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Application of radio frequency pasteurization to corn (*Zea mays* L.): Heating uniformity improvement and quality stability evaluation

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ABSTRACT

Mildews caused grain losses and serious outbreaks have been becoming increasing concerns in domestic and international corn processing industry. This study intended to explore the possibility of using radio frequency (RF) heating as an effective treatment to eliminate the mold contamination and reduce the damage to corn quality. A pilot-scale, 27 MHz, 6 kW RF unit was used to study the heating uniformity in corn samples with five moisture contents (MC) and using three plastic material containers, and develop a treatment protocol for a corn sample with the MC of 15.0% w.b. and evaluate quality attributes and storage stability of treated samples. The results showed that only 7.5 min was needed to raise the central temperature of 3.0 kg corn samples from 25 °C to 70 °C using the RF energy, but 749 min for samples to reach 68.6 °C using hot air at 70 °C. The RF heating uniformity was improved by adding forced hot air, moving samples on the conveyor, and mixing during the treatment. An effective RF treatment protocol was finally developed to combine 0.8 kW RF power with a forced hot air at 70 °C, conveyor movement at 6.6 m/h, two mixings, and holding at 70 °C hot air for 14 min, followed by forced room air cooling through thin-layer (2 cm) samples. Corn quality was not affected by RF treatments since quality parameters of RF treated samples were better than or similar to those of untreated controls after the accelerated shelf life test. RF treatments may hold great potential as a pasteurization method to control molds in corns without causing a substantial loss of product quality.

1. Introduction

Corn or maize (*Zea mays* L.) is a plant of American origin and consumed worldwide for various purposes (Velu et al., 2006). Approximately 75% of corn productions are used for feeding animals and humans, and 25% are processed into various value-added products (FAOSTAT, 2013). Corn kernels are rich and inexpensive sources of starch (62%) and protein (7.8%) (Singh et al., 2003), and are abundant sources of mineral elements (Gu et al., 2015), such as G_u, F_e, M_n, K, and so on. Due to high nutrition values, international export quantity and value of corn had been increased from 2009 to 2011 in the international market (FAOSTAT, 2013). China is the second largest corn producing country with 218 million Mt corn yield, about 11.5% of the total world production (FAOSTAT, 2013). Therefore, the corn storage quality and production losses due to mold contamination are becoming major concerns of the cereal industry.

About 25% of grains worldwide are infected by mold and its mycotoxin each year, of which 2% loses its nutritional and economical values owing to serious infections (FAO, 2007). *Aspergillus parasiticus* is one of the most common molds infecting corn during storage (Reddy et al., 2009). Corn contaminations by *Aspergillus parasiticus*, and consequently presences of the aflatoxins are unavoidable during storage (Liu et al., 2006), which is a threat to health of human and animal (Massey et al., 1995; Bankole et al., 2010). However, it is difficult to remove aflatoxins from corns due to their stabilized molecular structures. Eliminating *Aspergillus parasiticus* before the aflatoxins are produced must be the actual goal rather than removing aflatoxins. It is, therefore, of a great interest to develop a postharvest processing method to reduce or completely eliminate fungus in corns before aflatoxins are produced during storage.

There are a large number of suggested potential methods for suppressing fungal growth and reducing mycotoxin formation. Except chemical treatments with ethylene (Gunterus et al., 2007),

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physical methods are commonly applied, such as plasma (Hertwig et al., 2015), irradiation (UV, gamma rays) (Kanapitsas et al., 2015), microwave (Mendez-Albores et al., 2014) and modified atmospheres (Skandamis and Nychas, 2001). Although these can reduce surface fungal contaminations in some extent, each of these physical methods has limitations in terms of low efficiency, high cost and negative effects on product quality. Thus, it is desirable to develop an effective, practical, and environmentally-friendly physical method for corn pasteurization.

Novel thermal treatments using radio frequency (RF) energy hold potential for pathogen control in agricultural commodities. RF energy can directly interact with agricultural commodities to rapidly raise the temperature of a whole treated sample volume in industrial systems (Tang et al., 2000). A major advantage of RF energy is deeper penetration depth and better heating uniformity in bulk materials (Wang et al., 2003) compared with microwave heating. Thermal effects of RF treatments are found to be effective for controlling *Salmonella* in in-shell almonds (Gao et al., 2011) and inactivating molds, *Salmonella* and *Escherichia coli* on bread, black and red pepper spices, respectively, with acceptable product quality (Liu et al., 2011; Kim et al., 2012). But there have been no reported studies on RF control of *Aspergillus parasiticus* in corns.

Heating uniformity is an important consideration in developing and scaling-up RF treatment protocols. Factors resulting in non-uniform RF heating include non-uniform electromagnetic field distribution and different dielectric properties between samples and surrounding medium mainly caused by the MC of various products (Wang et al., 2007a). Many practical methods are used to improve the uniformity of RF heating in agricultural products, such as adding forced hot air for sample surface heating, sample movement, rotation or mixing of samples during RF heating and immersing products into water for fresh fruits (Birla et al., 2004; Tiwari et al., 2008; Sosa-Morales et al., 2009; Zhou et al., 2015; Zhou and Wang, 2016; Ling et al., 2016). Research is needed to improve the RF heating uniformity in developing corn postharvest treatment protocols for pasteurization while maintaining the product quality.

Objectives of this study were (1) to analyze heating rates in corn under two heating conditions (hot air and RF heating), and develop an effective cooling method after RF heating, (2) to compare the temperature distribution and the heating uniformity index in corn after RF heating with additional forced hot air surface heating, sample movement, and mixing, (3) to determine the heating uniformity of corn samples with five different MC and three plastic-type containers, and (4) to evaluate the effect of RF pasteurization on the quality attributes (MC, water activity, ash, color, starch, protein, fat, fatty acid) of corns during an accelerated storage.

2. Materials and methods

2.1. Material and sample preparation

Newly harvested yellow corn (*Zea mays* L.) used in this research was purchased from a local farmer's market in Yangling, Shaanxi, China. The average initial MC of corn was 9.1 ± 0.2% wet basis (w.b.). To explore the RF heating uniformity in corns with different moisture levels, other samples with MC of 12.0%, 15.0%, 17.9%, and 20.9% w.b. were prepared for the experiment. The initial samples were conditioned by direct addition of predetermined amount of distilled water to obtain the targeted MC (Wang et al., 2015). The preconditioned samples were shaken by hands for 10 min. Then the samples were sealed in hermetic plastic bags and stored at 4 ± 1 °C for more than 7 days in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) for equilibrium. During the storage, the bags were shaken 6 times per day. Before each test, samples were placed in an incubator (BSC-150, Boxun Industry & Commerce Co., Ltd, Shanghai, China) to equilibrate for 12 h at 25 ± 0.5 °C.

2.2. Hot air-assisted RF heating system

A 6 kW, 27.12 MHz pilot-scale free-running oscillator RF system (SO6B, Strayfield International, Wokingham, U.K.) with a hot air system (6 kW) was used for this study. A detailed description of the RF unit, the hot air and conveyor systems can be found in Wang et al. (2010) and Zhou et al. (2015). The top electrode (40 cm × 83 cm) was moved to obtain the required electrode gap, thus regulating the outputted RF power. To simulate continuous processes, the corn samples between electrodes were moved on the conveyor belt started from inlet side to outlet side of the RF system. The sample surface heating was provided using the hot air during RF heating and holding without the RF power. The hot air speed was setup to be 1.6 m/s inside the RF cavity and measured at 2 cm above the bottom electrode by an anemometer (DT-8880, China Everbest Machinery Industry Co., Ltd, Shenzhen, China).

2.3. Determining heating temperature and holding time

For developing effective pasteurization processes, the RF treatment protocol parameters should be designed based on the thermal death kinetics of target molds (Buzrul and Alpas, 2007). Jin et al. (2011) studied the inactivation kinetic model of *Aspergillus parasiticus* in moldy corn by microwave processing, and reported that 6-log reductions of *Aspergillus parasiticus* spores in mL suspensions were obtained at 50, 55, 60, 65, 70 and 75 °C for 19.6, 15.6, 15.2, 13.6, 13.2 and 13.1 min, respectively. Fang et al. (2011) investigated the effect of microwave radiation on biochemical characteristics and mortality of *Aspergillus parasiticus* compared to effects of conventional heating treatment, and the research results showed that effects of microwave treatments on inactivating *Aspergillus parasiticus* were also determined around 70 °C. Taking into consideration of the required inactivation of *Aspergillus parasiticus*, non-uniformity of RF heating, the corn quality and treatment efficiency, the target sample temperature of 70 °C was selected to develop the RF treatment protocol.

2.4. Material selection of surrounding containers

To study the effect of different surrounding containers on the RF heating uniformity of corns, three kinds of materials (polyetherimide, polystyrene, and polypropylene) were selected based on the reported improvement of RF heating uniformity (Jiao et al., 2014; Huang et al., 2016). The containers had the same inner dimensions (300 mm × 220 mm × 60 mm) (Fig. 1) with the 5 mm thickness, which consisted of perforated screens on the side and bottom walls to allow hot and room air to pass through the samples for surface heating and cooling. Effects of the three-material containers with different dielectric properties on RF heating uniformity were compared.

2.5. Determining electrode gap and conveyor belt speed

A corn sample of 3.0 kg with MC of 15.0% w.b. was used for full loads in a polypropylene container (300 mm × 220 mm × 60 mm) (Fig. 1). This MC level was selected since its water activity was closed to that in the growth boundary of *Aspergillus parasiticus* at room temperature. To determine an appropriate electrode gap for RF treatments, the polypropylene container was placed on the stationary conveyor belt between the two electrodes to obtain a general relationship between electrode gap and electric current (*I*,