Journal of Stored Products Research 68 (2016) 9–18

Contents lists available at ScienceDirect

Journal of Stored Products Research

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

Industrial-scale radio frequency treatments to control *Sitophilus oryzae* in rough, brown, and milled rice

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A R T I C L E I N F O

Article history:
Received 23 January 2016
Received in revised form
17 March 2016
Accepted 18 March 2016

Keywords:
Efficiency
Heating uniformity
Radio frequency
Rice weevil
Throughput

A B S T R A C T

Many previously studies have confirmed that radio frequency (RF) treatments have the potential to be developed as non-chemical alternative disinfestation methods. However, most of them are conducted in laboratory scale RF systems, and it is necessary to scale up the treatment protocol for industry scale applications. A pilot-scale, 27.12 MHz, 6 kW RF system was used to simulate the continuous industrial processing and finally estimate the heating efficiency and throughput for controlling adult rice weevils, Sitophilus *oryzae* (L.), in milled, brown, and rough rice. An electrode gap (11.5 cm) was chosen based on the appropriate heating rate (6–8 °C/min). RF heating uniformity in the three types of rice samples was improved by adding 50 °C forced hot air surface heating, sample movements on the conveyor belt at a speed of 12.5 m/h, and holding in 50 °C hot air for 6 min. The final industrial RF treatment achieved a complete mortality of adult S. *oryzae* and provided acceptable quality attributes in moisture content, water activity, color, protein, free fatty acid, and ash. The average heating efficiency and throughput of the RF treatments were 77.7, 76.3, and 74.3%, and 268.8, 247.3, and 224.8 kg/h for milled, brown, and rough rice, respectively. The industrial scale-up studies provide alternative physical methods for disinfesting milled, brown, and rough rice to replace chemical fumigation.

1. Introduction

Rice weevils (*Sitophilus oryzae*) are considered as ubiquitous phytosanitary and quarantine internal pests of stored rough, brown, and milled rice. They cause significant losses in weight, or seed germination, and produce sticky substances and feces, which increase susceptibility to fungal infestation (Padın et al., 2001; Yan et al., 2014). Furthermore, the adults bore small, circular emergence holes on rice samples, increasing moisture levels and reducing the carbohydrate content (Dal Bello et al., 2001). Chemical fumigations, such as phosphine and methyl bromide, have been used worldwide to disinfest rice of *S. oryzae* (Follett et al., 2013; Alfaifi et al., 2014; Wangspa et al., 2015). However, methyl bromide is being prohibited in developed countries by 2005 and in developing countries by 2015 (UNEP, 1992) due to the damage to the ozone layer and harmful to human health (Wang and Tang, 2004). Phosphine fumigation is also confronted with the problem of increasing pest resistance (Benhalima et al., 2004; Zhao et al., 2007a; Follett et al., 2013). Thus, rice industries have generated increased interests in applying non-chemical alternative disinfestation methods.

Radio frequency (RF) heating has been proposed as a potential physical method for postharvest disinfestations (Wang et al., 2006; Lagunas-Solar et al., 2007; Shrestha and Baik, 2013) and pasteurizations (Liu et al., 2011; Gao et al., 2012; Kim et al., 2012; Liu et al., 2015) due to its volumetric and fast heating. RF treatments have not been studied widely before signing the Montreal Protocol due to the accepted use of inexpensive chemical fumigation (Nelson, 1996). After that, many RF treatments combined with hot air surface heating have been used for control yellow peach moth in chestnuts (Hou et al., 2015), cowpea weevil in legumes (Wang et al., 2010), and navel orangeworm in walnuts (Wang et al., 2002, 2007b). Especially recently, Zhou et al. (2015) and Zhou and Wang (2016) have successfully developed an effective treatment protocol to control S. *oryzae* in rough, brown, and milled rice without significant quality degradation based on the heating uniformity studies. However, most of those previous studies are based on the small amount of samples treated in batches.

Recently, two 27.12 MHz, 25 kW RF systems have been used to

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http://dx.doi.org/10.1016/j.jspr.2016.03.002
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simulate the continuous industrial processing and finally estimate the heating efficiency and throughput (Wang et al., 2007a, b). The experiment results show that average heating efficiency is 79.5% when treating walnuts at 1561.7 kg/h. Jiao et al. (2012) use a 27.12 MHz, 6 kW RF unit by combining with forced hot air to conduct industrial scale-up studies and provide 100% cowpea weevil mortality in lentils. These studies demonstrate a promising physical method to develop an industrial-scale RF process without significant changes in quality parameters. Up to now, however, there is no report on developing industrial scale RF treatments for continuous processes that can handle large quantities of rough, brown and milled rice in commercial applications.

Heating uniformity is still an important factor for RF treatment technology to be applied in industrial applications. The non-uniform RF heating among and within agricultural products may lead to quality degradation in hot spots and insect or microbial survival in cold spots due to the non-uniform electromagnetic field distribution (Tiwari et al., 2011; Huang et al., 2015; Zhang et al., 2015). Most heating uniformity improvements have been conducted in RF systems depending on different treatment conditions, such as adding forced hot air surface heating during RF process, conveyor belt movement at a certain speed, mixing samples between two RF exposures, and holding samples in hot air (Gao et al., 2010; Jiao et al., 2012; Wang et al., 2010; Hou et al., 2014). Especially, adding hot air surface heating and conveyor movement could improve RF heating uniformity but excluding mixing to achieve high throughput for industrial applications.

The objectives of the current study were (1) to determine the RF treatment parameters (electrode gap and conveyor belt speed) in the industrial-scale RF treatment, (2) to investigate the RF heating uniformity in rough, brown, and milled rice, (3) to validate the practical RF treatment protocol using the infested rice, (4) to evaluate the product quality after RF treatments and for an accelerated storage at 35 °C for 60 days, and (5) to estimate the heating efficiency and throughput of the industrial-scale RF treatments.

2. Materials and methods

2.1. Materials

Dao Hua Xiang rough, brown, and milled rice (Oryza sativa L.) samples were purchased from a local grain and oil grocery store in Yangling, Shaanxi, China. The average initial moisture contents were 9.3 ± 0.1, 12.5 ± 0.2, and 12.8 ± 0.1 wet basis (w.b.) for rough, brown, and milled rice, respectively. The three types of rice samples were sealed into polyethylene bags at 4 ± 1 °C until testing. Prior to RF experiments, samples were taken out of the refrigerator and put into an incubator (BSC-150, Boxun Industry & Commerce Co., Ltd, Shanghai, China) for more than 12 h at 25 ± 0.5 °C for equilibrium.

2.2. Hot air-assisted RF heating system

A 6 kW, 27.12 MHz parallel plate RF heating system with a free-running oscillator (SO6B, Strayfield International, Wokingham, U.K.) was used for heating rough, brown and milled rice samples together with a customized auxiliary hot air system (Fig. 1). The dimension of the upper parallel-plate electrode was 830 mm × 400 mm. The gap between the two electrodes was adjustable from 90 mm to 190 mm to change the electrical current and RF power (Fig. 2), which was provided by Strayfield International, Wokingham, U.K. for the power calibration curve using water loads. Adjustable conveyor belt speeds from 1.0 to 60 m/h provided different product residence times and corresponding throughputs for a continuous industrial process. The schematic view of the RF and hot-air heating system was described in detail in Wang et al. (2010) and our previous studies (Zhou et al., 2015).

2.3. Electrode gap and conveyor belt speed determination

To develop a continuous RF treatment protocol, 6.0, 5.5 and 5.0 kg milled, brown, or rough rice samples with thickness of 9 cm in three plastic containers (360 mm × 278 mm × 90 mm) (Fig. 3) were placed on the conveyor belt above the bottom electrode to obtain a general relationship between electrode gaps and electric currents (I, A) without forced hot air and movement. After RF energy was turned on, the control screen of the RF system displayed the electrical current being used and was immediately recorded when the electrode gap was increased from 11 to 16 cm with a 0.5 cm interval. Based on the measured electric current, three electrode gaps (11.5, 12, and 12.5 cm) were selected as appropriate ones for further temperature-time history experiments. Under each of the three selected electrode gaps, the sample temperature at the geometric center of the container was recorded by a six-channel fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) with an accuracy of ±0.5 °C. The time needed to heat the milled, brown, and rough rice samples from ambient temperature (25 °C) to 50 °C was recorded. The final gap was fixed based on the target heating rate (6–8 °C/min) of samples with three replicates. The conveyor belt speed during the continuous RF heating was calculated by dividing the electrode length by the resulted heating time.

2.4. RF treatment procedure and heating uniformity evaluation

For RF heating treatment, 12 containers filled with rice samples were put on the conveyor belt to simulate a continuous operation with the 6 kW RF system (Fig. 4). At the beginning of the RF treatment procedure, the electric current was a constant (Fig. 4a), then increased as the first container moved between electrodes and stabilized once the containers were completely located between electrodes (Fig. 4b and c), and finally decreased as the last three containers moved out from the electrodes (Fig. 4d). The electric current was recorded every 30 s while the 12 containers passed through the electrodes. To prevent the influence of the transient condition, the fifth container was selected for heating uniformity, efficacy, and quality evaluations. This whole process was considered as a treatment run.

Heating uniformity is one of the most important considerations in scaling-up the established treatment protocol for milled, brown, and rough rice. Zhou et al. (2015) and Zhou and Wang (2016) proposed hot air surface heating, sample movement, mixing and holding, all of these improved the RF heating uniformity of milled, brown, and rough rice. Since excluding mixing could help increase the throughput in industrial applications (Wang et al., 2010), the optimal heating uniformity during industrial-scale RF treatment for *S. oryzae* disinfestation of milled, brown, and rough rice was obtained by the combination of all these methods except for mixing. For the fifth container, rice samples with 9 cm in depth divided into three layers (Fig. 3) by two thin gauzes with mesh opening of 1 mm to easily map the sample temperature distribution. Before and immediately after reaching the target temperature, the RF unit was turned off and the tested container was maintained for 6 min using hot air alone. Then the surface temperature of the top layer was measured with a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd., Hangzhou, China) having an accuracy of ±2 °C, followed by the middle and bottom layers. The uniformity tests were conducted in triplicate.

Wang et al. (2005, 2008) proposed a heating uniformity index (λ) to evaluate temperature distributions in RF treated samples. This index has been successfully applied to evaluate RF heating

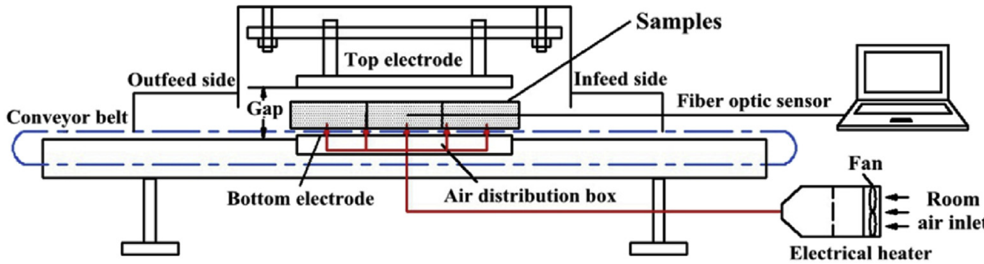

Fig. 1. Schematic view of the pilot-scale 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, and the hot air system (adapted from Wang et al., 2010).

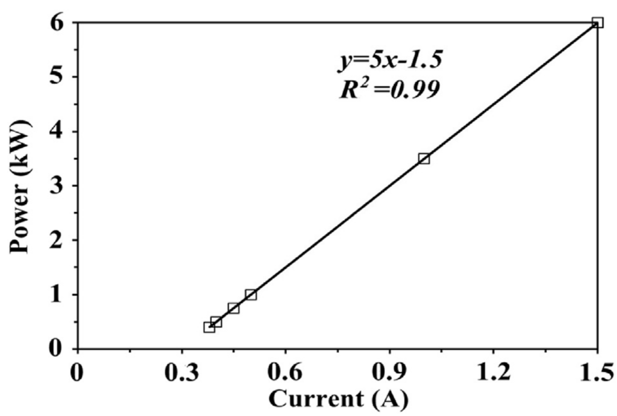

Fig. 2. The relationship between the output power and electrical current of the 6 kW RF unit obtained by Strayfield International, UK using water loads.

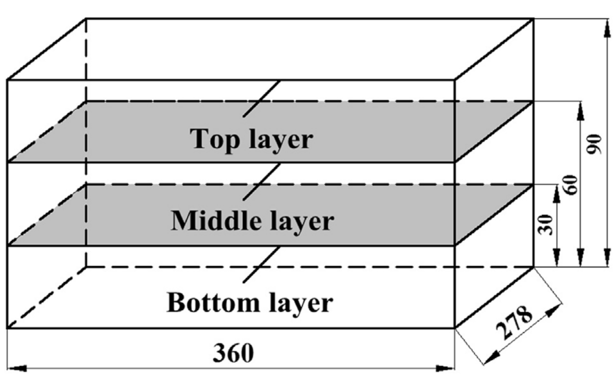

Fig. 3. Dimensions of the plastic container and three layers for temperature mapping using thermal imaging camera (all dimensions are in mm).

uniformity in different kinds of agricultural products, such as almond (Gao et al., 2010), chestnut (Hou et al., 2014), coffee bean (Pan et al., 2012), lentil (Jiao et al., 2012), small rice samples (Zhou et al., 2015; Zhou and Wang, 2016), and walnut (Wang et al., 2007a). It is derived experimentally from sample temperature measurements during treatment and can be calculated by the following equation (Wang et al., 2005):

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \quad (1)$$

where $\Delta\sigma$ is the rise in the standard deviation of sample temperature (°C) and $\Delta\mu$ is the rise (°C) in mean temperatures over the treatment time. The smaller λ values represent the better heating uniformity.

2.5. Effect of RF heat treatment on insect mortality

To validate the final industrial-scale RF treatment protocol, adult *S. oryzae*, the most RF-tolerant stage (Wangspa et al., 2015) was selected as the targeted insect for efficacy confirmation. Test insects were obtained from a laboratory culture originally obtained from Yangling, Shaanxi, China and reared in 600 mL glass jars containing insecticide-free rice. The detailed rearing conditions could be found in Zhou and Wang (2016). With the previously determined conveyor belt speed, three electrode gaps of 11.0 11.5, and 12.0 cm, and 50 °C hot air surface heating, 300, 275, and 250 actively moving adults were selected and placed in 30 small nylon-mesh bags (25 mm × 20 mm) and then randomly mixed into the rough, brown, and milled rice samples, respectively, in the fifth plastic container for continuous RF heating. This represented an artificial infestation level of 5%, well within 4–6% of the natural infestation rate in grain (Batta, 2004; Padin et al., 2002). The small nylon-mesh bags were used to limit the movement of adult *S. oryzae* and provide oxygen for their breath. Immediately upon completion of the RF treatment run, tested adult *S. oryzae* were gently brushed into a glass jar containing rice samples and held for 6 days for mortality evaluation. Control insects were placed in the RF cavity without running for the longest treatment time. The verification tests were conducted in 3 different days, with two runs each day for a total of 6 runs.

2.6. Quality analyses of rice samples during storage

Because rice samples without husk are sensitive to pest infestation and easy to quality degradation during storage, milled rice samples were selected to evaluate the main rice quality attributes after RF treatments and during a storage period. Moisture content, water activity, color, free fatty acid content, protein content, and ash content were selected as the main quality parameters. Controls and RF treated milled rice samples were packed individually in 10 bags and stored in the incubator set to 35 ± 1 °C with 80 ± 5% relative humidity for 2 months to simulate commercial storage at 25 °C for 6 months. The accelerated storage time of 2 months was calculated based on a Q_{10} value of 3.4 for food nutrition loss (Taoukis et al., 1997) and the shelf life (6 months) of milled rice at room temperature (Babu et al., 2009). During storage, controls and RF treated rice samples were taken out every 15 days for quality analysis.

Moisture content was determined according to the AOAC method (AOAC, 2000), and detailed test methods can be found in our previous research (Zhou and Wang, 2016). Water activity was measured by an Aqua Lab water activity meter (Model 4TE, Decagon Devices, Inc., Pullman, WA, USA) under ambient temperature (25 °C). Free fatty acid was determined according to the method of Aibara et al. (1986) with a slight modification. Protein content in the milled rice was determined by using the Kjeldahl method following the AOAC standard (AOAC, 2005). Percentage

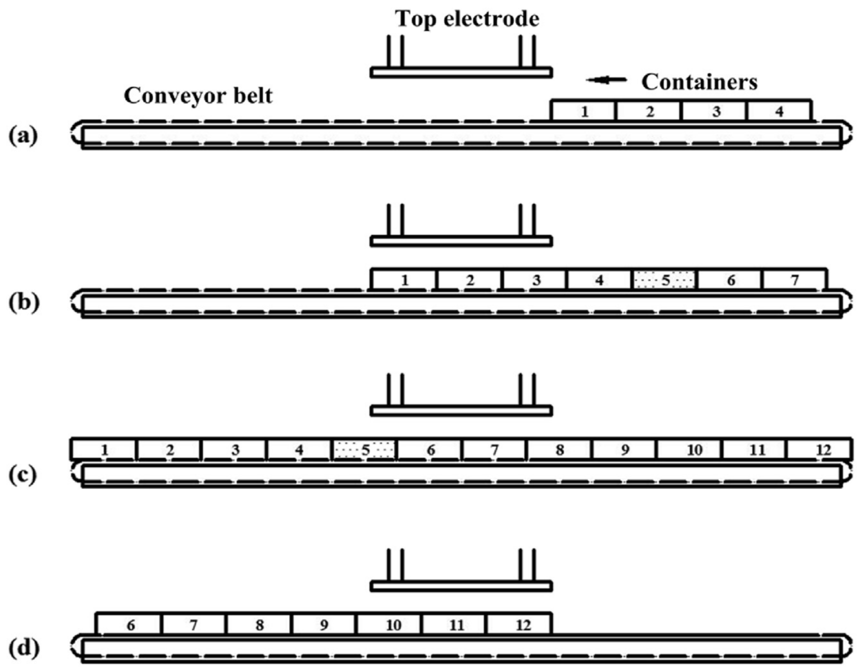

Fig. 4. Arrangement of containers during RF treatments: (a) beginning of the RF treatment, (b) point where the electric current was stabilized, (c) RF cavity fully loaded, and (d) point where current began to decrease. Only the container 5 (shaded) was used for uniformity, efficacy and quality evaluations.

protein was calculated as percentage nitrogen multiplied by the conversion factor of 5.95 (Ju et al., 2001; Tan et al., 2001; Chandi and Sogi, 2007). Ash content was determined by placing the samples in a muffle furnace at 550 °C for 4 h, then weighing the residual ash obtained by combustion. Surface color of milled rice was measured using a computer vision system (CVS). The main components of this system and measuring procedures of color image were described by Zhou et al. (2015). The color values are obtained from Photoshop (L, a, b) were converted to CIE LAB (L^*, a^* and b^*) values using the following formulas (Briones and Aguilera, 2005):

$$L^* = \frac{L}{2.5} \tag{2}$$

$$a^* = \frac{240}{255}a - 120 \tag{3}$$

$$b^* = \frac{240}{255}b - 120 \tag{4}$$

2.7. Heating efficiency and throughput

The average heating efficiency calculations for the industrial RF system were based on the entire treatment run, during which 12 containers all passed through the RF unit. As previously described, the electric current was stabilized once the containers were completely located between electrodes (Fig. 4b and c). This stable electric current value was used to estimate the RF input power based on the relationship shown in Fig. 2. The heating efficiency tests were conducted in 3 different days, with two runs each day for a total of 6 runs.

The heating efficiency (η, %) was calculated as the ratio of the total energy absorbed by the milled, brown, and rough rice samples (P_{output}, W) to the power input (P_{input}, W) (Jiao et al., 2012; Wang et al., 2007a):

$$\eta = \frac{P_{output}}{P_{input}} \times 100\% = \frac{mC_P\left(\Delta T/_{\Delta t}\right)}{P(I) + Ah(T_a - \bar{T}_s)} \tag{5}$$

Where m is the total mass of milled, brown, or rough rice (kg), C_P is the average specific heat of rice samples, and equals 1421 J/kg °C at room temperature (Iguaz et al., 2003), ΔT is the rise in mean temperature over treatment time (°C), Δt is the RF treated time period (s), A is the surface area (m^2) exposed to the hot air, h is the convective heat transfer coefficient, estimated to be 28 W/m^2 °C for hot air over a plate (Ozisik, 1985),T_a is the hot air temperature (50 °C), and $\bar{T}_s$ is the average surface temperature during RF treatment period (°C).

The throughput of the RF treatment (M, kg/h) was calculated by (Jiao et al., 2012; Wang et al., 2007a):

$$M = vNm \tag{6}$$

Where v is the conveyor belt speed in m/h, N is the number of containers within a unit of length and m (kg) is the mass of milled, brown, or rough rice samples per container.

3. Results and discussion

3.1. Determination of electrode gap and conveyor belt speed

The relationship between electric current and electrode gap is shown in Fig. 5 when three containers with or without milled, brown, and rough rice under the condition of no conveyor belt movement, and no hot air assisted heating. Without rice samples, the electric current of the three types of rice samples was almost a constant fluctuated between 0.29 and 0.32 A. With rice samples, the electric current decreased rapidly with increasing electrode gap from 11.0 to 13.0 cm and thereafter almost stable (Fig. 5a–c). Fig. 6 shows the temperature at the geometric center of the container of 9 cm deep milled, brown, and rough rice samples during RF heating under the three selected electrode gaps of 11.5, 12, and 12.5 cm.

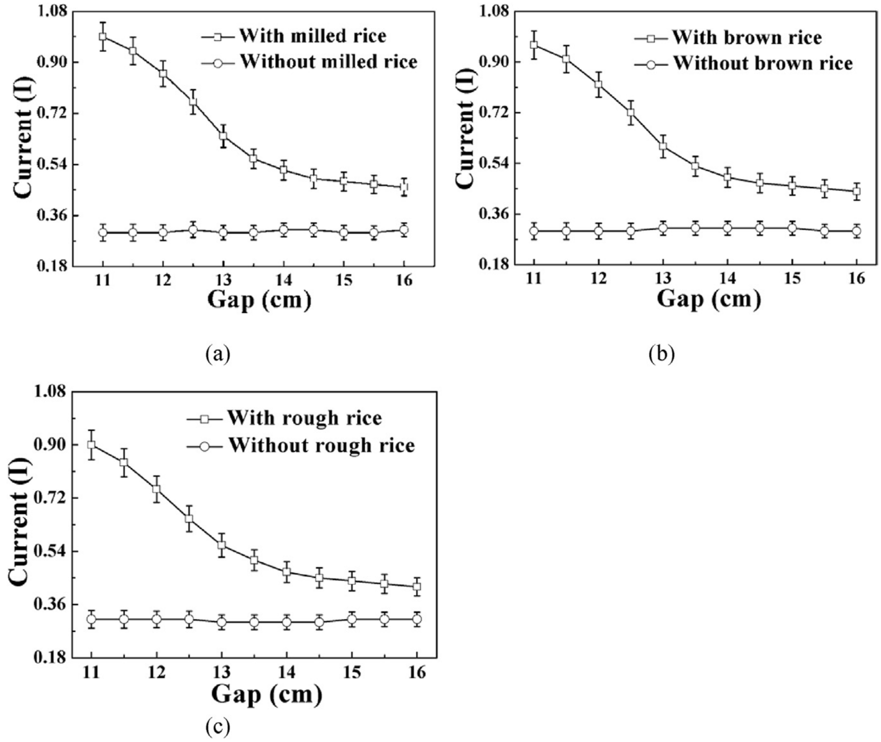

Fig. 5. The relationship between the electrical current and electrode gap with three containers filled with (a) milled, (b) brown, and (c) rough rice without movement and forced hot air heating.

About 4.1, 4.0, and 3.9 min were needed to heat the 6.0, 5.5, and 5.0 kg milled, brown, and rough rice samples from 25 to 50 °C and the heating rates were 6.1, 6.3, and 6.4 °C/min, respectively, for the electrode gap of 11.5 cm (Fig. 6a–c). The heating time increased with increasing electrode gap and correspondingly reducing heating rates. To obtain relatively high throughput with acceptable heating uniformity in industrial applications, the electrode gap of 11.5 cm was selected for further RF heating uniformity and

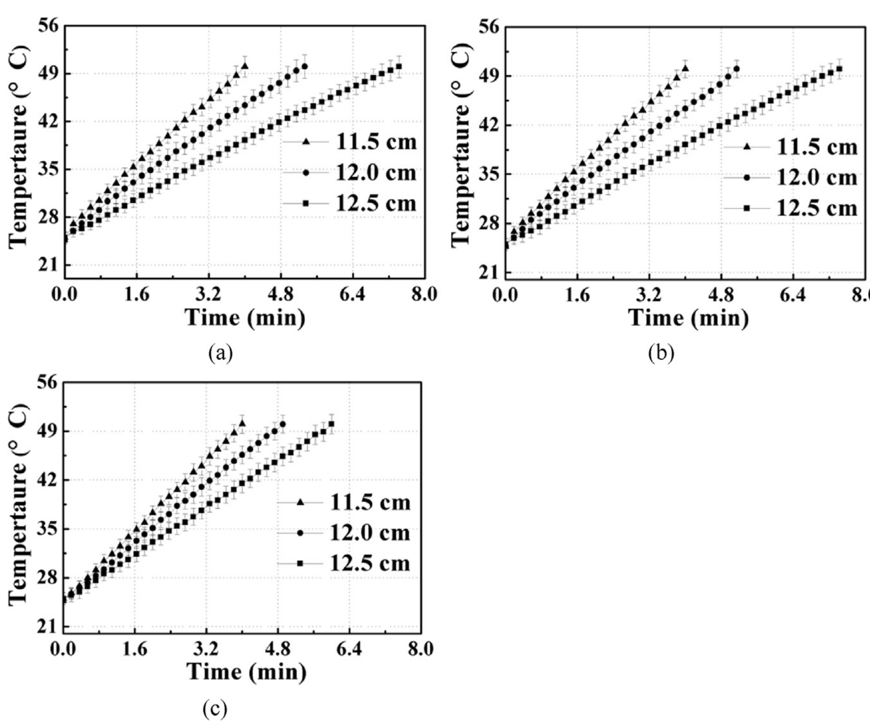

Fig. 6. Temperature-time histories of the RF heated milled (a), brown (b), and rough (c) rice in the geometric center of the middle container as a function of the electrode gap without movement and forced hot air heating.

Table 1
Comparisons of the temperature distribution and heating uniformity index (mean ± SD over 3 replicates) of continuous RF treated rice samples under hot air surface heating, conveyor belt movement, and holding in hot air for 6 min.

Layer	Sample temperature (°C)		
	Rough rice	Brown rice	Milled rice
Top	51.3 ± 2.1	50.9 ± 1.8	50.7 ± 1.6
Middle	52.5 ± 1.7	52.1 ± 1.6	51.8 ± 1.5
Bottom	53.6 ± 1.5	53.4 ± 1.5	53.1 ± 1.3
Heating uniformity index (λ)			
Top	0.047 ± 0.004	0.047 ± 0.004	0.043 ± 0.003
Middle	0.041 ± 0.006	0.038 ± 0.003	0.036 ± 0.003
Bottom	0.034 ± 0.002	0.032 ± 0.003	0.029 ± 0.002

disinfestation tests. The obtained heating rate is similar to those in RF treated lentils (Jiao et al., 2012) and almonds (Gao et al., 2010). Based on the RF heating time, the average speed of the conveyor belt was therefore set to 12.5 m/h.

3.2. Heating uniformity and S. oryzae mortality evaluation

Table 1 provides a detailed comparison of the temperature distributions and uniformity index values for milled, brown, and rough rice when the electrode gap was set to 11.5 cm, with 50 °C hot air assisted surface heating, conveyor belt movement at the speed of 12.5 m/h, and holding in 50 °C hot air for 6 min. From the top to the bottom layer, the temperatures of milled, brown, and rough rice showed an increase tendency, and the average temperatures of all layers were above 50 °C, ensuring the 100% mortality of adult S. *oryzae* (Yan et al., 2014). The uniformity index values were smaller than those observed for rice samples using single container in the small laboratory-scale RF systems (Zhou et al., 2015; Zhou and Wang, 2016). The validated computer simulation model has shown that as container size was close to the electrode size, the RF field distribution is improved, therefore the better RF heating uniformity could be obtained (Huang et al., 2015; Tiwari et al., 2011). Besides that, the containers on the conveyor belt one after another also reduced the phenomenon of edges overheating.

Table 2 shows insect mortality with the electrode gap of 11.0, 11.5, and 12.0 cm in milled, brown, and rough rice after the continuous RF treatments. The mortality of untreated controls was <5%, indicating little mortality caused by transport and handling. Therefore, the mortality data for samples after RF treatments were not required for further corrections (Yan et al., 2014). Under the selected appropriate electrode gap of 11.5 cm, the mortality levels of adult S. *oryzae* in the three rice samples achieved 100%. The results agreed with the thermal mortality of adult S. *oryzae* obtained by laboratory scale RF disinfestation (Zhou and Wang, 2016). When the electrode gap decreased from 11.5 to 11.0 cm, complete kill of test insects was also observed. This was mainly because the final target temperatures were located above 50 °C as the electrode gap decreased. However, when increased the electrode gap, only

Table 2
Average mortality of adult rice weevil in control and the continuous RF treated rice samples when exposed to radio frequency (RF) heating at 50 °C for 6 min.

Replicates	Runs	Gaps (cm)	Treatment	Mortality (%)		
				Rough rice	Brown rice	Milled rice
			Control	2.5 ± 3.2	3.1 ± 1.9	2.4 ± 2.3
	1	12.0	RF	76.3 ± 5.6	75.1 ± 6.4	73.4 ± 4.1
		11.5	RF	100 ± 0	100 ± 0	100 ± 0
Rep 1		11.0	RF	100 ± 0	100 ± 0	100 ± 0
			Control	2.8 ± 2.0	4.0 ± 3.6	3.5 ± 2.3
	2	12.0	RF	78.1 ± 7.2	77.6 ± 6.8	74.3 ± 6.5
		11.5	RF	100 ± 0	100 ± 0	100 ± 0
		11.0	RF	100 ± 0	100 ± 0	100 ± 0
			Control	3.6 ± 1.7	3.7 ± 4.0	4.3 ± 3.8
	1	12.0	RF	73.1 ± 8.2	72.7 ± 7.5	69.9 ± 7.3
		11.5	RF	100 ± 0	100 ± 0	100 ± 0
Rep 2		11.0	RF	100 ± 0	100 ± 0	100 ± 0
			Control	3.3 ± 3.9	2.8 ± 1.5	3.7 ± 2.8
	2	12.0	RF	80.2 ± 5.8	79.5 ± 6.3	77.5 ± 7.1
		11.5	RF	100 ± 0	100 ± 0	100 ± 0
		10.0	RF	100 ± 0	100 ± 0	100 ± 0
			Control	1.9 ± 2.0	3.4 ± 2.2	2.9 ± 2.5
	1	12.0	RF	76.4 ± 8.3	75.2 ± 7.6	72.1 ± 6.8
		11.5	RF	100 ± 0	100 ± 0	100 ± 0
Rep 3		10.0	RF	100 ± 0	100 ± 0	100 ± 0
			Control	2.7 ± 1.8	3.2 ± 3.7	4.2 ± 3.1
	2	12.0	RF	74.4 ± 6.9	72.9 ± 5.3	69.7 ± 6.0
		11.5	RF	100 ± 0	100 ± 0	100 ± 0
		10.0	RF	100 ± 0	100 ± 0	100 ± 0

Table 3
Moisture contents and water activity (mean ± SD over 3 replicates) of milled rice samples before and after the continuous RF treatments during storage at 35 °C.

Storage time (days)	Moisture contents (% w.b.)		Water activity	
	RF	Control	RF	Control
0	12.78 ± 0.09aA[a]	12.86 ± 0.12aA	0.559 ± 0.05aA	0.551 ± 0.04aA
15	12.75 ± 0.07aA	12.79 ± 0.10aA	0.554 ± 0.03aA	0.548 ± 0.04aA
30	12.71 ± 0.08aA	12.73 ± 0.08aA	0.547 ± 0.03aA	0.543 ± 0.02aA
45	12.68 ± 0.06aA	12.70 ± 0.05aA	0.542 ± 0.02aA	0.538 ± 0.02aA
60	12.66 ± 0.05aA	12.68 ± 0.06aA	0.540 ± 0.02aA	0.537 ± 0.02aA

[a] Different lower and upper case letters indicate that means are significantly different at P = 0.05 among treatments and storage time, respectively.

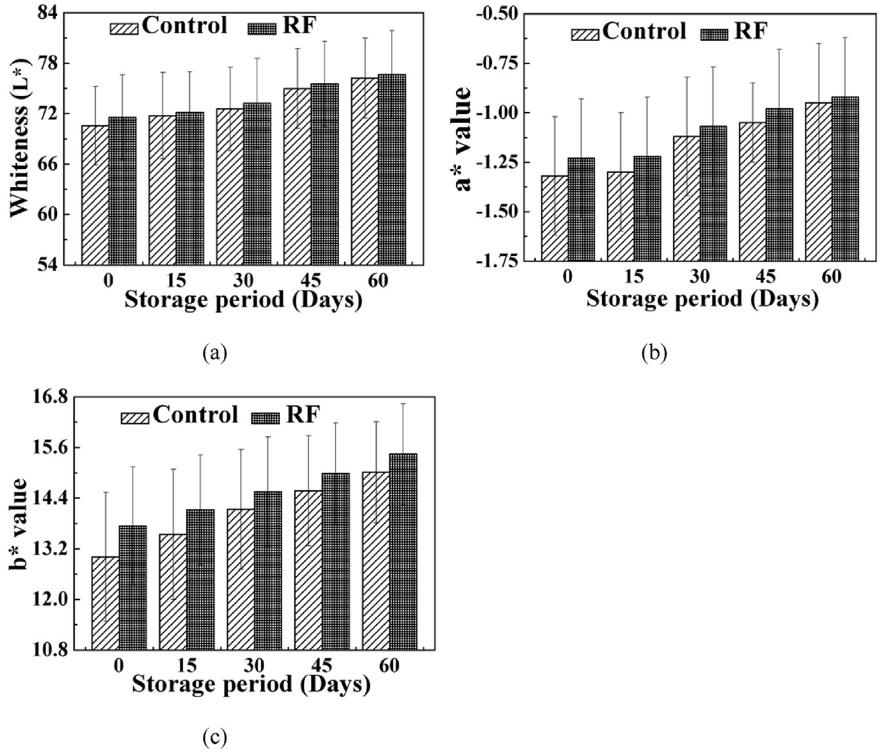

Fig. 7. Changes in color values (L^* (a), a^* (b), and b^* (c)) of RF treated and untreated milled rice samples during storage at 35 °C.

70–80% mortality was obtained (Table 2) because the larger electrode gap led to the final rice temperatures dropped below 50 °C. Generally, the electrode gap ≤11.5 cm may ensure the target surface temperature of milled, brown, and rough rice exceeded 50 °C to acquire complete mortality of adult S. *oryzae*. The minimum exposure time of 6 min at 50 °C was larger than that obtained by the heating block system (Yan et al., 2014). This phenomenon was caused by the non-uniform RF heating. The similar results were also reported in microwave treated cherries (Ikediala et al., 1999) and RF treated chestnuts (Hou et al., 2015), walnuts (Wang et al., 2001, 2007b), and small rice samples (Zhou and Wang, 2016).

3.3. Milled rice quality analysis

The RF heating treatments result in a decrease of milled rice moisture content and water activity. However, there was no significant difference between control and RF treated samples ($P > 0.05$) before and after RF treatments during 2 months storage (Table 3). Moisture content and water activity showed a similar decreasing trend as the storage time increased. This was mainly attributed to the water movement from the inside of milled rice samples into the air by evaporation (Sauer, 1992). The result is also observed by Haque et al. (2004), indicating that at a constant ambient temperature, the moisture content and water activity show a similar changing trend.

Fig. 7 illustrates the effect of RF treatment on color values (L^*, a^*, and b^*) of milled rice during the whole storage periods. With increasing storage time, L^*, a^* and b^* values slightly increased but there were no significant differences ($P > 0.05$) between the control and RF treatments (Fig. 8a–c). This tendency is consistent with that found by Suhem et al. (2013), showing that RF treatment did not influence the color of rice samples. The increase in b^* value indicated that the milled rice changed from creamy white to yellow as the storage time extended, this was may be due to the lipid oxidation and the acceleration of Mailard reaction between the protein and sugar contents (Park et al., 2012).

The quality parameters of milled rice before and after RF treatment are presented in Table 4. There were no significant differences in protein and ash content between the two treatments after 60 days of storage ($P > 0.05$). Similar results are also obtained by Suhem et al. (2013), indicating that RF heating did not affect the nutritional value (protein and ash) of rice samples. However, the free fatty acid values increased with storage time both for control and continuous RF treated milled rice and the increase rate of untreated rice samples was faster than that of RF treated. This was mainly caused by the partial inactivation of the lipase and lipoxidase during thermal treatment, which inhibited the formation of free fatty acids during storage (Zhao et al., 2007b; Zhong et al., 2013).

3.4. RF heating efficiency and throughput

Fig. 8 shows the electric current changes during six RF treatment runs for three replicates as 12 containers filled with milled, brown, and rough rice samples passed through the RF unit under the selected electrode gap of 11.5 cm with the conveyor belt movement at the speed of 12.5 m/h, together with hot air surface heating at 50 °C. The electric currents in milled, brown, and rough rice were fluctuated in 0.92–0.97, 0.85–0.92, and 0.81–0.86 A, respectively (Fig. 8a–c). Based on the relationship between current and power input (Fig. 2), the input powers of the three types of rice samples were 3.10–3.35, 2.75–3.10, and 2.55–2.80 kW, respectively.

Fig. 9 shows a summary of the estimated heating efficiency of the industrial-scale RF treatments for adult S. *oryzae* control in milled, brown, and rough rice based on the calculation over three treatment days and six complete runs. According to Eq. (5), the RF energy efficiency for milled rice ranged from 73.4 to 78.8% with an average value of 76.1% (Fig. 9). These values were similar to those

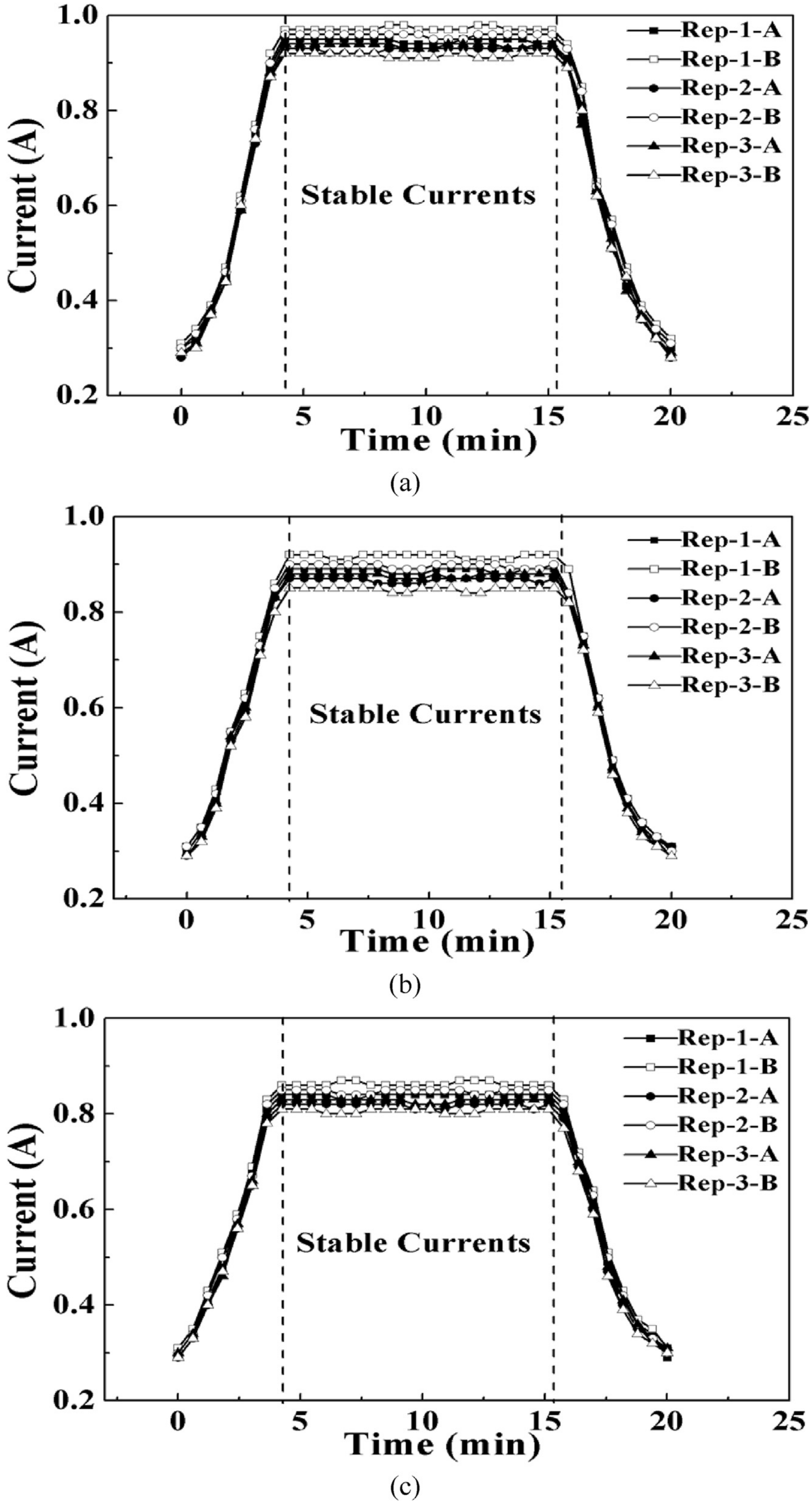

Fig. 8. The electric current change profile of milled (a), brown (b), and rough (c) rice when 12 containers passed through the RF unit electrodes with the electrode gap of 11.5 cm.

obtained by brown rice, which was changed from 72.2 to 80.6% with an average value of 76.3% (Fig. 9), but slightly larger than those found for rough rice, which ranged from 72.1 to 78.4% with an average value of 75.2%. The variations in heating efficiency of the same rice sample were probably caused by the different ambient conditions for different days and runs. The heating efficiency values in this study were comparable with the value (79.5%) for RF treated walnuts (Wang et al., 2007a) and the result (76.5%) for lentils (Jiao

Table 4
Storage quality (mean ± SD) of milled rice before and after the continuous RF treatment during storage at 35 °C.

Storage times (days)	Treatment	Quality characteristics		
		Protein (%)	Free fatty acid (%)	Ash (%)
0	RF	6.82 ± 0.08aA[a]	1.64 ± 0.52aA	0.296 ± 0.09aA
	Control	6.75 ± 0.05aA	2.22 ± 0.73aA	0.312 ± 0.08aA
15	RF	6.76 ± 0.06aA	2.41 ± 0.54aAB	0.285 ± 0.06aA
	Control	6.69 ± 0.08aA	3.37 ± 0.58aAB	0.295 ± 0.05aA
30	RF	6.80 ± 0.07aA	3.57 ± 0.88aBC	0.280 ± 0.05aA
	Control	6.71 ± 0.04aA	4.36 ± 0.61aBC	0.286 ± 0.04aA
45	RF	6.73 ± 0.03aA	4.56 ± 0.65aCD	0.274 ± 0.04aA
	Control	5.67 ± 0.05aA	5.27 ± 0.69aCD	0.281 ± 0.04aA
60	RF	6.68 ± 0.09aA	5.29 ± 0.57aD	0.269 ± 0.03aA
	Control	6.64 ± 0.06aA	6.07 ± 0.58aD	0.273 ± 0.04aA

[a] Different lower and upper case letters indicate that means are significantly different at P = 0.05 among treatments and storage time, respectively.

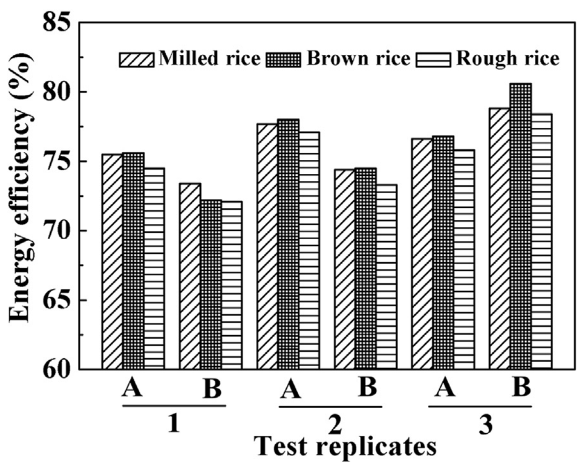

Fig. 9. The heating efficiency of the RF unit estimated for milled, brown, and rough rice with two passes (A and B) through the 6 kW RF unit for three full-load replicated tests.

et al., 2012). The calculated throughputs of the continuous RF treatment of milled, brown, and rough rice samples were 268.8, 247.3, and 224.8 kg/h, respectively, according to Eq. (6). To improve the throughput, it is effective and reasonable to scale up from pilot-scale (6 kW unit) to industrial-scale applications (e.g. 80–100 kW unit) or multiple small pilot-scale systems in parallel.

4. Conclusions

A 27.12 MHz, 6 kW radio frequency (RF) system with an appropriate electrode gap of 11.5 cm, conveyor belt speed set to 12.5 m/h, together with 50 °C forced hot air surface heating was used to conduct industrial-scale experiments for disinfesting *S. oryzae* in milled, brown, and rough rice. The heating uniformity was greatly improved by using hot air, conveyor belt movement, and holding for 6 min in hot air alone. This industrial treatment caused 100% mortality of adult *S. oryzae*, the most damaging and serious stored pests worldwide in rice. The effect of RF treatments on milled rice quality and storage stability was not significant, indicating that rice samples were tolerant to a short exposure at the selected treatment temperatures for RF disinfestations. The average heating efficiency and throughput of the RF system for milled, brown, and rough rice were 76.1, 76.3, and 75.2%, and 268.8, 247.3, and 224.8 kg/h, respectively. This study may enhance sustainability and competitiveness of the rice industry in international markets for postharvest disinfestations without affecting product quality.

Acknowledgments

This research was conducted in the College of Mechanical and Electronic Engineering, Northwest A&F University, and supported by research grants from General Program of National Natural Science Foundation of China (31371853) and Program of Introducing International Advanced Agricultural Science and Technologies (948 Program) of Ministry of Agriculture of China (2014-Z21). The authors thank Shuang Zhang, Rui Li, Bo Ling, and Kun Wang for their helps in conducting experiments.

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