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Research Paper

Developing and validating radio frequency pasteurisation processes for almond kernels

Rui Li [a], Xiaoxi Kou [a], Lixia Hou [a], Bo Ling [a], Shaojin Wang [a,b,*]

[a] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, China
[b] Washington State University, Department of Biological Systems Engineering, Pullman, WA 99164-6120, USA

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The efficacy of radio frequency (RF) treatment to inactivate *Escherichia coli* ATCC 25922 used as a surrogate of pathogenic *Salmonella* in almond kernels was investigated. A pilot-scale, 27 MHz, 6 kW RF unit was used to study the heating uniformity of almond kernels at the moisture content of 10.01% w.b. using two types of plastic containers. Pasteurisation processes were developed and validated for almond kernels and the product quality after RF treatments was evaluated. The results showed that only 6.4 min was needed to raise the central temperature of 1.5 kg almond kernels from 25 °C to 72 °C by using RF energy as compared to 276 min using 72 °C hot air in a five-layer container. An effective RF treatment protocol was obtained using an electrode gap of 11 cm, 72 °C hot air surface heating, intermittently rearranging the five-layers in less than 1 min, and holding in 72 °C hot air for 15 min for pasteurisation to achieve more than 4-log reductions of *E. coli* ATCC 25922, drying to reduce the moisture level, and cooling in the single layer by forced room air to avoid product quality degradation. The moisture content, fatty acid, peroxide value and colour values of RF treated almond kernels met the good quality standard used by the almond industry. Therefore, RF treatments are an effective and rapid heating method for potentially pasteurising *Salmonella* in almond kernels.

1. Introduction

Almonds are one of the most valuable nuts in the world with excellent sources of unsaturated fatty acids, micronutrients and vitamins. The global production of almonds was approximately 2.74 million metric tons in 2014, which are mainly contributed by the USA, Spain, Australia, Italy, Turkey and China (FAOSTAT, 2017). *Salmonella* PT 30 outbreaks associated with raw almonds occurred in USA and Canada in 2000–2001 and 2004 (CDC, 2004; Isaacs et al., 2005), which brought the great attention of the US Department of Agriculture (USDA) for establishing regulations to pasteurise almonds in a reasonably acceptable level prior to export (Anon, 2007).

Radio frequency (RF) heating is a highly appealing technology, in which electromagnetic energy at frequencies between 1 and 300 MHz is used to generate heat through rotational movement of the polar dielectric molecules and the electronic charge displacement (Piyasena, Dussault, Koutchma, Ramaswamy, & Awuah, 2003). The RF treatments

* *Corresponding author*. College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, China. Fax: +86 29 87091737.
E-mail address: shaojinwang@nwsuaf.edu.cn (S. Wang).
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provide rapid and volumetric heating within the large-bulk food (Marra, Zhang, & Lyng, 2009). Several studies have evaluated the possibility of using RF energy for controlling pathogens. For example, RF heating may result in more than 4 log reductions of target pathogens in shell eggs (Geveke, Bigley, & Brunkhorst, 2017), red and black peppers (Jeong & Kang, 2014; Kim, Sagong, Choi, Ryu, & Kang, 2012), ground beef homogenates (Nagaraj et al., 2016), wheat flour (Liu et al., 2018) and non-intact steaks (Rincon & Singh, 2016) without quality analyses. RF treatments can also be used for controlling pathogens meanwhile maintaining the quality of product, such as corn (Zheng, Zhang, & Wang, 2017), and in-shell almonds (Li, Kou, Cheng, Zheng, & Wang, 2017). However, there is an essential need for studying the RF heating uniformity using systematic and engineering methods to achieve wide applications of the developed RF treatment protocol.

Heating uniformity in RF treatment is very important for controlling food-borne pathogens and maintaining product quality. However, non-uniform heating, generally overheating in sample corners or edges of a rectangular container still exists when developing effective RF treatments, especially in intermediate and high moisture content foods (Tiwari, Wang, Tang, & Birla, 2011a; 2011b). Many studies have been conducted to reduce the RF overheating in the corner or edge of the container and meanwhile maintain the quality of products. For example, hot air assisted surface heating, sample movement, intermittent mixing, and surrounding container have been explored to improve the RF heating uniformity (Hou, Huang, Kou, & Wang, 2016; Ling, Hou, Li, & Wang, 2016; Ozturk, Kong, Singh, Kuzy, & Li, 2017; Zheng, Zhang, Zhou, & Wang, 2016; Zhou, Ling, Zheng, Zhang, & Wang, 2015; Zhu, Li, Li, & Wang, 2017). Since $D_{72^{\circ}C}$ value of *Salmonella* PT 30 decreased from 12.75 to 0.96 min after raising the moisture content from 6% to 10% w.b. in almonds (Villa-Rojas et al., 2013), the quality of almonds was not affected after RF treatments at the final temperature around 75.5 °C for 19 min (Gao, Tang, Villa-Rojas, Wang, & Wang, 2011). Almond kernels with the moisture content of 10.01% w.b. and 72 °C were thus selected to determine RF heating uniformity in developing effective treatment protocols for controlling Salmonella PT 30 and maintaining the product quality.

Salmonella PT 30 cannot be used directly for pasteurisation validation tests in general research labs and processing plants because the safety is strictly required for operators and processing environment. Except for *Enterococcus faecium* (ATCC 8459 or NRRL B-2354) proposed as a surrogate microorganism in almond process validation (Liu et al., 2018), a nonpathogenic *Escherichia coli* ATCC 25922 has been recommended as a surrogate species of pathogenic *Salmonella* for validation of thermal pasteurisation (Eblen, Annous, & Sapers, 2005; Li, Kou, et al., 2017). Also, in our preliminary test, $D_{71^{\circ}C}$ value of *E. coli* ATCC 25922 in almonds at the moisture content of 10% w.b. was 2.98 ± 0.02 min, which was higher than 2.04 ± 0.03 min of Salmonella PT 30 in almonds (Villa-Rojas et al., 2013). Therefore, *E. coli* ATCC 25922 could be used to replace Salmonella PT 30 for thermal pasteurisation validation tests.

The objectives of this study were (1) to analyse the heating rates of almond kernels in two types of containers under hot air and RF heating conditions, (2) to compare the heating uniformity of almond kernels in two types of containers when using RF heating with additional forced hot air, mixing, holding and intermittently rearranging single layers in a five-layer container, (3) to establish an effective cooling method after RF heating, (4) to develop and validate a RF treatment protocol for achieving 4-log reduction of *E. coli* ATCC 25922 in almond kernels, and (5) to evaluate the almond quality before and immediately after RF treatments.

2. Materials and methods

2.1. *Materials and hot air assisted radio-frequency heating system*

Raw and dried almond kernels (Nonpareil) were purchased from Paramount Farming Company (Modesto, CA, USA). The average initial moisture content of almond kernels was 4.15 ± 0.03% wet basis (w.b.). For pasteurisation of *Salmonella PT* 30 in a short time and maintaining the quality of almond kernels, the moisture content of raw almond kernels was adjusted to 10.01% w.b. by directly adding pre-calculated distilled water. Then the preconditioned almond kernels were equilibrated before RF treatments. The methods for adding water and equilibrating are described in detail in Zheng et al. (2016). RF heating experiments were conducted by using a 6 kW, 27.12 MHz pilot-scale RF unit (SO6B, Stray field International, Wokingham, U.K.) with hot air system (Fig. 1). The detail information about the RF and hot air systems could be found in Wang, Tiwari, Jiao, Johnson, and Tang (2010). The

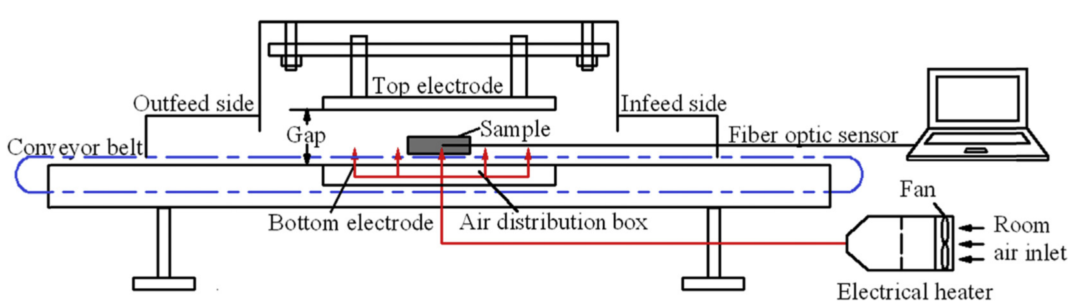

Fig. 1 – Schematic view of the pilot-scale 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, and the hot air system (Adapted from Wang et al., 2010).