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Pulsed electric field assisted vacuum freeze-drying of apple tissue

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ABSTRACT

Impact of apple treatment by pulsed electric field (PEF) on vacuum freeze-drying was studied. Apple discs were PEF treated at an electric field strength of $E = 800$ V/cm for the different values of disintegration index Z. Then vacuum cooling was applied to decrease the temperature to sub-zero level and freeze-drying experiments were done at a pressure of 10 mbar. Time evolution of temperature and moisture content were compared for the PEF treated and untreated apple samples. Acceleration of cooling and drying processes was observed for the PEF treated samples. The microscopic, macroscopic analysis and data of capillary impregnation test evidenced that the PEF treatment facilitates preservation of the shape of the dried samples, allows avoiding shrinking and results in increase of the tissue pores. The sample rehydration capacity strongly depends on Z. At $Z = 0.96$ a high level of rehydration capacity (≈ 1.3) was observed.

Industrial relevance: Different methods of food drying are very popular for food processing and are widely used for food preservation. However, they are very energy intensive processes and can cause undesirable changes of colour, flavour, nutrient and textural properties of foods. Vacuum freeze-drying allows obtaining high-quality food products. On the other hand, this process is power consuming, requires long time and low pressure and can provoke the damage of final dried product. Thus, the development of efficient and optimal methodology for freeze-drying of foodstuff is relevant. Application of PEF as a pretreatment procedure may be useful for improving the efficiency of drying and the quality of dried products.

1. Introduction

Drying is very popular in processing of foodstuffs and widely used for food preservation. However, this process is very energy intensive (Kudra, 2004) and can cause undesirable changes of colour, flavour, nutrient and textural properties of foods (Stoecker, 1998). Drying and dehydration can be performed using different processes, e.g., thermal drying, vacuum freeze-drying, osmotic dehydration, and mechanical expression (Chen & Mujumdar, 2008; Rahman & Perera, 2007; Reis, 2014).

Recent studies demonstrated that the efficiency of different modes of drying can be noticeably improved by application of pulsed electric field (PEF) (Barba et al., 2015; Vorobiev & Lebovka, 2011). PEF pretreatment provokes the damage of cell membranes and accelerates mass and heat transfer processes without undesirable changes in food tissues (Donsi, Ferrari, Maresca, & Pataro, 2011; Jaeger, Reineke, Schoessler, & Knorr, 2012; Odriozola-Serrano, Aguiló-Aguayo, Soliva-Fortuny, & Martín-Belloso, 2013). The positive effects of PEF-pretreatment on freeze-drying of different foods have been demonstrated (Ben Ammar, Lanoiselle, Lebovka, Van Hecke, & Vorobiev, 2010; Jalte, Lanoiselle, Lebovka, & Vorobiev, 2009; Phoon, Galindo, Vicente, & Dejmek, 2008; Wiktor, Schulz, Voigt, Witrowa-Rajchert, & Knorr, 2015; Wu & Zhang, 2014).

This work is devoted to the effects of PEF on vacuum freeze-drying of apple tissue. Note that vacuum freeze-drying is widely used in processing of different food products (McDonald & Sun, 2000). The main principle of vacuum cooling and freeze-drying in application to foodstuff as well as their advantages and disadvantages was recently comprehensively reviewed (Drummond, Zheng, & Sun, 2014). When water evaporates, an amount of heat equal to the latent heat of evaporation must be absorbed by the product, resulting in a reduction of the temperature. If the pressure is dropped below 611 Pa (the saturation pressure of water at 0 °C is about 0.6 kPa), the freezing can occur during vacuum cooling. Moreover, the rapid boiling of water during the freezing stage can result in development and formation of a complex porous structure inside the sample (Cheng & Lin, 2007). In general, vacuum cooling provides a high rate of ice-growing (Lin & Chou, 2001) and allows processing with low energy consumption and in high-quality food products (Feng, Drummond, Zhang, Sun, & Wang, 2012).

PEF treatment can greatly affect the heat and mass processes in plant tissues during freezing (Ben Ammar et al., 2010; Jalte et al., 2009). However, the effect of PEF-treatment on vacuum cooling and freeze-drying practically has not been studied yet.

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The aim of this study was to evaluate the effect of PEF treatment on the responses of apple tissue in the processes of vacuum cooling and freeze-drying. The evolution of temperature and moisture content was compared for PEF treated and untreated samples. The microscopic, macroscopic analysis and data of capillary impregnation tests were also done.

2. Materials and methods

2.1. Sample preparation

Commercial apples (*Jonagold*) were purchased in a local supermarket (Compiegne, France). The moisture content, measured by drying 25 g of the fresh apple tissue at 105 °C to constant weight, was about 85 wt.%. The apple disc-shaped samples ($d_i = 29$ mm in diameter and $h_i = 5$ mm in thickness) were manually prepared immediately before experiments using a special cylindrical knife.

2.2. Treatments

The general scheme of experiments performed in the present work is shown in Fig. 1.

The apple samples were initially treated by PEF, and then submitted to vacuum cooling at sub-zero temperature for freeze-drying.

2.2.1. Pulsed electric field pre-treatment

Pulsed electric field (PEF) treatment was applied using a monopolar PEF generator (5 kV–1 kA, Hazemeyer, France). The PEF generator provided pulses of a near-rectangular shape, and N series of pulses were applied. Each separate series consisted of n pulses with pulse duration t_i, time interval between pulses Δt and pause Δt_t after each train. The total time of PEF treatment was regulated by variation of the number of series N and was calculated as $t = N \cdot n \cdot t_i$. The current and voltage values were measured during the period between two consecutive series of pulses. The following protocol was used in PEF experiments: $E = 800$ V/cm, $n = 10$, $t_i = 1000$ μs, $\Delta t = 100$ ms, $\Delta t_t = 10$ s, and the value of N was varied in order to obtain the desirable t_t, e.g., $N = 10$ corresponded to $t = 0.1$ s.

The chosen protocol of successive trains with long pause after each train allowed fine control of the plant tissue permeabilization without any significant temperature elevation ($\Delta T \leq 3$ °C) during PEF treatment. The electrical treatment cell consisted of a Teflon cylindrical tube (Atelier Genie des Procédés Industriels, UTC, France) with ≈110-mm inner diameter and an electrode at the bottom. The apple disc-shaped sample wetted with fresh apple juice was placed inside the cell on the bottom electrode, and covered by the second electrode on the top of the sample. Fresh juice was chosen as a natural medium in order to reduce the sample degradation and to improve electrical contact between the electrodes and the sample. The distance between the electrodes, 5 mm, was determined by the thickness of the sample. The temperature inside the geometrical centre of sample was recorded by a teflon-coated thermocouple Thermocoax type 2 (AB 25 NN). All data (electrical conductivity, voltage, current, temperature) were collected using a data logger and software adapted by Service Electronique (UTC, France). After PEF treatment samples were loaded immediately in pilot freeze-drier.

The degree of apple tissue permeabilization was evaluated using the electrical conductivity disintegration index, Z (Lebovka, Bazhal, & Vorobiev, 2002):

$$Z = (\sigma - \sigma_i)/(\sigma_d - \sigma_i), \quad (1)$$

where σ is the measured electrical conductivity and subscripts i and d refer to the conductivities of the intact and completely damaged tissue, respectively. All values of σ were measured at the same temperature, $T = 20$ °C. The value of σ_d was estimated as the maximum attainable level of σ for the given mode of treatment. It can be attained using long-lasting treatment (e.g., treatment duration of 1 s at 800 V/cm for PEF treatment).

The $Z(t_{PEF})$ dependence for the same apple variety (*Jonagold*) was previously investigated in details (Parniakov, Lebovka, Bals, & Vorobiev, 2015). In this work, the samples with different values of Z using the different values of t_{PEF} were obtained. For example, the high value of Z ($Z \approx 0.95$) required a PEF treatment during $t_{PEF} = 0.1$ s.

2.2.2. Vacuum cooling and freeze-drying experiments

Vacuum cooling and freezing-drying experiments using a MUT 002A pilot freeze-drier (Cryotec, France) for 300 min (5 h) were performed. The initial temperature of the sample was 25 °C. The chamber temperature was fixed at $T = 40$ °C and the pressure was maintained at $P =$ 10 mbar. Preliminary experiments had shown that this pressure was reasonable for vacuum cooling of intact and PEF-treated samples to sub-zero temperature. The experiments were started immediately after the loading of a sample. The temperature inside the geometrical centre of the sample was measured with a thermocouple (T-type, accuracy of ±0.1 °C, diameter of 0.5 mm, TC S.A., France). The weight of the sample during freeze-drying was controlled using a balance (Cubis MSA, Sartorius, France). The moisture content in the sample during drying (wet basis content of water, $0 \leq W \leq 1$) was calculated as

$$W = m^w/m^w{}_i, \quad (2)$$

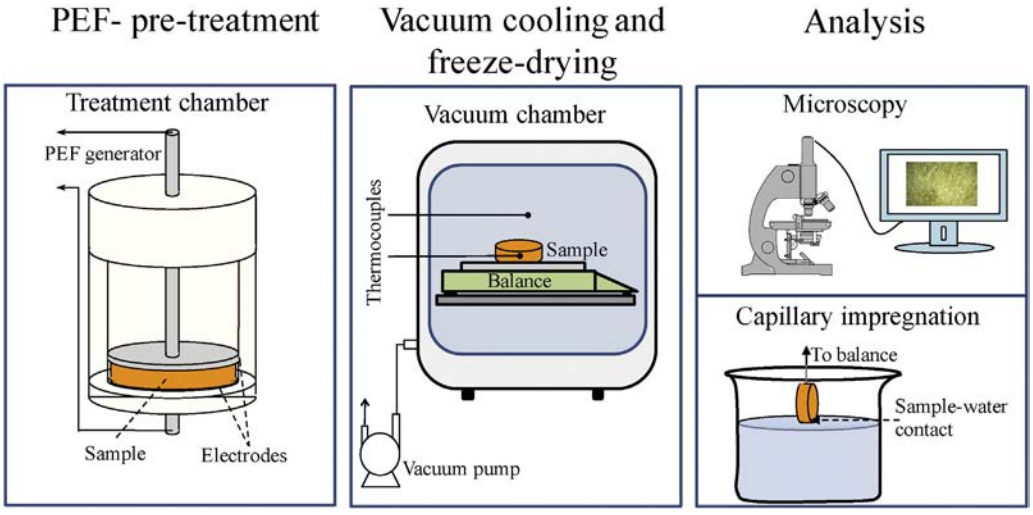

Fig. 1. The scheme of PEF-assisted vacuum cooling and freezing-drying experiments as well as microscopy and capillary impregnation analysis.