature (Grimi et al., 2010a,b).

2.2. PEF treatment experiments

Fig. 1 shows a schematic diagram of the experimental setup. Two generators were used ensuring moderate (400–1000 V/cm) and high (10,000 V/cm) PEF treatments. The moderate PEF treatment was applied with generator providing the trains of bipolar pulses of near-rectangular shape (Service Electronique UTC, Compiègne, France). An individual train consists of 100 pulses with pulse duration $t_i = 100$ μs and distance between two pulses $\Delta t = 200$ μs. The number of trains (N) was varied from 1 to 65. The temperature elevation during the individual train was about 0.8 °C. In majority of experiments, the pause between the individual trains was fixed at $\Delta t_t = 1$ s. This pause was too short for the noticeable sample cooling. Therefore, ohmic heating was induced with increase of the number of trains N. In some experiments, the pause between the individual trains was increased to $\Delta t_t = 20$ s to nearly avoid ohmic heating during the PEF treatment. The total time of PEF treatment was calculated as $t_t = n \times N \times t_i$.

The treatment cell consisted of a polypropylene cylinder with an inner diameter of 20 mm and an electrode at its bottom (Fig. 1(a)). The sample and electrode has the same diameter and surface, the sample was placed inside the cell, then the second electrode was installed on the top of the sample in order to obtain a good contact without addition of liquid. The distance between electrodes was varied from 10 to 4 mm, which corresponds the electroporation volume of 3.14–1.26 cm^3 and the PEF intensity of 400–1000 V/cm. The temperature inside the sample under the PEF treatment was recorded in the online mode during the inter-train period by a Teflon-coated K-type thermocouple (±0.1 K) connected to the PEF generator. The electrodes were connected to the PEF generator and the electrical conductivity of samples was measured during the inter-train period at the frequency 0.5 kHz, selected as optimal for purposes of removing the polarizing effects on the electrodes and tissue sample. All the output data (current, voltage, electrical conductivity, and temperature) were collected using a data logger and special software adapted by Service Electronique UTC, Compiegne, France.

The high PEF treatment of 10,000 V/cm was applied using the 40 kV PEF generator (Tomsk Polytechnic University, Tomsk, Russia) (Fig. 1(b)) described elsewhere (Boussetta et al., 2012). The electrodes of the treatment chamber were two parallel disks. The electrode area was 95 cm^2. The distance between two electrodes was fixed at 4 cm to attain the PEF intensity of 10,000 V/cm. The volume of electroporation was 3.8×10^2 cm^3 (containing 110 g of chicory disk samples and 330 g water). The water was added in order to obtain a good contact with electrodes. The generator provided exponential decay pulses. Pulse duration was $t_i = 10$ μs (the pulse width is defined as the time until decay to 37% for exponential decay pulses) (Toepfl et al., 2006). One train of 100 pulses was used for the chicory treatment. Temperature and electrical resistance of chicory tissue were measured immediately after the treatment.

2.3. Extraction experiments

Extraction cell was a glass beaker supplied with magnetic stirrer and digital thermoregulator (10–1300 min^{-1}, Fisher Scientific) (Fig. 1c). For moderate PEF (400–1000 V/cm) pretreatment the extraction cell with distilled water (150 g) was preheated at the desired temperature (30 °C), then the electrically treated or untreated chicory samples (50 g) (in disk shape) were placed into the extraction cell. For high PEF (10,000 V/cm) pretreatment 110 g chicory sample and 330 g