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Influence of material structure on air-borne ultrasonic application in drying

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ABSTRACT

This work aims to contribute to the understanding of how the properties of the material being dried affect air-borne ultrasonic application. To this end, the experimental drying kinetics (40 °C and 1 m/s) of cassava (*Manihot esculenta*) and apple (*Malus domestica* var. *Granny Smith*) were carried out applying different ultrasonic powers (0, 6, 12, 19, 25 and 31 kW/m^3). Furthermore, the power ultrasound-assisted drying kinetics of different fruits and vegetables (potato, eggplant, carrot, orange and lemon peel) already reported in previous studies were also analyzed. The structural, textural and acoustic properties of all these products were assessed, and the drying kinetics modeled by means of the diffusion theory.

A significant linear correlation ($r > 0.95$) was established between the identified effective diffusivity (D_W) and the applied ultrasonic power for the different products. The slope of this relationship (SDUP) was used as an index of the effectiveness of the ultrasonic application; thus the higher the SDUP, the more effective the ultrasound application. SDUP was well correlated ($r \geqslant 0.95$) with the porosity and hardness. In addition, SDUP was largely affected by the acoustic impedance of the material being dried, showing a similar pattern with the impedance than the transmission coefficient of the acoustic energy on the interface. Thus, soft and open-porous product structures exhibited a better transmission of acoustic energy and were more prone to the mechanical effects of ultrasound. However, materials with a hard and closed-compact structure were less affected by acoustic energy due to the fact that the significant impedance differences between the product and the air cause high energy losses on the interface.

1. Introduction

The structural properties of vegetable tissues are of great scientific interest and an important subject of research [1,2]. The vegetable cell wall, which, among other functions, serves as mechanical support and external barrier, is the main structural component [3]. During fruit and vegetable processing, such as drying, the macrostructure, microstructure and composition of the cell walls undergo a series of changes that affect the functional properties [4] and also modify their ultrasonic properties [5]. In addition, the structure of the vegetable tissues itself can also largely influence the processing, e.g. affect the mass transfer rate during drying [6].

Convective drying is one of the most common unit operations used to dehydrate fruits and vegetables [7]. During drying, the plant tissue is subjected to high stress caused by the water removal and the high temperatures applied. These facts produce macroscopic changes, such as shrinkage or color and textural modifications, which are mostly linked to tissue alterations on a microscopic level [8].

The increasing need for the production of high quality dry products at reduced cost has led to traditional drying methods being combined with non-conventional energy sources [9]. In this regard, air-borne ultrasound application represents a very promising technique due to its low heating effect, which is particularly relevant for products containing thermo-labile compounds [10,11]. The improvement in the water transfer rate produced by ultrasound is linked to the effect it has, not only on the solid–gas interfaces (pressure variations, oscillating velocities and microstreaming) [12,13] but also on the internal structure (series of cyclical and rapid [>20 kHz] compressions and expansions, a mechanism known as the sponge effect) [14,15]. The intensity of ultrasonic effects during drying has been shown to be largely dependent on the process variables, such as the temperature [16], air velocity [17], acoustic power applied [18], and also even on product characteristics [19]. In this sense, previous studies have shown that a minimum ultrasonic power must be applied in order to observe any significant effects of ultrasound. This ultrasonic power threshold depends on the product being dried [20], and it is likely that this

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Nomenclature

d. m.	dry matter
D_W	effective moisture diffusivity (m^2/s)
L	half height (m)
S_y	standard deviation of the sample
S_{yx}	standard deviation of the estimation
TC	air/solid transmission coefficient (dimensionless)
V	volume (L)
W	moisture content (kg w/ kg d.m.)
Z	acoustic impedance (MRayl)
m	mass (kg)
t	time (s)
v	ultrasonic velocity (m/s)
x, y, z	characteristic coordinates in cubic geometry (m)

Greek letters

ρ	density (kg/m^3)
ε	porosity

Subscripts

0	initial
b	bulk
e	equilibrium
p	local
s	solid particle

could be linked to the different internal structure. Previous studies have highlighted the fact that porosity could explain how ultrasonic effects during drying are largely dependent on the product being dried [17,20]. This statement stems from the comparison between the air-borne ultrasound assisted drying of carrot and persimmon (low porosity products) and that of lemon peel and analyzing how the effective diffusivity was dependent on the acoustic power [20] or the air velocity applied [17]. However, the comparison was merely qualitative and no quantitative analysis was performed. In addition, an analysis of instrumental texture and microstructure could also contribute to a better understanding of ultrasound-solid interaction [21].

Since the structural and textural properties affect the propagation of acoustic waves [22], the study of the materials' ultrasonic properties could also provide relevant information about how efficiently the energy is transferred during drying. The ultrasonic velocity and the attenuation are the most common parameters used for product characterization due to their good correlation with several physical and chemical properties of foodstuffs [23,24]. Conventional ultrasonic techniques involve an intimate contact between the transducer and the sample, and frequently require the use of a coupling medium (such as gel, water or oil) and a certain pressure, which, to a certain extent, delays the measurement and may contaminate and modify the product. Recently, novel non-contact ultrasonic techniques are being tested in which new sensors provide an efficient energy transmission using air as the coupling medium [25]. Thus, Sancho-Knapik et al. [5] used an air-borne broadband ultrasonic technique to characterize biological materials, such as leaves.

This works aims to contribute to understanding how the material being dried affects air-borne ultrasonic application in the drying of biological materials. For that purpose, how ultrasound affects drying kinetics will be correlated with the structural, textural and acoustic properties of different fruits and vegetables. Furthermore, microstructural observations (Cryo-SEM) will help to explain the results obtained.

2. Materials and methods

2.1. Ultrasonic assisted drying kinetics

Drying experiments were carried out with cassava (*Manihot esculenta*) and apple (*Malus domestica* var. *Granny Smith*) purchased in a local market. For both products, cubic samples (side 10 mm) were obtained from the flesh using a household tool. For that purpose, an ultrasonically assisted convective drier was used, which mainly consists of a vibrating cylindrical radiator (internal diameter 100 mm, height 310 mm and thickness 10 mm) [11], working as the drying chamber, driven by a piezoelectric transducer (21.8 kHz). Riera et al. [26] described thoroughly the ultrasonic system and reported how it was designed and adapted in conventional convective driers. An impedance matching unit permits the impedance output of the generator to be tuned to the transducer resonance frequency providing the system with a better electrical yield. This ultrasonic device is able of achieving a sound pressure level of up to 154.3 dB [26]. The drying air goes through cylindrical radiator where samples are randomly placed using a customized sample holder [17].

The drying experiments were conducted at 40 °C and 1 m/s, applying different ultrasonic powers (UP: 0, 6, 12, 19, 25, 31 kW/m^3), defined as the electric power supplied to the ultrasonic transducer divided by the volume of the drying chamber. The drying experiments were extended until a sample weight loss of 50% and 80% was achieved for cassava and apple, respectively. Drying kinetics were determined from the sample weight during drying, measured at preset times, and the initial moisture content (AOAC method N° 934.06) [27]. For each condition tested, the drying experiments were carried out at least four times.

2.2. Modeling

The experimental drying kinetics of apple and cassava were modeled according to the diffusion theory. The differential equation of diffusion was obtained combining Fick's law and the microscopic mass balance. For cubic geometry and considering the effective moisture diffusivity as constant and the solid as isotropic, the diffusion governing equation is shown as follows:

$$\frac{\partial W_p(x,y,z,t)}{\partial t} = D_W\left(\frac{\partial^2 W_p(x,y,z,t)}{\partial x^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial y^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial z^2}\right) \quad (1)$$

The diffusion equations were solved by assuming the solid to be symmetrical, the initial moisture content and temperature uniform and the product shape constant during the drying process. The external resistance to mass transfer was neglected, thus, mass transfer was assumed to be entirely controlled by diffusion mechanisms. The analytical solution [28] of the governing equation for cubic geometry in terms of the average moisture content is given in Eq. (2).

$$W(t) = W_e + (W_0 - W_e)\cdot\left[\sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}e^{\left(-\frac{D_W(2n+1)^2\pi^2 t}{4L^2}\right)}\right]^3 \quad (2)$$

Eq. (2) was fitted to the experimental drying kinetics in order to identify the effective moisture diffusivity (D_W). The identification was performed by minimizing the squared differences between the experimental and calculated average moisture contents.