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Influence of ultrasound on the microstructure of plant tissue

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ABSTRACT

The aim of this work was to assess the influence of ultrasound on the microstructure of plant tissue during direct sonication via air (without liquid medium). Two different materials (apple and onion) were tested under two experimental conditions: direct sonication in an acoustic chamber and convective drying enhanced with ultrasound in a laboratory hybrid dryer. The impact of ultrasound on the material being processed was analyzed through direct observation with the naked eye, analysis of thermograms, and observation of dyed in Lugol's solution specimens, using an inverted optical microscope and SEM images. The results obtained revealed both the thermal and the mechanical effects of ultrasonic action. The temperature of the materials processed with the use of ultrasound attained values higher than the temperature of ambient air, even during convective drying at 313 K. Moreover, application of ultrasound led to irreversible changes in structure (growth of porosity, loss of tissue coherence, formation of microchannels, etc.) and cell composition (destruction of cell components, e.g., the nucleus). Aberrations in cell walls or cell membranes due to ultrasonic passage were not observed. Explanations of the observed phenomena were proposed.

1. Introduction

Convective drying (CV) is one of the most commonly used methods of preservation, especially for highly perishable products such as fruit and vegetables. Reduction of moisture content, thus water activity, during drying allows for the stabilization of materials in terms of microbial activity, and significantly moderates other deteriorative processes, such as enzymatic and non-enzymatic reactions, lipid oxidation, browning, etc. (Mujumdar, 2004). Unfortunately, convective drying may negatively affect the final product's quality. Changes in color and taste, shrinkage and deformations, surface hardening, and loss of important nutrients are among the examples of the negative effects of this preservation method (Bonazzi & Dumoulin, 2011). Moreover, due to the low energy efficiency of dryers, this process is usually lengthy and energy consuming (Kudra, 2004).

The disadvantages of currently used drying techniques motivate the search for new, sustainable technologies. Chemat, Rombaut, Meullemiestre, et al. (2017) and Chemat, Rombaut, Sicaire, et al. (2017) stated that all new techniques of food processing should be 'green and innovative' and introduced the 'Green Food Processing' (GFP) concept. The GFP complements the 'green chemistry' and 'green engineering' conception and implies '*discovery and design of technical processes which will reduce energy and water consumption, allows recycling of by-products through bio-refinery, and ensure a safe and high quality product*' (Chemat, Rombaut, Meullemiestre, et al., 2017). Authors enumerated several techniques which may be useful during elaboration of the 'green' processing, pasteurization and extraction procedures. These include supercritical fluid extraction and processing, microwave processing, controlled pressure drop process, pulse electric field and finally ultrasound-assisted processing.

Although ultrasound is used in a variety of food processing operations such as cooking, filtration, freezing, pasteurization, extraction, cutting etc. (Chemat, Zill-e-Huma, & Khan, 2011), it has recently been also utilized in the drying processes. The 'acoustic drying' conception is not new and was developed in the mid of the previous century in ZSRR (Boucher, 1959; Greguss, 1963). The main constraint of the wide application of the proposed by these authors technology was poor effectiveness of the ultrasonic transducers. Development of modern, high-power, ultrasonic generators in recent years resulted in a renewed interest in this technique (Cárcel, García-Pérez, Riera, Rosselló, & Mulet, 2014). It was found that ultrasound could work synergistically with other drying methods to accelerate this unit operation. Moreover, ultrasound, in contradistinction to other processing techniques, such as microwaves, gamma radiation, or pulsed electric fields, has been perceived as benign by the general public, thus it may be applied in the food industry (Kentish & Ashokkumar, 2011).

The use of ultrasonic energy as a factor that intensifies mass exchange during food drying has been examined over the past few decades. In general, it is claimed that ultrasound accelerates the drying operation, but the advantages of its application depend on the following

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factors:

- *the process parameters such as the temperature and velocity of the air* (Cárcel, García-Pérez, Riera, & Mulet, 2007; Fernandes, Rodrigues, Cárcel, & García-Pérez, 2015; García-Pérez, Cárcel, de la Fuente-Blanco, & Riera-Franco de Sarabia, 2006; García-Pérez, Cárcel, Simal, García-Alvarado, & Mulet, 2013; J. Rodríguez, Mulet, & Bon, 2014),
- *the physical properties of the material that are type of skin, porosity, composition* (Ozuna, Cárcel, Santacatalina, Mulet, & García-Pérez, 2011; Ozuna, Gómez Álvarez-Arenas, Riera, Cárcel, & García-Pérez, 2014; Ozuna, Mulet, García-Pérez, Riera, & Cárcel, 2014)
- *the acoustic wave parameters, such as frequency, amplitude, intensity,* etc. (García-Pérez, Cárcel, Riera, & Mulet, 2009; García-Pérez et al., 2013; Ortuño, Pérez-Munuera, Puig, Riera, & García-Pérez, 2010; Ozuna et al., 2011; Ozuna et al., 2014; Rodríguez et al., 2014).

Most of the papers concerning ultrasonic-assisted drying refer generally to the influence of acoustic waves on the kinetics of the basic process. To determine the effect of ultrasound on the drying process authors analyze different:

- *configurations of apparatus: convective* cf. (Gallego-Juárez, Rodriguez-Corral, Gálvez Moraleda, & Yang, 1999), freeze dryer cf. (Bantle & Eikevik, 2011; Schössler, Jäger, & Knorr, 2012) or hybrid dryer cf. (Kowalski & Pawłowski, 2015),
- *variants of ultrasound transmission: contact* cf. (Riera, Gallego-Juárez, Rodríguez-Corral, Acosta-Aparicio, & Andrés-Gallego, 2002), or contactless cf. (de la Fuente-Blanco, Riera-Franco de Sarabia, Acosta-Aparicio, Blanco-Blanco, & Gallego-Juárez, 2006),
- *power of acoustic waves* (García-Pérez et al., 2013; Ortuño et al., 2010; Ozuna, Gómez Álvarez-Arenas, et al., 2014; Rodríguez et al., 2014).

It was generally stated that ultrasound may influence both external and internal resistances to mass transfer, causing an increase in drying rate, and thus a reduction in drying time but interactions between ultrasonic waves and the material being dried have not been thoroughly examined.

The mechanisms involved in the heat and mass transfer intensification during drying, extraction etc. have not been fully determined so far. Kowalski (2015) and Musielak, Mierzwa, and Kroehnke (2016) divided the ultrasonic effects into two groups thermal and mechanical ones. Chemat, Rombaut, Meullemiestre, et al. (2017) and Chemat, Rombaut, Sicaire, et al. (2017) distinguished in details the main phenomena which may influence the effectiveness of basic unit operation (e.g. extraction) assisted with ultrasound that is: fragmentation, erosion, sonoporation, sonocapillary effect, shear stresses and detexturation. Irrespective from the considered division, it may be assumed that all the main phenomena induced by ultrasound are of thermal, cavitation and stress type.

The thermal/heating effect occurs when part of the energy is absorbed and converted into heat which leads to the growth of the material temperature. Because the temperature increase depends on the amount of energy absorbed, thus this effect is strongly contingent on the intensity and frequency of the ultrasound, and the specific heat of the material as well. On the other hand, implosion of the steam bubbles created in the sonicated liquid (cavitation phenomenon) causes creation of shock-waves, micro-jets, macro-turbulence, micro-mixing, local violent increase in the temperature and pressure, formation of harmful reactive oxygen, etc. All these occurrences may cause the fragmentation, reversible or irreversible sonoporation, surface peeling, erosion, particle breakdown, bio-chemical conversion etc. (Chemat, Rombaut, Sicaire, et al., 2017; Kentish & Ashokkumar, 2011). The stress effects result mainly from changes triggered in the material during the ultrasonic waves' passage, e.g., alteration/oscillation of pressure, acoustic flows, compression and expansion of elastic skeleton (the so-called 'sponge effect') and so on. As a result, the capillary effect (increase of depth and velocity of penetration of liquid into canals and pores), growth of the diffusion coefficient, local changes in the liquid properties (viscosity, density), etc. occur and affect the effectiveness of the process.

It should be also emphasized that the mechanisms which accelerate mass transport, also cause irreversible changes in the product structure. Despite a meaningful number of papers concerning the kinetics of ultrasonically-assisted drying, only a few papers have been devoted to the study of the effect of ultrasound on the structure of materials. In these few existing papers, the authors focused mainly on the analysis of microscopic images, which show the strong influence of the sound wave on the structure of the plant tissue, with respect to changes both in composition and internal configuration.

In (Ortuño et al., 2010) and (García-Pérez, Ortuño, Puig, Cárcel, & Perez-Munuera, 2012), the authors studied the effect of ultrasonic drying on the microstructure of orange peel. High power ultrasound was utilized at a moderate acoustic intensity of 45 and 90 W. The structure of fresh and dried samples was assessed on the basis of images obtained from a low-temperature scanning electron microscope (CryoSEM). Microscopic pictures of the flavedo (the thin external colorful part of the orange peel), the albedo (the white inner layer of orange peel), cross-sections, as well as the epidermis were presented in the paper. Both hot air drying and ultrasonically-aided hot air drying caused shrinkage of the material, which is a commonly-occurring phenomenon. The water removed during the drying process caused a high load (tension) on the plant cells, which led to the collapse of their cellular structure. It was also found that, in the case of albedo cells, higher degradation occurred if the ultrasound was applied. The authors reported more intercellular spaces, which increased the porosity of the material, and therefore improved water diffusion, but also weakened the overall structure. Moreover, due to the alternating expansion and compression induced by ultrasound, significant degradation of the non-gas-albedo tissue occurred, facilitating mass transport and speeding up the drying process.

Puig, Perez-Munuera, Cárcel, Hernando, and García-Pérez (2012) studied the effect of ultrasonic power on the microstructure of eggplant dried convectively. The structure of the material was analyzed with the use of SEM and CryoSEM techniques. The authors found that convective drying (at 313 K) with moderate power ultrasonic enhancement (45 W) caused less severe degradation of tissue, compared to drying at the same conditions, but without ultrasound. The endocarps retained their individuality, and the cell walls were almost intact. However, in the case of higher acoustic energy (90 W), meaningful deterioration of the structure occurred, despite the relatively short time of the drying operation (exposure to acoustic radiation). Analysis of the microscopic pictures of samples dried with higher acoustic energy (90 W) revealed similar changes to those observed for specimens dried convectively without ultrasonic enhancement. The authors concluded that in the case of convectively dried products, deterioration in their quality resulted from a long drying time at relatively high temperature. Meanwhile, in the case of ultrasonically-assisted convective drying (with an ultrasonic power equal to 90 W), structural changes came from the amount of energy delivered by the acoustic waves. Finally, it was proven that the effect of ultrasound on the internal structure depends not only on the drying time but also on the power of the applied ultrasound.

The next two papers, (Sabarez, Gallego-Juárez, & Riera, 2012) and (Santacatalina, Contreras, Simal, Cárcel, & García-Pérez, 2016), refer to the use of ultrasound in the drying process of apples. The first one (Sabarez et al., 2012) relates to convective drying at 313 and 333 K, without (0 W) and with ultrasonic enhancement (75 and 90 W). Confocal microscopy was used to analyze changes in the structure of apple slices. Due to the application of a different light source (laser), compared to an optical microscope, pictures made with the confocal devices