Journal of Stored Products Research 77 (2018) 112–121

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Radio frequency heating as a disinfestation method against *Corcyra cephalonica* and its effect on properties of milled rice

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ARTICLE INFO

Article history:
Received 15 February 2018
Accepted 16 April 2018

Keywords:
Milled rice
Radio frequency
Rice moth
Dielectric properties
Quality

ABSTRACT

Radio frequency (RF) heating has the potential to be developed as an alternative non-chemical disinfestation method. In contrast to microwave (MW), RF exhibited higher penetration depth, which helps RF to be a useful technique in disinfesting packaging foods. A 3 kW, 27.12 MHz RF system was used to validate the practical of radio frequency technology for rice moth (*Corcyra cephalonica*) control in milled rice. Rice samples were placed in the polystyrene bag and moved at a speed of 0.8 m/min, and heated in the RF system with intermittent mixing. Four electrode gaps and five sample thicknesses were chosen to confirm the optimal conditions of RF treatment. The results showed that the sample thickness of 15 mm and electrode gap of 40 mm could provide the optimum heating rate for rice. Mortality of each stage (adult, larva, egg) of *C. cephalonica* increased with increasing heating temperature and reached 100% while RF heated 180 s (45.8 °C), 300 s (56.9 °C), and 420 s (70 °C), respectively. No *C. cephalonica* was determined in the samples during 45 days storage incubation period at RF treatment to 70 °C. There were no significant differences between control and RF treated samples in quality parameters (moisture, protein, fat, gelatinization, and sensory attributes). Therefore, RF treatment may provide a practical and effective method for disinfesting milled rice without affecting product quality.

1. Introduction

Rice (*Oryza sativa* L.) is one of the major food crops in the world with rich carbohydrates and high-quality rice protein (Fan et al., 2012). Rough rice is vulnerable to insect pests' infestation, resulting in significant economic loss during storage (Sun et al., 2015). In commercial processing, most rough rice is converted into milled rice with removal of hull, bran and germ from the underlying endosperm by applying friction and/or abrasion forces (Buggenhout et al., 2013). The hull was found to confer some level of tolerance to stored-product insects such as *Rhyzopertha dominica* (Chan et al., 2008). The absence of hull provide an access point for the neonate larvae, which caused milled rice more easier to be infested by stored pests (Arthur et al., 2012).

Chemical fumigations, mainly methyl bromide and phosphine, have been widely used to control insects due to low cost, fast speed in processing and ease of use (Victoria et al., 2006; Wang and Tang, 2001). However, Montreal Protocol (UNEP, 1992) has mandated phasing out the production or importation of methyl bromide by 2005 in developed countries and by 2015 in developing countries (Bell, 2000) due to the damage to the ozone layer and harmful to human health (Wang and Tang, 2004). Resistance to phosphine has been a major challenge of this disinfestation method (Kaur and Nayak, 2014). Therefore, there is an urgent need to develop an alternative non-chemical disinfestation method for milled rice.

Heat treatments, such as hot air, hot water, infrared radio (IR), microwave (MW) and radio frequency (RF) heating, have been proposed to replace chemical fumigation for postharvest disinfestation due to no chemical residue and no environmental pollution (Self et al., 2012; Liu et al., 2017; Athanasiou et al., 2016; Das et al., 2014; Zhou and Wang, 2016a). However, hot air and hot water treatments may result in long treatment time in high medium temperatures and cause undesirable changes in product quality (Kocabiyik et al., 2014; Michal et al., 2006; Wang et al., 2001). IR

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https://doi.org/10.1016/j.jspr.2018.04.004
0022-474X/

heating has been used as a drying technology for obtaining high quality food due to fast and relatively uniform heating (Athanasiou et al., 2016; Khir et al., 2011). In recent years, it has been an increasing trend towards the utilization of IR as an non-chemical method for disinfestation of stored rice (Pan et al., 2008; Wasan et al., 2017). However, with the limited penetration capability of IR, mixing is necessary if the rice is dried in a thick bed, in order to achieve uniform heating of the rice (Nindo et al., 1995).

Dielectric heating, which includes microwave (915 and 2450 MHz) and radio frequency (13.56, 27.12, and 40.68 MHz) treatments, has been studied as an non-chemical alternative method for postharvest insect control in agricultural products due to rapid volumetric heating and quality maintenance (Li et al., 2017; Yadav et al., 2014). In dielectric heating, electromagnetic field polarizes the molecules of dielectric materials and creates dipole moments that cause these molecules to rotate resulting in heat generation in the body (Sinha and Huang, 2016; Vittorio and Rino, 2015; Clark et al., 1993). An important key to develop successful thermal treatments is the dielectric properties of the materials, which depend on the frequency of the applied electric field, the chemical structure and properties of the material, and the amount of water in the material. When a mixture of dry food stuffs and insects are heated, the insects are heated upto lethal temperature because they contain more water as compared to the food stuff which is either left unaffected or gets slightly heated (Yadav et al., 2014). Due to the rapid and internal direct interaction between microwaves and food products, MW heating provides much faster rate of heating than conventional heating, which relies on the processes' conduction and convection to transport heat from the heating sources to the product (Piyasena et al., 2003). However, it was recently reported that the qualities of the treated product may affected by microwave treatment (Khatoon and Prakash, 2007). Lewandowicz et al. (2000) found that microwave radiation led to a shift in the gelatinization range of starch to higher temperature, and a drop in solubility and crystallinity.

Recent research has initiated the investigation of the application of RF heating treatment on disinfestation of dry agricultural products (Wang et al., 2010; Jiao et al., 2012; Mitchama et al., 2004; Gao et al., 2010; Hou et al., 2014; Zhou et al., 2015). Zhou and Wang (2016a), demonstrating RF achieved 100% insect mortality of adult rice weevils (*Sitophilus oryzae*) and provided acceptable quality attributes. Lower frequency levels of RF contribute to a larger penetration depth than MW and thus provide RF a better application in larger size foods (Ramaswamy and Tang, 2008). However, the non-uniform heating problem is the major obstacle of RF heating in food industry, which could be caused by the non-uniform temperature distribution of the treated materials depending on product statuses (size, shape, position, and dielectric properties) and equipments (electrode gap, top electrode configuration) (Tiwari et al., 2011a, 2011b; Ozturk et al., 2017; Ramaswamy and Tang, 2008; Guo et al., 2017). Several methods have been developed to reduce the edge or corner RF overheating, such as hot air assisted surface heating (Wang et al., 2014; Jiao et al., 2012), combining with moving (Birl et al., 2004; Jiao et al., 2012; Bedane et al., 2017), intermittent mixing (Chen et al., 2015; Wang et al., 2005), electrode modification (Wang et al., 2008), and plastic surrounding (Jiao et al., 2014; Huang et al., 2016).

Rice moth (*Corcyra cephalonica*) is a serious pest of stored products, especially nuts and grains (Coelho et al., 2007; Rani et al., 2018; Yang et al., 2015; Charles et al., 2015). Up to now, most of the research work on RF heating on the disinfestation of stored milled rice was focused on *S. oryzae* (Zhou and Wang, 2016a, 2016b), however, RF treatment on *C. cephalonica* control was seldom studied. For further insight into the feasibility of using RF heating for disinfesting milled rice without important product quality loss, more experimental data on quality parameters (moisture, protein, fat, gelatinization, and sensory attributes) are required. The objectives of this research were (1) to study the dielectric properties of rice with radio frequency and microwave treatment, respectively; (2) to investigate the effect of sample thickness and electrode gap on RF heating rates; (3) to determine the thermal mortality of each stage (adult, larva, egg) of *C. cephalonica* with different final temperatures; (4) to investigate the nutritional quality and cooking quality of rice after RF treatment; (5) to compare the effect of rapid cooling and natural cooling on cooked rice quality.

2. Materials and methods

2.1. Chemicals and materials

Commercial milled rice (FULINMEN, MC = 14.13%) purchased from the local supermarket (Wuxi, Jiangsu, China) was used for conducting the RF treatment disinfestation tests. *C. cephalonica* (cultured in our previous study) was chosen for the disinfestation study. All reagents and chemicals used were of analytical grade.

2.2. RF processing system

The continuous RF treatment device developed by Jiangnan University (China) College of Internet of Things consisted of an operating system, processing chamber, auxiliary heating system, and cooling system. The radio frequency processing cavity is composed of two parallel aluminum electrode plates (800 mm × 600 mm and the thickness is 5 mm). The output power of the system could be controlled by changing the distance of electrode plates. Milled rice samples in a plastic container between electrodes were moved on a conveyor belt during RF heating to simulate continuous processes. After going through all chambers the treated sample was cooled by continue packaging the sample in a polyethylene plastic bag (natural cooling) or spreading it on the table (rapid cooling).

2.3. Dielectric properties assay

The dielectric properties of the particulate material associated with the sample density according to the study of Berbert (Berbert et al., 2002), the rice was fully ground with a basic analysis grinding machine (A11, IKA Co., Ltd, Germany) in this study. To eliminate the affect of water absorption of rice on the determination of density, toluene was selected used as the solvent to measure the density of rice at room temperature. The hydraulic device (SFLS-20T, Rongmei Co., Ltd, Taizhou, China) was used to compress the rice flour into a certain volume to ensure that the density of the compressed sample is close to or equal to the true density of the rice grain. Prior to RF treatment, all samples were sealed with a plastic bag and kept in a 25 °C water bath (DK-824, Jinghong Experimental Equipment Co., Ltd. Shanghai, China) for one hour, then quickly placed under the coaxial probe of RF device to measure the dielectric properties.

The dielectric properties measurement system consisted of ENA-L RF network analyzer, coaxial cable, open ended coaxial probe, computer and software (85070E, Agilent, the United States). In this study, the frequency range of the radio frequency band and the microwave band were 10–60 MHz and 300–1500 MHz, respectively. The dielectric constant (ε') and dielectric loss factor (ε'') were calculated by the Dielectric Probe Kit software. According to the dielectric properties obtained, the penetration depth was estimated at the four selected frequencies. Penetration depth was used as an important parameter to evaluate heating uniformity and