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Acoustic and mechanical properties of carrot tissue treated by pulsed electric field, ultrasound and combination of both

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ABSTRACT:

Both ultrasound (US) and pulsed electric field treatment (PEF) allow achieving similar technological aims. Their application can for instance improve food preservation or enhance heat and mass transfer based processes. However, the mechanisms of action and the impact of these technologies on the structure of biological systems are different. Based on the knowledge concerning the behaviour of tissue subjected to pulsed electric field or sonication it can be assumed that the combination of these techniques can be beneficial. Therefore the aim of this study was to analyse the impact of pulsed electric field, ultrasound and combined (pulsed electric field followed by ultrasound or ultrasound followed by pulsed electric field) treatment on electrical conductivity, intercellular structure, mechanical and acoustic properties of plant tissue as exemplified by carrot samples. Performed research proved that the mechanism of action and the consequences of US treatment are different in comparison to pulsed electric field application. The efficiency of sonication cannot be evaluated on the basis of electrical conductivity like it is usually done in the case of electroporation efficacy assessment. The results concerning mechanical and acoustic properties also indicate that pulsed electric field causes higher alterations of intercellular structure than ultrasound. In general the utilization of US prior to PEF treatment can enhance the effectiveness of electroporation.

1. Introduction

Ultrasound (US) and pulsed electric field (PEF) treatment belong to the most promising nonthermal food processing technologies. These techniques can be utilized to replace conventional unit operations or to assist traditional processes present in food technology. Since 2007 more than 6000 and 2000 articles, indexed in the Web of Science database on utilization of ultrasound and pulsed electric field, respectively, have been published. These numbers confirm the great importance of the possible industrial utilization of US and PEF treatment. Both techniques can be useful in food preservation or in unit operations enhancement (Barba et al., 2015b; Tao and Sun, 2015). For instance, it has been proved that sonication can enhance the extractability of bioactive compounds from lemon balm, peppermint leaves, Psidium guajava leaves or peaches and pumpkins (Altemimi et al., 2016; Dìaz-de-Cerio et al., 2017; Žlabur et al., 2016). Furthermore, pulsed electric field can be used to enhance extraction of valuable compounds from white button mushroom (Parniakov et al., 2014; Xue and Farid, 2015). Both PEF and US can be used in valorisation of food wastes and by-products. For example, PEF facilitates the extraction of steroidal alkaloids from potato peels (Hossain et al., 2015) and sonication can improve extractability of bioactive compounds from carrot pomace (Jabbar et al., 2015). There is a high number of publication which indicate that these techniques (utilized as pre-treatment) can reduce drying time and improve quality of dried plant material (Witrowa-Rajchert et al., 2014). However, despite the fact that both PEF and US treatment can provoke similar or the same effects in the biological cell and thus they can be used to achieve the same or similar technological aim, their mechanism of action is different in many ways.

Ultrasounds are mechanical waves with frequency varying from 20 kHz to 10 MHz, which makes them inaudible for humans. The frequency of ultrasound, used for the technological purposes, ranges from 20 kHz to 1 MHz (power ultrasound) whereas waves vibrating with frequency between 5 and 10 MHz are mainly used in diagnostics (Bastarrachea et al., 2017). Mechanical waves, vibrating at ultrasound frequencies, can propagate through solid or liquid media inducing a series of compressions and rarefactions. In the case of liquid media the forces generated by the vibrations can cause cavitation phenomenon (Ashokkumar, 2015). The vast majority of formed cavitation bubbles exhibit transient character and they collapse rapidly which generates

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local heat and pressure increment (up to 5000 K and 100 MPa, respectively) (Cheng et al., 2015). Shockwave (generated as a consequence of cavitation bubble implosion) is sufficient enough to break chemical bounds and to disrupt the continuity of biological cell walls or membranes (Joyce et al., 2011). This phenomenon is accompanied by the formation of the free radicals or other reactive chemical compounds. (Okitsu et al., 2005). It is also worth emphasizing that ultrasound are very often used to clean small and precise items or to degas solutions (Eskin, 2014; Gonçalves et al., 2014). In the case of solid or solid-like materials (e.g. tissue food) ultrasound application can cause so called ‘sponge effect’ and creation of microchannels (Kowalski and Rybicki, 2017) modifying cellular structure.

Application of PEF leads to electroporation, which should be considered both as a process and phenomenon (Barba et al., 2015b). Depending on parameters electroporation can be reversible or irreversible. Regardless of its character it depends on formation of permanent or transient pores in the cell membrane (Angersbach et al., 2000). Moreover, PEF can modify the structure of cell wall – by changing its mechanical properties (Pillet et al., 2016). Similarly to ultrasound, pulsed electric field application can result in reactive oxygen species formation (Bonnafous et al., 1999).

Based on the scientific data, it is evident that both PEF and US can be used to achieve similar technological purposes, even if their mechanisms of action are different (Table 1). Nevertheless, considering the effects of sonication and pulsed electric field, it could be expected that combination of these techniques can be beneficial regarding effectiveness of the treatment, and processed material quality. However, only few reports present results regarding combined US and PEF treatment of food systems. For instance, Dellarosa et al., 2017 studied the effect of PEF, US and PEF treatment followed by US on the drip loss, cell disintegration index and water distribution of mushroom stalks. Noci et al., 2009 studied the effect of thermosonication and PEF treatment on inactivation of Listeria innocua in milk. Similarly, Xin et al., 2009 analysed the impact of combined PEF and US on the inhibition of biocorrosion by microorganisms inactivation. Both publications demonstrated that combination of sonication and PEF treatment can be more effective than the processes applied separately. Also Aadil et al. (2018) showed that US and PEF coupled together in a sequence, can improve the microbial quality of grapefruit juices. Based on the literature data, it can be stated that combination of US and PEF treatment can enhance extraction of bioactive compounds from berry puree (Medina-Meza et al., 2016). However, to the best of the authors knowledge, there are no articles presenting the quality of solid-like food matrices treated by combined PEF and US.

Therefore, the aim of this study was to analyse the impact of US, PEF and combined treatment (applied in a sequence of PEF followed by US and US followed by PEF) on electrical, mechanical (texture) and acoustic properties of carrot tissue.

Table 1
Effects caused by sonication and pulsed electric field application.

Effect	Source	
	PEF	US
Intercellular compounds leakage	(Ersus and Barrett, 2010)	(Tabatabaie and Mortazavi, 2008)
Intercellular structure rupture, membrane and membrane-related structure degradation	(Pillet et al., 2016; Angersbach et al., 2000)	(Lammertink, Deckers, Storm, Moonen and Bos, 2015)
Enzymes activation or inactivation	(Leong and Oey, 2014; Tian, Fang, Du and Zhang, 2016)	(Mawson, Gamage, Terefe and Knoerzer, 2011)
Free radicals and reactive oxygen species formation	(Bonnafous et al., 1999)	(Okitsu et al., 2005)

2. Material and methods

2.1. Material

Carrots (var. “*Baltimore*”) purchased in the local supermarket (Warsaw) were stored in plastic bags in darkness at 4 °C before each experiment. Only roots characterized by the similar thickness and length were selected to the experiment. The storage time was not longer than one week. Prior to the analysis carrots were withdrawn from the storage compartment, washed with potable water and left to reach room temperature (20 ± 2 °C). Afterwards, the samples were peeled and cut with corkbore knife in the cylindrical form ($d = 30$ mm and $h = 5$ mm), parallel to the main axis of the root. Samples were cut always from the same place of the roots to maintain the samples as homogenous as possible.

2.2. Pulsed electric field treatment

PEF treatment was performed in a prototype reactor (ERTEC-RI-1B, ERTEC, Wroclaw, Poland) with output voltage up to 30 kV and capacitance of 0.25 µF. The apparatus generated exponential shaped, monopolar pulses of average 7 µs width each. The frequency of treatment was equal to 0.5 Hz in order to minimize the samples’ temperature increase. After preparation, samples were placed in the treatment chamber made of Corian type material. At the bottom of the cell, one stationary electrode was placed. Subsequently, the cell was filled with potable water (917.6 µS/cm; 20 ± 1 °C) to improve electrical contact between electrodes. The ratio between the mass of the water in the baker and material was equal to 4:1. Afterwards, the pre-treatment cell was closed with the mobile electrode. Parameters of electric field applied in the experiment are listed in the Table 2. Specific energy intake W_s, in kJ/kg, was calculated according to the following equation: $W_s = (V^2Cn)/2m$, where V [V], C [F], n, and m [kg] are the voltage, capacitance of the energy storage capacitor, number of pulses and mass of the sample and the water in the treatment chamber (0.05 ± 0.001 kg), respectively. The temperature increment of the sample (measured in geometrical centre of the carrot samples) after PEF application was not higher than 12.0 °C. PEF treatment was conducted in triplicate following parameters listed in the Table 2. The processing parameters were selected on the basis of our previous studies (Wiktor et al., 2016a,b), i.e. treatment protocols were selected based on similar electroporation efficiency (similar electrical conductivity) achieved with different specific energy input.

2.2.1. Immersive sonication (iUS)

Carrot samples (58.6 ± 1.8 g) were put into the glass baker filled with tap water (5000 g; 917.6 µS/cm; 20 ± 1 °C) and transferred to the ultrasound bath. The ratio between the mass of the water in the baker and material was equal to 4:1. The ultrasound application was carried out by ultrasound bath (MKD-3, MKD Ultrasonics, Poland) working at 21 kHz and 180 W. Sonication lasted for 20 min (42.3 kJ/kg) and the time was controlled by the internal bath processor. Treatment time was selected based on our preliminary studies for apple (Wiktor et al., 2016a,b) and carrot tissue (data not published). The experiment was performed in three repetitions. After the treatment the temperature of samples increased by 2.6 ± 0.5 °C. Sonication parameters are listed in the Table 2.

2.2.2. Contact sonication (cUS)

Cut carrots (59.6 ± 0.7 g) were placed on the stainless-steel screen (Retsch, 500 µm aperture, Germany) attached to the ring sonotrode (RIS200, Hielsher Ultrasonics, Germany). The sonotrode was controlled by the ultrasonic processor (UIS250L, Hielsher Ultrasonics, Germany) which it was connected to. The frequency of applied ultrasonic waves was equal to 24 kHz and the power of device was equal to 250 W. Both the amplitude and the duty cycle were set to 100%. Screen acted as a