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Dielectric properties of dried vegetable powders and their temperature profile during radio frequency heating

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ABSTRACT

Dielectric properties of selected vegetables powders as influenced by moisture content (MC), compaction density and temperature were determined using a precision LCR meter and liquid test fixture at radio frequency (RF) ranging from 1 to 30 MHz. The RF heating rate of samples was evaluated using a 27.12-MHz, 6-kW RF oven.

The results showed that dielectric properties, namely, the dielectric constant, ε', and loss factor, ε'', of vegetable powders were influenced by MC, compaction density and temperature of the samples and the RF frequency. Both the dielectric constant and loss factor increased with increasing MC and temperature, but decreased with increasing frequency. Additionally, dielectric properties of samples increased with compaction density to a peak, then decreased. The relationship between MC, temperature and dielectric properties of broccoli powder at 13.56 and 27.12 MHz can be described by quadratic models with high correlation coefficients ($R^2 > 0.96$). The RF heating rate in samples increased linearly with dielectric loss factor and MC. The information provided in this study is useful to develop an effective RF heating strategy to pasteurize dried vegetable powders.

1. Introduction

Low-moisture foods, with water activity (a_w) level less than 0.7 (Blessington et al., 2013), are commonly used for various applications in food industry. In the last decade, *Salmonella* contaminated low-moisture foods, including powdered vegetables and infant formula, dry fruit and nuts, spices etc., have become a major safety concern (CDC, 2007, 2010); Sotir et al. (2010) reported an outbreak of *Salmonella* Wandsworth and Typhimurium in broccoli powder used for coating of snacks. The high heat resistance of *Salmonella* in low-moisture foods makes pasteurization of dried foods a difficult task. The conventional pasteurization methods such as steam and hot air heating require long processing times due to the slow heating rate, leading to severe quality degradation. RF heating is a volumetric heating with the radiation frequency ranging from 3 kHz to 300 MHz, but only 13.56, 27.12 and 40.68 MHz are used for industrial, scientific and medical applications (Wang and Tang, 2001). When the dielectric materials are exposed to an alternating electric field at RF and microwave (MW) frequency ranges, electrical energy is directly converted into heat. Therefore, RF heating is more rapid than conventional heating, requiring less process time that can result in improved final product quality and reduced treatment cost (Guo et al., 2011; Nelson, 1996). RF heating systems have been applied in the food industry for various applications such as disinfestation, enzyme inactivation, pasteurization, sterilization, and insect control (Gao et al., 2011; Lagunas-Solar et al., 2007; Manzocco et al., 2008). Because of its fast heating rate and relatively low cost, RF heating can be applied as an alternative pasteurization method for low-moisture foods, including dried vegetable powder such as broccoli powder.

To develop an effective RF pasteurization method for food products, it is important to understand dielectric properties, the major factor characterizing the interaction between the electromagnetic energy and the food. Several studies have been conducted to investigate the dielectric properties of various food powders such as grain seeds, flour, and coffee (Berbert et al., 2001; Lawrence et al., 1990; Nelson and Trabelsi, 2006; Nelson, 1984; Shrestha and Baik, 2015; Trabelsi et al., 1998). The dielectric properties of materials and the RF heating rate are mainly dependent on MC, temperature, and bulk density of sample, and applied frequencies

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Nomenclature

ε_0, ε', ε''	The permittivity of vacuum (8.854×10^{-12} F m^{-1}), dielectric constant (Dimensionless), dielectric loss factor (Dimensionless)
t, D	Time (s) and Gap between electrodes in test fixture (m)
C_p, c	Capacitance (F), Speed of light (3×10^8 m s^{-1})
T, T_i	Temperature (°C), Initial temperature (°C)
f	Frequency (Hz)
LCR	Inductance, capacitance, and resistance
CDC	The Centers for Disease Control and Prevention
d_p	Penetration depth (m)
ρ	Compact density (kg/m^3)
A	Electrode area (m^2)
RF	Radio frequency
R_p	Resistance (Ω)
SD	Standard deviation
W, MC	Moisture content
% w.b.	Wet weight basis (water/wet mass × 100)

(Piyasena et al., 2003). The influence of frequency, temperature and MC on dielectric properties of chickpea, legume and chestnut flour, and red pepper were reported (Guo et al., 2008, 2010, 2011; Guo and Zhu, 2014; Zhu et al., 2012a). However, there is no information published in the dielectric properties of dried vegetable powder as well as their heating rate during RF treatment. It is also important to understand how compaction densities affect the dielectric properties of food powder, as it can change greatly when subjected to compression pressure, which is frequently encountered during storage and transportation.

The objective of this study was to investigate the dielectric properties of selected vegetables powders, including broccoli, chili and onion powder, tapioca flour, and potato starch, and determine the temperature increase profile during RF heating. Different factors including RF frequency (ranging from 1 to 30 MHz), MC (6.9–14.9%, w.b.), temperature (from 20 to 80 °C), and compaction density (0.14–0.88 g/ml) were studied for their influence on dielectric constant, loss factor and penetration depth. Mathematical models were developed describing broccoli powder's dielectric properties as a function of MC and temperature at selected frequencies. The temperature history profiles of the vegetable powders at 27.12 MHz ware determined, and the heating rate of RF was evaluated as a function of MC and dielectric loss factor. The information obtained from this study is expected to help develop guidelines for using RF technology to pasteurize dried vegetables.

2. Material and methods

2.1. Physical characterization of vegetable powders

Broccoli powder was obtained from Z Natural Food Products (West Palm Beach, FL, 33407). Chili and onion powders, tapioca flour, and potato starch were purchased in a grocery store. The initial MCs of the food powders, determined by drying the samples in a vacuum oven at 105 °C for 16 h (AOAC, 1998), were for onion powder 1.4%, broccoli 3.9%, tapioca flour 5.7%, chili 7.8%, and potato starch 12.6%. The pictures of the four products are shown in Fig. 1.

To study the effect of moisture, samples of broccoli powder with MC 6.9, 9.1, 12.2, and 14.9% were obtained by spraying distilled water to the powder. The mixtures were stored in plastic containers for 2 day at 4 °C, and shaken twice in a day to obtain a uniform moisture distribution throughout the sample.

2.2. Determination of dielectric properties of vegetable powder

The dielectric properties of the vegetable powders were determined by measuring the parallel capacitance (C_p) and resistance (R_p) with an Inductance Capacitance and Resistance (LCR) meter (4285A, Agilent Technologies, Palo Alto, CA) and a liquid test fixture (16452, Agilent Technologies, Palo Alto, CA). Detailed information about the system was presented in the paper of Izadifar and Baik (2008) and Shrestha and Baik (2013). All parts of the test fixture were washed with distilled water and completely dried before and after each test. The system was calibrated before taking measurement. For each test, vegetable powder (2 g) was placed into the test fixture, which was then tightly closed. The test fixture was placed into a temperature chamber (625G, Thermo Fisher Scientific Inc., Waltham, MA, USA) and connected to the LCR meter by its BNC connecter as shown in Fig. 2. The sample was heated in the chamber for 50 min to reach target temperatures ranging from 20 to 80 °C with 10 °C interval. The change in temperature of the sample during heating was recorded using a data logger with fiber optic temperature sensor (Fiso Tech. Inc., Quebec, Canada). The C_p and R_p of the vegetable powder were measured with changing frequency in a range from 1 to 30 MHz at each temperature.

The obtained values of C_p and R_p by the LCR meter were used to calculate the values of dielectric constant ε' and loss factor ε'' using the following equations (Agilent Technologies, 2000; Halliday et al., 2001; Von Hippel, 1954):

$$\varepsilon' = \frac{DC_p}{A\varepsilon_0} \tag{1}$$

$$\varepsilon'' = \frac{D}{2\pi f R_p \varepsilon_0 A} \tag{2}$$

where, D is the gap (m) between electrodes of the test fixture, C_p is parallel capacitance (F), R_p is the resistance (Ω), f is the frequency (Hz), ε_0 is the permittivity of vacuum (8.854×10^{-12} F m^{-1}), and A is the electrode area (m^2).

To determine influence of compaction density on dielectric properties of selected food powders, different sample weight ranging from 0.5 to 3 g were placed into the test fixture, which has a 1.5 mm depth fixed by a spacer. The sample was tapped 10 times to spread uniformly and compressed by the top of the test fixture to squeeze the air out from inside powder. Then the test fixture was tightly closed and its inlet and outlet were sealed from inside to prevent air and moisture escaping from the fixture. The compaction density (g/mL) was calculated by the sample weight divided by the volume, which equals to $\pi \cdot (0.01\ m)^2 \cdot (0.0015\ m) = 4.71 \times 10^{-7}$ m^3, where 0.01 m is the radius of inside bottom of the fixture, 0.0015 m is the depth.

2.3. Determination of power penetration depth (d_p)

Guan et al. (2004) defined the power penetration depth of RF as the distance below a material surface where the power has decreased by 1/e (e = 2.718) of the power value at the surface. The penetration depth is an important parameter to evaluate heating uniformity and design an RF heating system. It can be calculated using the following equation (Buffler, 1993; Von Hippel, 1954):