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Verification of radio frequency heating uniformity and *Sitophilus oryzae* control in rough, brown, and milled rice

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ABSTRACT

Radio frequency (RF) heating is considered to be an alternative physical method for disinfesting postharvest agricultural products to replace chemical fumigation due to its inherent dangers on human health and environment. A pilot-scale, 27.12 MHz, 6 kW RF system was used to study the RF heating uniformity and validate the developed RF treatment protocols for disinfesting rough, brown, and milled rice. The results showed that the optimum RF heating uniformity in rough and brown rice was obtained by an appropriate electrode gap of 11 cm with a forced hot air heating at 50 °C, movement of the conveyor with a speed of 12.4 m/h, two mixings, and holding at 50 °C hot air for 5 min. Mortality of adult rice weevils, *Sitophilus oryzae* (L.), increased with increasing heating temperature and holding time, and reached 100% while RF heating at 50 °C holding in hot air for at least 6 min. There were no significant differences in quality parameters (moisture, protein, water activity, starch, free fatty acid, ash, and color) between RF treatments and untreated controls during storage ($P > 0.05$). The developed non-chemical alternative RF technology may hold potential for disinfesting rough, brown, and milled rice required by the growing organic market.

1. Introduction

Postharvest losses caused by insects, mites, rodents and microbes in stored grains have been reported around 1% and 10–30% in developed and developing countries, respectively (Yadav et al., 2014). Out of the total grain losses, 5% are caused by insect pests (Rajendran, 2002). Rice weevils (*Sitophilus oryzae*) are considered one of the most damaging and serious stored pests worldwide in rice (Batta, 2004). They cause both quantitative and qualitative damages, such as weight losses, and reduced nutritional and aesthetic values, leading to food safety issues (Padın et al., 2002). Thus, there is an urgent need to develop an effective, novel, and safe method of controlling infestations in rough, brown, and milled rice during processing and storage (Zhao et al., 2007a).

Traditionally, chemical fumigations, such as phosphine and methyl bromide, have been the most widely and commonly applied method throughout the world for insect control due to its efficacy and relatively low cost (Alfaifi et al., 2014). However, resistance to phosphine poses a major challenge to the control of *S. oryzae* (Follett et al., 2013; Nayak et al., 2007). The Montreal Protocol (UNEP, 1992) has mandated phasing out the applications and productions of methyl bromide for postharvest phytosanitary treatments by 2015 in developing countries, such as in China (Li et al., 2015; Wang and Tang, 2004; Zhou et al., 2015). The adverse effects of chemical fumigation on insect resistance, environmental concerns and the growing of organic markets have increased the demand of non-chemical alternative insect control methods for rough, brown, and milled rice.

In recent years, heat treatments, such as hot air, hot water, and RF heating, have attracted more and more attentions and been widely studied in laboratories to disinfest postharvest products due to no chemical residues, no environmental pollutions, easy to apply, and fungicidal effects (Wang et al., 2006a). However, hot air and hot water treatments have disadvantages based on the treatment effectiveness and processing time. To shorten treatment time and minimize thermal impact on product quality, RF heating has been suggested for control of various postharvest insects (Nelson, 1996; Tang et al., 2000), such as Mexican fruit fly in persimmons (Monzon et al., 2007; Tiwari et al., 2008) and mangoes (Sosa-Morales et al., 2009), codling moth in cherries (Hansen et al., 2005; Ikediala

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et al., 2002), apples (Wang et al., 2006a), and walnuts (Wang et al., 2001), navel orangeworm in almonds (Gao et al., 2010) and walnuts (Wang et al., 2002a, 2007a, b), yellow peach moth in chestnuts (Hou et al., 2015), rusty grain beetle in wheat (Shrestha et al., 2013), coffee berry borer in coffee beans (Pan et al., 2012), cowpea weevil in dried legumes (Jiao et al., 2012), angoumois grain moth in rough rice (Lagunas-Solar et al., 2007), Mediterranean fruit flies in oranges (Birla et al., 2005), and pecan weevil in pecans (Nelson and Payne, 1982). Especially recently, a RF treatment protocol has been developed after improving RF heating uniformity in milled rice using hot air surface heating, moving, mixing, and holding (Zhou et al., 2015). To scale up the treatment protocol for continuous industry applications, confirmation and efficacy tests against *S. oryzae* using combination of hot air and RF treatments should be evaluated for various rice products, such as rough, brown, and milled rice.

Developing a successful thermal treatment relies on a thorough knowledge of the thermal death kinetics of the targeted insects. A heating block system eliminates the effect of heat transfer on the intrinsic thermal death kinetics of insect pests and is able to generate highly repeatable results of insect mortality in dry products (Wang et al., 2002b). The thermal death kinetics of adult *S. oryzae* have showed that the required holding times for achieving 100% mortality are 130, 50, 12 and 4 min at 44, 46, 48 and 50 °C, respectively and the mortality at high heating rates (1–10 °C/min) was significantly higher than that at low heating rates (0.1–0.5 °C/min) under the same condition (Yan et al., 2014). Consequently, efficacious treatments at 50 °C or above with high heating rates under RF treatments should control the adult *S. oryzae* in rice.

The objectives of this research were: (1) to analyze the RF heating uniformity in rough and brown rice based on the developed treatment protocol for milled rice, (2) to determine the thermal mortality of adult *S. oryzae* at 4 selected temperatures, (3) to validate the practical RF treatment protocol using the infested rice with different holding time at 50 °C, and (4) to evaluate the main rice quality attributes after RF treatments and for an accelerated storage at 35 °C for 60 days.

2. Materials and methods

2.1. Materials

Taohuaxiang rough, brown, and milled rice (*Oryza sativa* L.) samples were obtained from a local grain and oil grocery store in Yangling, Shaanxi, China. Table 1 shows the average original moisture contents and weights of rough, brown, and milled rice. All the rice samples were stored with polyethylene bags in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) at 3 ± 1 °C before the experiment. Prior to RF treatments, all 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.

Table 1
Moisture contents and weights of rough, brown, and milled rice samples in the test container (300 × 220 × 60 mm^3).

Sample	Moisture contents (%, w.b.)	Weights (kg)
Rough rice	9.5 ± 0.1	2.6
Brown rice	12.6 ± 0.1	3.8
Milled rice[a]	12.7 ± 0.1	3.9

[a] Moisture content and weight of milled rice samples were adapted from Zhou et al. (2015).

2.2. RF heating system and test insects

A 6 kW, 27.12 MHz pilot-scale free running oscillator RF system (SO6B, Strayfield International, Wokingham, U.K.) together with a hot air system supplied by a 6 kW electric heater was used for RF heating experiments (Fig. 1). The RF system mainly comprises a generator and an applicator consisting of a pair of parallel plate electrodes inside a large rectangular metallic enclosure (Alfaifi et al., 2014; Huang et al., 2015). A hot air flow was forced from the bottom electrode to the sample to provide surface heating and maintain the sample temperature during holding when the RF power was turned off.

Adult *S. oryzae* were selected to determine the treatment efficacy, because removal of internal stages from the seeds causes high mortality and the adult *S. oryzae* was the most RF-tolerant stages (Wangspa et al., 2015). 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 under ambient conditions of about 26 ± 2 °C with 65% relative humidity and a photoperiod of 14:10 (L:D) h using artificial light.

2.3. Validating RF heating uniformity in rough and brown rice

Zhou et al. (2015) proposed 3.9 kg milled rice samples with thickness of 6 cm in the plastic container under the selected electrode gap of 11 cm, conveyor belt movement at the speed of 12.4 m/h, hot air at 50 °C for surface heating, two mixings during the whole heating time of 5.4 min, and then holding 5 min only with forced hot air at 50 °C can improve heating uniformity and maintain the good quality of milled rice samples. To validate RF heating uniformity of rough and brown rice, the whole treatment protocol was developed by following the procedure reported by Zhou et al. (2015). Before and immediately after RF treatment was completed, first layer surface temperature was measured by a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd., Hangzhou, China) having an accuracy of ±2 °C, and then the middle- and bottom-layer temperatures of 12 positions were obtained by two Type-T thermocouple thermometers (TMQSS-020-6, Omega Engineering Ltd., CT, USA). Detailed locations of these 12 temperature measurements were described in Fig. 2 and those on the mixing method and the infrared imaging system to measure product surface temperatures after RF treatment can be found elsewhere (Wang et al., 2006b; Zhou et al., 2015).

Uniformity index (λ) is a key factor in developing successful postharvest quarantine treatments using RF energy and proposed by Wang et al. (2008). The λ value has been successfully used for evaluating RF heating uniformity in different kinds of agricultural products (Gao et al., 2010; Hou et al., 2014; Jiao et al., 2012; Pan et al., 2012; Wang et al., 2007a, 2010) and can be calculated by the following equation (Wang et al., 2005):

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

Where $\Delta\sigma$ and $\Delta\mu$ are the rise in the standard deviation and mean values, respectively, from the initial to final sample temperatures (°C) over treatment time. The smaller λ values represent the better heating uniformity.

2.4. Determine the effect of sample temperatures on insect mortality

Based on the thermal-death-time curves for P. *interpunctella* (Johnson et al., 2003), T. *castaneum* (Johnson et al., 2004), and S. *oryzae* (Yan et al., 2014), four temperatures of 44, 46, 48 and 50 °C

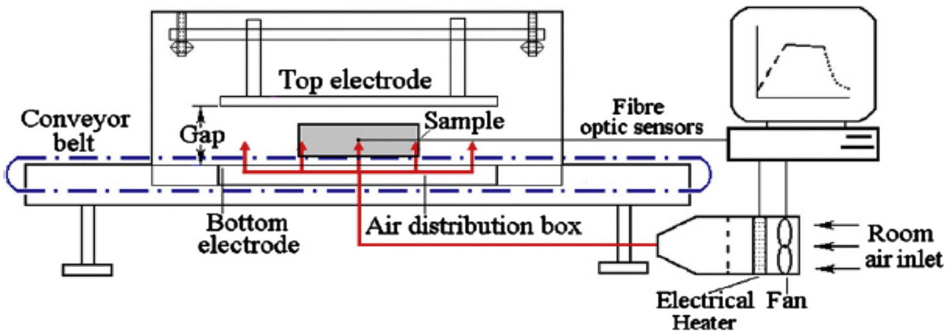


Fig. 1. Schematic view of the pilot-scale 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, and the hot air system (adapted from Wang et al. (2010)).

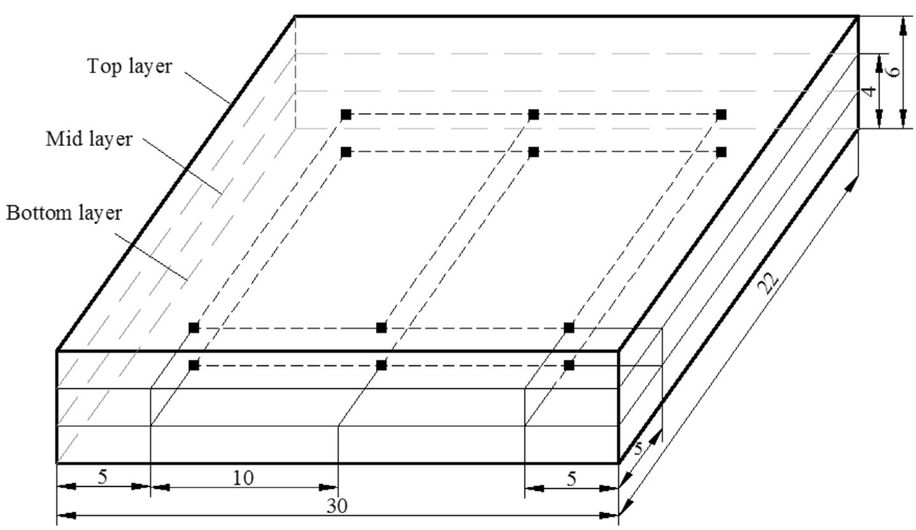


Fig. 2. Rectangular plastic container with 12 locations for sample temperature measurements (all dimensions are in cm, adapted from Zhou et al. (2015)).

were selected to determine mortality levels of adult *S. oryzae*. At the beginning of each treatment, 200 actively moving adults were selected and placed in 20 small nylon-mesh bags (25 mm × 20 mm) to limit their movement and provide oxygen for insects (Li et al., 2015; Yan et al., 2014). Then, they were randomly mixed into the rough, brown, and milled rice samples in a plastic container with perforated side and bottom walls to allow the hot and room air to pass through (300 mm × 220 mm × 60 mm) (Fig. 2). This represented an artificial infestation level of 5%, well within 4–6% of the natural infestation rate in grain (Batta, 2004; Padın et al., 2002).

To determine the effect of sample temperatures on the insect mortality, the sample container was first placed on the stationary conveyor belt under the selected electrode gap of 11 cm with forced hot air at corresponding target temperatures (44, 46, 48 and 50 °C). The electrode gap at 11 cm was used based on the appropriate heating rate of milled rice achieved by RF energy (Zhou et al., 2015). Sample temperature was measured at the central position of the container using a six-channel fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) with an accuracy of ±0.5 °C. When achieved the target temperature, the RF system was turned off and the rice sample was held in hot air for 5 min. Immediately upon completion of the treatment procedures, all the bags were removed from the plastic container and gently brushed into a glass jar containing rice samples. Control insects were placed in the RF cavity without running for the longest processing time at each temperature. The tested *S. oryzae* adults were held for 6 days after treatment for observation under the above rearing conditions. The pests were considered dead if no movement was observed. Each test was repeated three times.

2.5. Determine the effect of holding time on insect mortality

Yan et al. (2014) proposed the minimum exposure time to achieve 100% mortality of adult *S. oryzae* was 4 min at 50 °C using a heating block system. According to the heating non-uniformity of milled rice using RF energy, four different holding times (0, 2, 4, and 6 min) were selected after RF heating to 50 °C (Zhou et al., 2015). The whole treatment protocol developed for 2.61 kg rough rice, 3.81 kg brown rice, and 3.9 kg milled rice samples (6 cm in depth) consisted of RF heating under the selected electrode gap of 11 cm with the conveyor belt movement at the speed of 12.4 m/h, hot air surface heating at 50 °C, and together with a twice mixing. Then the RF system was turned off and the rice sample was held at 50 °C hot air for the four different times, followed by forced room air cooling single-layer (2 cm in depth) samples as determined by Zhou et al. (2015). Unheated infested rough, brown, and milled rice samples were used as controls. After RF treatments, the insect reared conditions and mortality observations followed the procedures described above.

2.6. Quality analyses before and after RF treatment with storage

To achieve effective treatments with the complete insect control, rough, brown, and milled rice quality should be acceptable after RF heating. Since rice samples without shell are vulnerable to insect attacks and easy to damage and aging during storage, milled rice samples were selected to evaluate the main rice quality attributes after RF treatments.

Moisture content, water activity, free fatty acid content, protein content, color, ash content, and starch content were evaluated immediately after RF treatments and for a given storage period. The storage time at 35 ± 1 °C and 78 ± 5% relative humidity for 60 d was calculated based on a Q_{10} value of 3.4 for food nutrition loss (Taoukis et al., 1997) and the common storage time (6 months) of milled rice at room temperature (Babu et al., 2009). Similar methods have been successfully used for accelerated shelf life tests in RF treated in-shell walnuts (Wang et al., 2001, 2002a, 2006b), chestnuts (Hou et al., 2014), and milled rice (Zhou et al., 2015). Controls and RF treated samples were packed in 5 bags in the incubator and taken out every 15 days for quality analysis. Each storage experiment was replicated three times.

Moisture content in the milled rice was determined by using the oven drying method described by AOAC (2000a). The rice sample was placed in aluminum dishes and dried in a vacuum oven (DZX-6020B, Nanrong Laboratory Equipment Co., Ltd., Shanghai, China) at 105 °C until constant weight, and then it was cooled in a desiccator with CaSO4 (Calcium sulphate) and weighed at room temperature. The weight loss was used to calculate the moisture content. Water activity was measured by an Aqua Lab water activity meter (Model 4TE, Decagon Devices, Inc., Pullman, WA, USA) under ambient temperature (25 °C). This parameter is important for grain as being a hygroscopic material, and extremely important for biological activities, such as the growth of microorganisms.

The method of Aibara et al. (1986) with slight modification was used to determine the free fatty acid content of rice. A detailed description of the test method can be found in Zhao et al. (2007b). Protein content in the milled rice was determined by using the Kjeldahl method following the AOAC method (AOAC, 2005). The percentages of nitrogen were transformed into protein content by multiplying a conversion factor of 5.95 (Chandi and Sogi, 2007; Ju et al., 2001). Total ash content was determined by weighing the residual ash obtained by combustion in a Muffle furnace at 550 °C for 4 h. Starch content was determined by using enzymatic hydrolysis method following the AOAC standard (AOAC, 2000b).

A computer vision system (CVS), including a lighting system, a Cannon EOS 600 Digital camera with 1800 megapixel resolution and EF-S 18e55 mm f/3.5e5.6 Zoom Lens, and a computer with image-processing software was used to measure the degree of lightness (L*), redness-greenness (+or − a*) and yellowness-blueness (+or − b*). The measuring procedures of color image were described by Zhou et al. (2015). An Adobe Photoshop CS3 (Adobe Systems Inc., USA) system was used to analyze color values: lightness (L), redness-greenness (+or − a) and yellowness-blueness (+or − b), which 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. Statistical analysis

The mean values and standard deviations (SD) for all measurements were calculated over three replicates. All statistical analyses were performed at a 5% significance level with the least significant difference t-test using a Microsoft Excel variance procedure (Microsoft Office Excel, 2007).

3. Results and discussion

3.1. Heating uniformity in RF treated rough and brown rice

Table 2 lists a detailed comparison of the temperature distributions and uniformity index values for rough and brown rice at the sample surface and at depths of 2 and 4 cm from the surface after RF heating under the optimal heating uniformity condition of milled rice. The average temperatures of the top, middle, and bottom layers of all samples after RF heating were higher than the target temperature 50 °C to obtain 100% insect mortality (Yan et al., 2014). Bottom layer average surface temperatures of rough, brown, and milled rice were the highest, followed by the middle and top layers. This phenomenon was also observed by Birla et al. (2008) and Marra et al. (2007). The uniformity index values were slightly larger than those found for lentils (Jiao et al., 2012) and coffee beans (Pan et al., 2012), but similar to those found for chestnuts (Hou et al., 2014), and smaller than those observed for walnuts (Wang et al., 2007a).

3.2. Effect of temperature on thermal insect mortality

Table 3 shows the mortality of adult *S. oryzae* under four different RF treatment conditions. The insect mortality for unheated controls at the four temperatures was <5%, showing that little mortality was caused by handling. Therefore, the effects of handling procedure could be negligible (Yan et al., 2014). High temperatures, as commonly used, reduced the survival rate of adult *S. oryzae* in rough, brown, and milled rice. When RF heating to 50 °C and maintained at 50 °C hot air for 5 min, the mortality levels of adult *S. oryzae* of the three samples did not achieve 100%, which is different from that obtained by using the heating block system (Yan et al., 2014). This was probably caused by the non-uniform RF heating in the whole rice samples. The similar phenomenon was also observed in RF treated chestnuts (Hou et al., 2015) and walnuts (Wang et al., 2001, 2007b), and microwave treated cherries (Ikediala et al., 1999).

Table 2
Comparisons of the temperature and heating uniformity index (mean ± SD over 3 replicates) of each sample under the best uniformity condition of milled rice.

Layer	Sample temperature (°C)		
	Rough rice	Brown rice	Milled rice[a]
Top	50.5 ± 2.7Aa[b]	50.0 ± 2.4 aA	50.2 ± 1.8 aA
Middle	51.3 ± 2.0 aA	50.6 ± 1.8 aA	50.8 ± 1.6 aA
Bottom	52.2 ± 1.8 aA	51.4 ± 1.6 aA	51.4 ± 1.5 aA
Heating uniformity index (λ)			
Top	0.053 ± 0.004 aA	0.052 ± 0.004 aA	0.048 ± 0.003 aA
Middle	0.044 ± 0.006abA	0.042 ± 0.003 aA	0.041 ± 0.003 aA
Bottom	0.036 ± 0.002bA	0.035 ± 0.003 aA	0.033 ± 0.002bA

[a] Temperature and heating uniformity index of milled rice were adapted from Zhou et al. (2015).
[b] Different lower and upper case letters indicate that means are significantly different at P = 0.05 among layers and samples, respectively.

Table 3
Mortality (mean ± SD, %) of adult *Sitophilus oryzae* after RF heating to 4 temperatures for holding 5 min.

Treatment	Temperatures (°C)			
	44	46	48	50
Control	3.3 ± 1.6	4.1 ± 2.1	2.8 ± 1.8	3.5 ± 1.6
Rough rice	67.7 ± 8.0 aA[a]	79.4 ± 9.2aAB	92.3 ± 6.8aBC	99.7 ± 0.6 aC
Brown rice	64.7 ± 8.3 aA	75.7 ± 2.8 aA	89.5 ± 7.2 aB	99.3 ± 0.6 aC
Milled rice	66.2 ± 7.6 aA	76.4 ± 6.1 aA	91.7 ± 3.8 aB	99.9 ± 1.0 aC

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

3.3. Protocol validation studies with different holding times at 50 °C hot air

The effect of holding time on the mortality of adult *S. oryzae* is present in Table 4. There was no significant difference of insect mortality at each holding time among three types of rice ($P > 0.05$). After RF heating to 50 °C, the mortality of adult *S. oryzae* in rough, brown, and milled rice samples increased with increasing holding time. The 100% mortality of adult *S. oryzae* was finally achieved for holding 6 min, which is 2 min more than that obtained by the heating block system (Yan et al., 2014).

3.4. Milled rice quality analysis

As shown in Fig. 3a, with the increase of storage time, the moisture content changed mostly between 12.6 and 12.3% w.b. both for control and RF treated rice samples. The moisture content was slightly reduced after RF heating. However, there were no significant differences between control and RF treated samples ($P > 0.05$) before and after RF treatments during accelerated shelf life storage (Fig. 3a). A similar result was observed by Theanjumpol et al. (2007) who reported that after RF heating at 45, 60, 75 and 90 °C for the duration of three minutes, there was no significant difference in milled rice moisture content ($P > 0.05$). Similarly, water activity changed in a narrow range both for control and RF treated milled rice samples (Fig. 3b). This phenomenon is also observed by Haque et al. (2004), indicating that the higher the moisture content of the kernel, the higher is the water activity value at a constant ambient temperature.

Fig. 4a shows that the mean free fatty acid values increased with storage time both for control and RF treated milled rice. This trend was mainly caused by the degradation of fat by lipase and oxidation (Zhou et al., 2002). Such changes have also been reported in several studies. For example, Park et al. (2012) and Sung et al. (2014) suggest that fatty acid values increase during 4 months of storage and the values at higher temperatures (30 °C and 40 °C) are higher than those of rice stored at lower temperatures (0 °C, 4 °C and 20 °C). However, RF treatments did not significantly affect the free fatty acid values immediately after treatment and during 2 months of storage ($P > 0.05$). The rate of increase in free fatty acid content of RF treated is similar to that in the untreated rice samples. Similar results are also obtained by Zhong et al. (2013) and Zhao et al. (2007b), showing that microwave irradiation restrains the formation of free fatty acids during the rice storage, which might be due to the decreased activity of ipase and lipoxidase. For both RF treated and untreated milled rice, the final free fatty acid values during accelerated storage for up to 60 days remained within the acceptable range (12,000 ml KOH/100 g) for avoiding rancidity in rice (Zhao et al., 2007b).

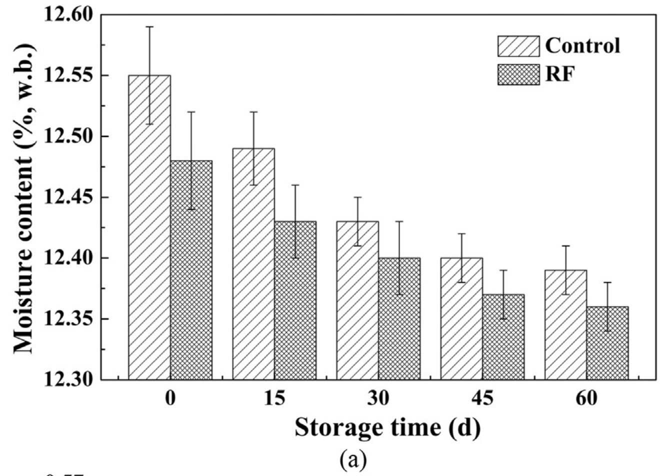
Fig. 4b shows that untreated milled rice was lower in protein content than RF treated milled rice. However, there were no significant differences in protein content between the two treatments after 60 days of storage ($P > 0.05$). Fig. 4c shows the ash content of control and RF treated milled rice before and after RF treatments during accelerated shelf life storage. There were no significant differences between control and RF treated samples ($P > 0.05$). Similar results are also obtained by Suhem et al. (2013), indicating that low pressure radio frequency plasma treatments do not influence the protein and ash contents of the rice samples.

Fig. 4d illustrates the effect of RF treatment on starch content during the whole storage periods. With increasing storage time, the starch values fluctuated in a narrow range both for control and RF treated milled rice samples. However, no significant changes ($P > 0.05$) in starch content were observed between control and RF treated samples both after RF treatment and during whole storage periods, indicated that starch content was relatively stable.

Table 4
Mortality (mean ± SD, %) of adult *Sitophilus oryzae* after RF heating to 50 °C for four different holding times.

Sample	Holding times (min)			
	0	2	4	6
Control	4.7 ± 3.3	3.9 ± 1.8	2.1 ± 3.0	4.0 ± 2.2
Rough rice	83.7 ± 6.0 aA[a]	90.0 ± 4.8 aA	99.0 ± 0.7 aB	100±0 aB
Brown rice	80.2 ± 5.9 aA	88.3 ± 4.3 aA	98.8 ± 0.9 aB	100±0 aB
Milled rice	81.5 ± 6.3 aA	89.7 ± 5.1 aA	98.8 ± 0.9 aB	100±0 aB

[a] Different lower and upper case letters indicate that means are significantly different at P = 0.05 among holding times and samples, respectively.



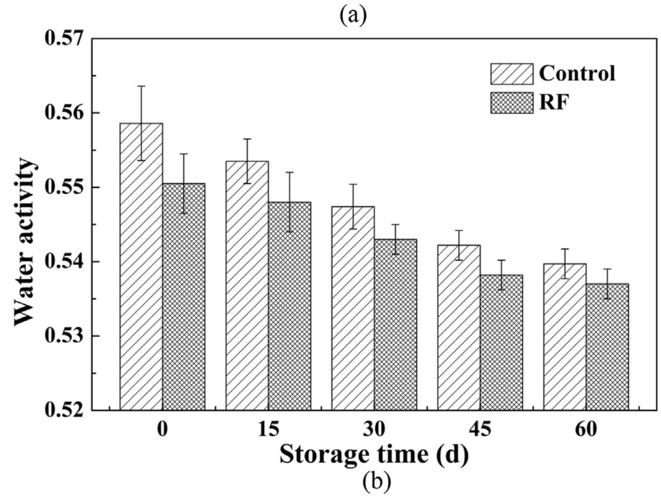


Fig. 3. Changes in moisture content (a) and water activity (b) of RF treated and untreated milled rice samples during storage at 35 °C.

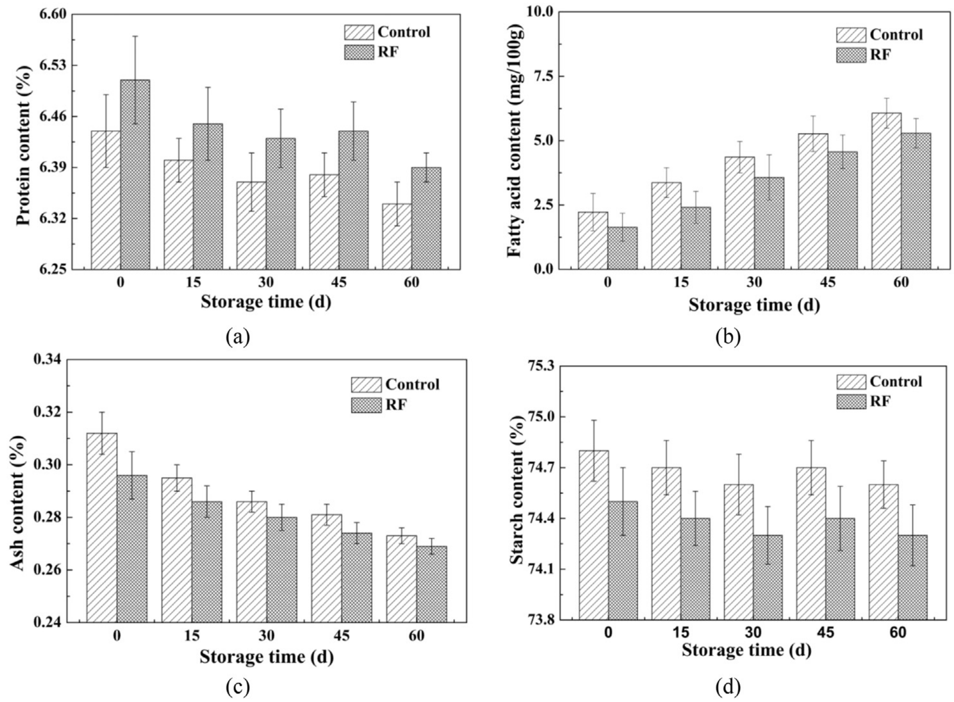


Fig. 4. Changes in free fatty acid content (a), protein content (b), ash content (c), and starch content (d) of RF treated and untreated milled rice samples during storage at 35 °C.

Table 5
Changes in color values of RF treated and untreated milled rice samples during storage at 35 °C.

Color parameters	Storage time (Days)[a]					
	Treatment	0	15	30	45	60
L*	Control	69.1 ± 4.4 aA[b]	71.0 ± 4.9 aA	71.3 ± 5.3 aA	72.7 ± 4.1 aA	74.4 ± 5.1 aA
	RF	70.2 ± 4.7 aA	71.5 ± 5.4 aA	72.0 ± 4.8 aA	73.3 ± 4.5 aA	75.1 ± 5.2 aA
a*	Control	(−1.4 ± 1.3)aA	(−1.4 ± 1.1)aA	(−1.3 ± 1.2)aA	(−1.2 ± 1.1)aA	(−1.1 ± 1.2)aA
	RF	(−1.4 ± 1.3)aA	(−1.3 ± 1.0)aA	(−1.3 ± 1.3)aA	(−1.1 ± 1.0)aA	(−1.0 ± 1.3)aA
b*	Control	10.4 ± 2.4 aA	12.1 ± 3.1 aA	12.9 ± 3.0 aA	13.3 ± 3.1 aA	14.0 ± 2.9 aA
	RF	10.8 ± 2.7 aA	12.8 ± 2.9 aA	13.2 ± 2.7 aA	13.6 ± 2.7 aA	14.3 ± 3.2 aA

[a] 60 d at 35 °C to simulate 6 months storage at 25 °C.
[b] Mean values are not significantly different ($p > 0.05$) for the same capital letters within a row among the storage time, and for the same lower case letters within a column among the treatment.

Generally, storage temperature, duration and relative humidity are storage factors and conditions affecting the starch content in rice quality (Sauer, 1992; Theanjumpol et al., 2007).

It is shown in Table 5 that the color values (L^*, a^*, and b^*) of milled rice samples were not significantly different ($p > 0.05$) before and after RF treatment during the whole storage period. These results showed that the loss of saleable color could be negligible during RF treatment for disinfestations. Similar studies are also reported by Suhem et al. (2013) and Theanjumpol et al. (2007), showing that the RF technology do not affect the color quality of rice samples. The increasing in b* values of milled rice samples during storage are due to lipid oxidation (Park et al., 2012). The result is consistent with that observed by Kim et al. (2004), in which the phenomenon is resulted from the acceleration of Mailard reaction between the protein and sugar contents of milled rice. Furthermore, Dillahunty et al. (2000) reported that the temperature and treatment duration did not affect the yellowing of rice when it was treated with temperature over 50 °C for less than 12 h.

4. Conclusions

RF heating uniformity of rough and brown rice was improved by 50 °C hot air surface heating, sample movement, a twice mixing, and holding 5 min at the hot air of 50 °C. High temperatures resulted in low survival rate of adult *S. oryzae* in rough, brown, and milled rice. When RF heating to 50 °C and the hot air holding time increased from 0 to 6 min, the 100% mortality of adult *S. oryzae* was obtain and the quality parameters of RF treated milled rice had no significant changes. This study provided a solid basis in developing a practical non-chemical alternative *S. oryzae* control methods for rough, brown, and milled rice. The future study is desirable to scale up the treatment protocol for continuous industry applications.

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