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Dielectric properties, heating rate, and heating uniformity of various seasoning spices and their mixtures with radio frequency heating

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ABSTRACT

Low moisture foods, including seasoning spices, have been associated with a number of multi-state outbreaks of salmonellosis in the past decade. The long-term objective of this study was to develop an effective in-package pasteurization treatment for seasoning mixtures based on radio frequency (RF) heating. Seasoning spices obtained from grocery stores included red, white, and black pepper; cumin; curry powder; and garlic powder with moisture contents ranging from 3.1 to 12.3% (wet basis). The dielectric properties (DP) of the seasoning spices and their mixtures as influenced by frequency, moisture, temperature, mixing fraction and salt content were determined using a precision LCR meter and liquid test fixture at frequency ranging from 1 to 30 MHz. The RF heating rates of each spice and their mixtures were evaluated using a 27.12-MHz, 6-kW pilot scale RF system with 105 mm gap between electrodes. To evaluate the effect of mixing on heating uniformity, a sample (50 g) was placed into a polystyrene plastic cylindrical container and heated to 70 °C, and surface images were taken by an infrared camera. The results showed that the relationship among moisture content, temperature and DP of white pepper can be explained by a second-order model at 13.56 and 27.12 MHz. The DP and heating rates of spice mixtures ranged between the highest and lowest values of their respective individual spices. Increase in salt content resulted in a decrease in heating rate, which resulted a better heating uniformity with smaller uniformity index (UI). The RF heating rate of samples ranged from 2.97 to 23.61 (°C min^{-1}). The highest heating rate in samples was in a correspondence to the worst heating uniformity, and highest average temperature on the sample surface. The most uniform heat distrubition on top surface was obtained for garlic powder as 0.012 (UI) at 70 °C. The information obtained from this study is important to develop an effective RF heating strategy for pathogen control in seasoning mixture.

1. Introduction

Foods with low water activity such as vegetable powders and spices have been used as flavoring and seasoning agents. Over the past decade, however, outbreaks were frequently reported in connection with *Salmonella* contamination of spices, including white, red and black pepper (CDC, 2010), paprika (Lehmacher et al., 1995), cumin (Moreira et al., 2009), turmeric and curry powder (Hara-Kudo et al., 2006), and garlic powder (Banerjee and Sarkar, 2003). Although the growth of microorganisms is not supported by foods with low water activity, spices are liable to be contaminated by microorganisms at all stages through production and supply chain including growing, harvesting, processing, packing, handling and transportation (McKee, 1995). Previous studies found that *Salmonella* in foods with low water activity can survive for extended storage time and has high heat tolerance (Hiramatsu et al., 2005; Lehmacher et al., 1995; Ristori et al., 2007). Recent studies have shown that the presence of *Salmonella* in spices can lead to serious foodborne illnesses when added to foods that do not undergo further thermal processing (Rico et al., 2010; Waje et al., 2008).

In general, spices are widely known to contain inhibitory compounds that can inhibit the growth of foodborne pathogens during storage (Arora and Kaur, 1999; Billing and Sherman, 1998; Ceylan

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Nomenclature

ε_0, $\varepsilon\prime$, ε''	The permittivity of vacuum (8.854×10^{-12} F m^{-1}), dielectric constant (Dimensionless), dielectric loss factor (Dimensionless)
T	Gap between electrodes in test fixture (m)
C	Speed of light (3×10^{-8} m s^{-1})
C_p	Capacitance (F)
T	Temperature (°C)
f	Frequency (MHz or Hz)
LCR	Inductance, capacitance, and resistance
CDC	The Centers for Disease Control and Prevention
UI	Uniformity index
DP	Dielectric properties
tanδ	$\frac{\varepsilon'}{\varepsilon'}$
A	Electrode area (m^2).
ρ	Bulk Density (g cm^{-3})
RF	Radio frequency
R^2	Regression coefficient
RSME	Root mean square error
R_p	Resistance (Ω)
SD	Standard deviation
w.b.	Wet weight basis

and Fung, 2004; Dorman and Deans, 2000; Weerakkody et al., 2011), but it is not clearly known whether or not the antimicrobial effect of spices is sufficient to resist microbial growth. Several post-harvest decontamination methods such as fumigation with ethylene oxide, irradiation, and steam treatment have been used to pasteurize contaminated spices. For example, to pasteurize black pepper, packaged black pepper is traditionally treated by steam for 16 min at 1020 mbar and 100 °C. However, the steam treatment of black pepper caused quality degradation with loss of color and flavor (Waje et al., 2008). Due to its carcinogen effect, the use of ethylene oxide is forbidden by the Europe Union, and irradiated foods have not found acceptance by the customers even if it is allowed to be used for pasteurization of spices (Farkas, 2006; Schweiggert et al., 2007).

Consequently, there is a need to develop a more effective alternative pasteurization technique while maintaining the quality of spices. Radio frequency (RF) heating, also known as dielectric heating, has been applied as a promising technique for various food products (Balakrishnan et al., 2004; Bengtsson and Risman, 1971; Wang et al., 2005c; Zielinska et al., 2013). RF is in the range of 1–300 MHz, particularly 13.56, 27.12 and 40.68 MHz, when used for commercial applications, which provides longer wavelength and deeper penetration than those of microwaves at 915 or 2450 MHz (Luechapattanaporn et al., 2005; Marra et al., 2009; Metaxas and Meredith, 1988). As heat is generated volumetrically in foods, RF heating offers significant advantages such as faster heating, better quality, more uniform heat distribution and higher energy efficiency for solid and semi-solid foods with low thermal conductivity as compared to other conventional treatment methods (Casals et al., 2010; Luechapattanaporn et al., 2005; Marra et al., 2009; Pereira and Vicente, 2010). Recent studies also suggested that RF heating has great potential to be used for postharvest disinfection (Jiao et al., 2012; Lagunas-Solar et al., 2007), and pasteurization of dry foods (Gao et al., 2012; Jeong and Kang, 2014; Kim et al., 2012).

Although RF heating is considered a promising pasteurization method, its application is still limited due to challenge in non-uniform heating which is related to heterogeneous dielectric properties and heating rate of different food components. The dielectric properties (DP) of food materials are the most important factors affecting RF heating since the DP values play an important role in energy absorption and conversion in food, which directly affect heating rates and uniformity (Tang, 2005). The DP of foods are mainly influenced by moisture content, temperature, frequency, bulk density and salt content (Nelson, 1996; Orsat and Raghavan, 2005; Tang, 2005). Additionally, because different spices are often mixed to achieve a desired flavor, the DP values of these mixtures differ from the DP of their individual spices. While dielectric properties of various spices have been investigated separately, dielectric properties of spice mixtures have never been measured to our knowledge. There is a lack of in-depth knowledge regarding the DP, heating rate and heating uniformity of spices and their mixtures. Such knowledge is important for developing an effective RF pasteurization procedure for spices. Mixture equations have been reported to predict the DP of air-particle mixtures (Lal and Parshard, 1973; Nelson and Datta., 2001; Sihvola and Kong, 1988), but have not been used to describe the DP of spice mixtures.

The aim of this study was 1) to determine the DP of selected spices and their mixtures as influenced by frequency (1–30 MHz), moisture content (10.2 − 21.7% w.b.) and temperature (20–90 °C), 2) to develop regression models to describe the DP of spices as a function of temperature and moisture content at selected frequencies (13.56 and 27.12 MHz) using white pepper as an example, and predict the DP of spice mixtures using different mixture equations, and 3) to evaluate the heating rate and heating uniformity of spices and their mixtures.

2. Material and methods

2.1. Sample preparation and characterization

Garlic powder, curry powder, cumin, turmeric, paprika, and black, white and red pepper were purchased from a local grocery store. The moisture contents (w.b.) of the spices were determined as garlic powder 3.1%, curry powder 8.3%, cumin 9.2%, turmeric 9.5%, paprika 12.3%, black pepper 11.02%, white pepper 10.2% and red pepper 10.5% by drying samples in an oven at 105 °C until constant weight was obtained (AOAC, 1998).

To study the effect of moisture on the DP values, the moisture content of white pepper was adjusted by adding distillated water to the sample to reach 13.7, 17.1 and 21.7% (w.b.). To obtain a uniform moisture distribution in white pepper samples, water-added samples were stored in Ziploc bags for 48 h at 4 °C and shaken twice daily.

Spice mixtures were prepared using garlic powder (GP); curry powder (CP); paprika (P); black (B), white (W) and red (R) pepper; and salt. Mixtures were made including paprika, curry powder and black pepper (P-CP-B), white pepper and red pepper (W-R), black pepper and garlic powder (B-GP) with different proportions on mass basis. Additionally, black pepper and garlic powder were mixed with seasoning salt using different ratios on mass basis. The mixtures were stored in Ziploc bags at 4 °C for 48 h and manually mixed twice daily to obtain moisture equilibrium and uniform distribution throughout the mixture. The mixtures were placed at room temperature for 12 h for temperature equilibration before measurement.

The bulk density (ρ) of each sample and their mixtures were determined gravimetrically as

$$\rho = \frac{m}{v} \tag{1}$$

where m is total mass (g) of the sample and v is its volume (cm^{-3}) (Trabelsi et al., 2001). The particle density of each material in