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ORIGINAL PAPER

Investigation of the Feasibility of Radio Frequency Energy for Controlling Insects in Milled Rice

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Abstract Many studies showed that radio frequency (RF) holds great potential to control insects in grains, while a few more technical issues need to be addressed to further make this technology ready for industrial application. Therefore, the effect of RF heating rate on rice fissure ratio and broken rate, RF heating lethality on immature rice weevils, and RF disinfestation treatment on cooking and eating quality of milled rice was investigated in this study. Results indicated that RF heating rate had no significant influence on rice broken rate, while fast RF heating rate (>7.2 °C/min) had adverse effects on rice fissure ratio, and mild RF heating rate (<5.8 °C/min) had no significant influence on fissure ratio of milled rice. RF treatment (50 °C, 5 min) could completely control immature rice weevils in rough, brown, and milled rice. Even though RF disinfestation treatment (50 °C, 5 min) influenced the cooking quality (water absorption, adhesive strength) of milled rice, it had no significant effect on overall sensory quality. This study provided valuable information for considering the application of RF energy in milled rice process to control insects.

Keywords Radio frequency (RF) · Rice weevil · Disinfestation · Quality · Rice

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Introduction

Milled rice (*Oryza sativa* L.) is one of the major staple foods worldwide and rich in carbohydrates and high-quality proteins. Milled rice is produced from rough rice by a series of process, mainly including cleaning, milling, polishing, color sorting, and packaging. China is one of the major milled rice producing countries with about one third of world production (Zhou et al. 2015). Insect infestation is a big issue during processing and preservation of milled rice since 5–10% cereals are lost during storage as a result of insect infestation, and many countries have zero tolerance for grain contaminated by insects (Follett et al. 2013).

During manufacturing process of milled rice, there are two major pests: rice weevil (*Sitophilus oryzae*) and red flour beetle (*Tribolium castaneum*). For rice weevil and other insects existed in rough rice, chemical fumigation method is generally applied to kill them, and most commonly used fumigant is phosphine. However, even though chemical fumigation can kill most of the insects, the eggs of rice weevil (generally located inside the rough rice) are extremely difficult to kill. On the other hand, the use of some chemical fumigants have been banned, such as methyl bromide because of the hazards to human health and environment (Zhou et al. 2015). Meanwhile, the red flour beetles are very easy to grow inside the processing equipment due to the grain residues and are extremely difficult to completely clean. Fortunately, most of red flour beetles can be killed by color sorting process. Therefore, for milled rice, the eggs of rice weevil are most commonly existed pests, and when the exterior environment changes, such as high temperature and relative humidity, they would begin to propagate and lead to quality loss and lower consumer acceptance.

Many physical methods have been proposed as an alternative disinfestation method for grains, such as microwave disinfestation (Yadav et al. 2014; Zhao et al. 2007), irradiation

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(Follett et al. 2013), and radio frequency (RF) heating (Lagunas-Solar et al. 2007; Wang and Tang 2004). Irradiation requires high equipment investment and is limited by irradiation source and poor consumer acceptance of irradiated products. Compared with microwave heating, RF heating has deeper penetration depth and uniform electric field distribution (Zhu et al. 2012). RF disinfestation has obtained more attention lately because it is an environment-friendly treatment method without chemical residues. The earlier studies related to the application of RF energy on pests control in grains was mainly conducted by Nelson (1996), after that, many studies focused on developing RF disinfestation treatments for various agricultural products, including walnuts (Wang et al. 2007a, b), legumes (Jiao et al. 2012; Wang et al. 2010), almonds (Gao et al. 2010), coffee beans (Pan et al. 2012), chestnuts (Hou et al. 2014), dry fruits (Alfaifi et al. 2014), and milled rice (Zhou et al. 2015; Zhou and Wang 2016a, b).

Zhou et al. (2015) developed RF disinfestation treatment protocol for disinfesting milled rice without affecting its quality (moisture, protein, fat, starch, hardness, and color). Zhou and Wang (2016a) investigated the RF heating uniformity and validated the developed RF treatment protocol for disinfesting rough, brown, and milled rice, and Zhou and Wang (2016b) further developed industrial-scale RF disinfestation treatment for milled rice and evaluated heating efficiency and throughput of RF treatment. Those studies indicated that RF holds great potential as an alternative non-chemical disinfestation method for controlling insects in milled rice. To further make this technology ready for industrial application, a few more technical issues need to be addressed. First, it is necessary to figure out the best point in the milling process line where to add RF disinfestation treatment, i.e., at the beginning stage as rough rice, in the middle stage as brown rice, or at final stage as milled rice. Secondly, very few studies investigated the influence of RF heating rate on fissure ratio and broken rate of milled rice. Finally, limited information could be found on the effect of RF disinfestation treatment on eating quality of milled rice.

Therefore, the current study focused on evaluating the feasibility of applying RF disinfestation treatment in industrial milled rice production process by addressing those concerns. The main objectives of this study were (1) to investigate the influence of RF heating rate on fissure ratio and broken rate of rice, (2) to validate the killing effect of RF treatment on immature rice weevils, and (3) to study the influence of RF disinfestation treatment on cooking and eating quality of milled rice.

Materials and Methods

Materials and RF Heating System

A 12-kW, 27.12-MHz parallel electrode, pilot-scale free-running RF system (310 × 100 × 165 cm^3) (GJD-6A-27-JY, Huashi Jiyuan Co. Ltd., Hebei, China) was applied in the current study. The RF system also contains a built-in hot air system and an imbedded conveyor belt. Hot air temperature can be set to different values (20–80 °C) based on the different treatments. There are small holes uniformly distributed on the bottom electrode for allowing hot air to get into RF cavity. Conveyor belt can be used to move the sample back and forth. Different RF heating rates could be obtained by adjusting the position of top electrode (75.0 × 55.0 cm^2). Fiber optic sensors (ThermAgile-RD Optsensor, Xi'an Heqiguangdian Co. Ltd., Shanxi, China) connected with a computer were used to record the real-time temperature changes during RF treatment. More information related to the RF system can be found elsewhere (Jiao et al. 2015, 2016). Milled rice was purchased from a local grocery store produced by Wilmar International Ltd. (Xiangmanyuan, Shanghai, China), and rough rice, brown rice, and rice weevil were kindly provided by Wilmar International Ltd. Initial moisture content of rough, brown, and milled rice was 9.2 (w.b.), 11.1, and 14.0%, respectively. Polypropylene (PP) plastic cuboid container (16.0 L × 10.5 W × 6.8 H cm^3) with small holes on the side and bottom was used to hold samples for hot air-assisted RF treatments (Fig. 1).

Effect of RF Heating Rate on Fissure Ratio and Broken Rate

To investigate the influence of heating rate on fissure ratio and broken rate, four different electrode gaps (8.5, 9.0, 9.5, and 10.0 cm) were selected after conducting preliminary experiments to obtain different RF heating rates. To make sampling more uniform and convenient, a plastic cylinder-shaped container (6.8 cm dia. × 3.4 cm H) filled with samples without lid was placed at the central part of the cuboid container. A fiber optic sensor was placed at the geometry center to record the temperature changes during RF heating. After the sample temperature reached 50 °C, the cylinder-shaped container was taken out immediately, and the samples were spread out in a thin layer, cooled by forced air, and then collected for determining fissure ratio and broken rate of the samples.

Fissure ratio (%) was measured based on the method described by Ma et al. (2009). In brief, 300 granules of samples (rough rice, brown rice, and milled rice) were selected randomly and 100 granules as one group. Samples were observed under lamp with hand lens (10-fold), and those with cracks were considered as fissure. If the sample only contained one transverse crack, it belonged to mild fissure and that containing two or more cracks was considered as serious fissure. Fissure ratio was the sum of mild fissure ratio and serious fissure ratio. Broken rate (%) of samples were determined based on Chinese National Standard Method (GB/T 5503–2009). In brief, 10 g of samples was selected randomly and then screened out broken rice and calculated the broken rate.

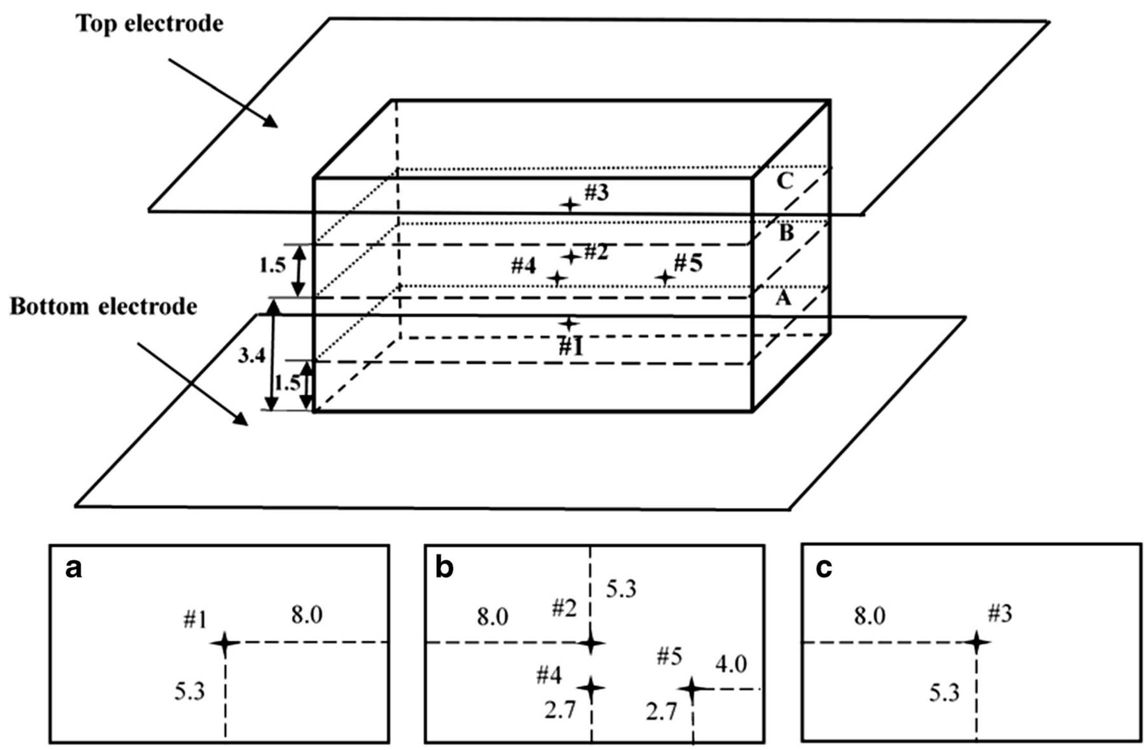

Fig. 1 The dimension (cm) of plastic cubic container and the positions of fiber optic sensors in the container filled with rice samples when subjected to hot air-assisted RF treatment (from Jiao et al. 2016)

RF Treatment for Controlling Immature Rice Weevils

A rice weevil colony was started from a heavily infested bag of whole grain rice provided by Wilmar International Ltd. The stock colonies were divided into three parts and kept in glass jar covered with nylon-mesh-screen containing about 500 g of rough, brown, and milled rice, respectively. They were reared in a constant temperature (26 ± 1 °C) and relative humidity (65%) room for a photoperiod of 14:10 h (L/D) with artificial light (Yan et al. 2014). Since it was difficult to prepare samples only containing eggs of rice weevil (Zhou and Wang 2016a), Zhou and Wang (2016a, b) have investigated the lethal effects of RF heating on adult rice weevils; adult rice weevils were removed manually and mixed-age immature (eggs, larvae, pupae) rice weevils were used in this study for RF disinfestation study.

The small plastic cylinder-shaped container filled with rough rice (60 g), brown rice (85 g), or milled rice (100 g) with infested immature rice weevils was placed in the central part of the big cuboid container filled with un-infested rough, brown, and milled rice, respectively, and then subjected to RF treatment (50 °C with 5 min holding) to evaluate the mortality. Electrode gap of RF system was set as 9.5 cm to obtain an appropriate heating rate, and hot air was adjusted to 50 °C to hold the sample temperature after RF heated to the desired temperature. After RF treatment, samples were reared under above described conditions up to 5 weeks to ensure that they grew to adult stage for easier identification (Follett et al. 2013). A same amount of samples without insects infested and RF treatment, and samples with insects infested but without RF treatment were collected and cultured under the same conditions and used as two controls.

Table 1 Effect of radio frequency (RF) heating rate on the fissure ratio and broken rate of milled rice

Electrode gap (cm)	RF heating rate (°C/min)	Mild fissure ratio (%)	Serious fissure ratio (%)	Fissure ratio (%)	Broken rate (%)
Control	–	15.8 ± 1.8a	9.8 ± 5.3a	25.7 ± 6.2a	3.1 ± 0.1a
8.5	19.0 ± 1.6	30.2 ± 1.6b	16.0 ± 2.5b	46.2 ± 3.4b	3.1 ± 0.1a
9.0	7.2 ± 0.3	21.3 ± 1.0c	16.1 ± 1.0b	37.5 ± 1.1c	3.0 ± 0.1a
9.5	5.8 ± 0.1	16.3 ± 2.5a	14.0 ± 2.5a	30.3 ± 1.8a	3.0 ± 0.1a
10.0	3.8 ± 0.2	16.2 ± 2.3a	10.9 ± 0.9a	27.1 ± 2.6a	3.0 ± 0.1a

Different letters in the same column indicated that the means were significantly different ($P = 0.05$)

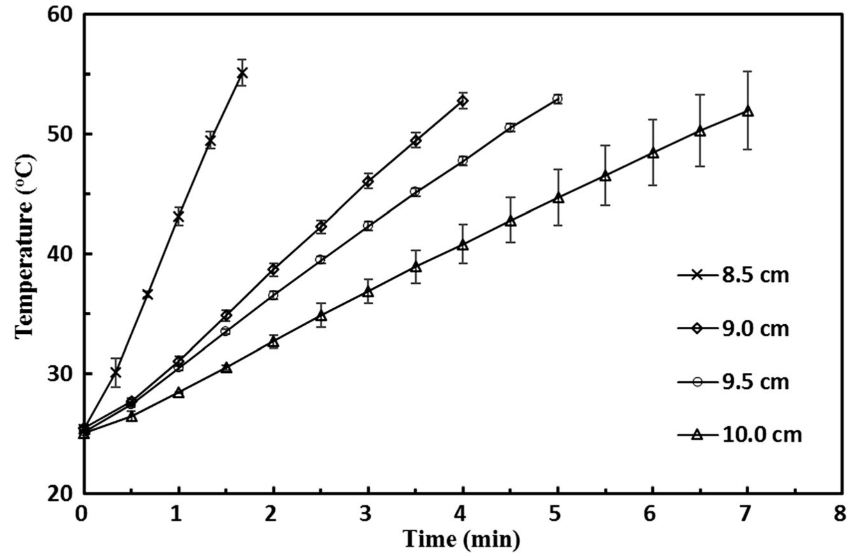

Fig. 2 RF heating profile of milled rice under different electrode gaps. Temperature was measured by fiber optic sensor placed at the geometry center (#2) of the milled rice

Effect of RF Treatment on Rice Quality

To evaluate the effect of RF disinfestation treatment on the sample quality, the nutritive composition (protein, fat, amylose, and fatty acid value), cooking quality (water absorption, expansion rate, and adhesive strength), and sensory attributes were conducted in this study.

Determination of Nutritive Quality

Protein content (%) was determined using Kjeldahl method following the AOAC method (AOAC 2005); nitrogen conversion factor was selected as 5.95 based on the method and literatures (Chandi and Sogi 2007; Zhou et al. 2015). Fat content (%) was measured using Soxhlet extraction method according to the AOAC method (AOAC 2006). Amylose content (%) in rice was evaluated using spectrophotometry method according to the method described in NY/T 2639-2014. Fatty acid value (mg/100 g) was determined according to Chinese National Standard Method (GB/T 20569-2006), in which fatty acids were extracted by absolute ethyl alcohol under room temperature and potassium hydroxide standard solution was used for titration.

Determination of Cooking Quality

Water absorption (%) and expansion rate (%) were determined based on the method described by Li et al. (2012). Briefly,

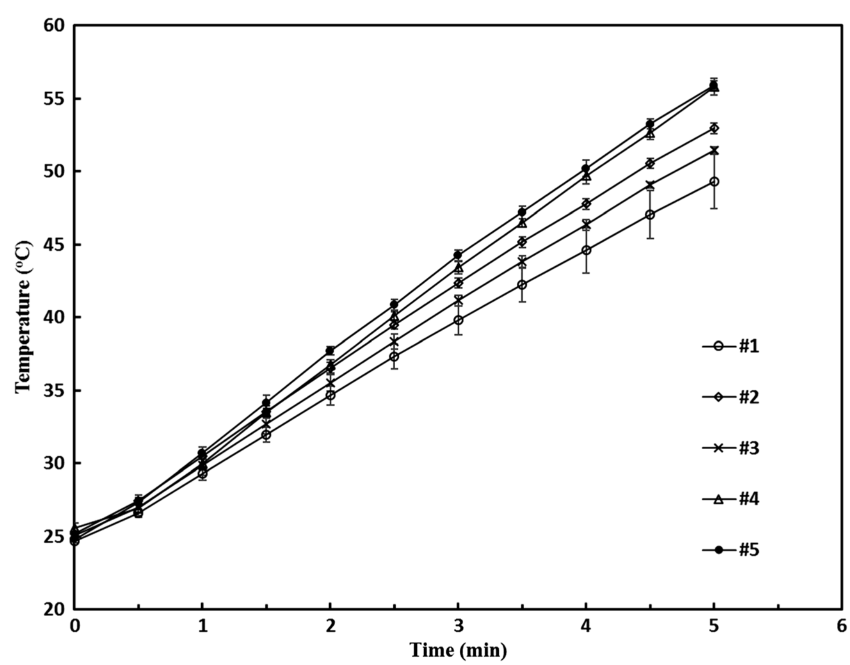

Fig. 3 Temperature increasing curves of milled rice under RF heating with electrode gap of 9.5 cm. Temperature was measured by placing fiber optic sensor in milled rice at the point of *#1*, *#2*, *#3*, *#4*, and *#5*, respectively (Fig. 1)

Table 2 Effect of adding hot air and sample movement on fissure ratio and broken rate of milled rice

Treatments	Mild fissure ratio (%)	Serious fissure ratio (%)	Fissure ratio (%)	Broken rate (%)
Control	15.8 ± 1.8a	9.8 ± 5.3a	25.7 ± 6.2a	3.1 ± 0.1a
RF	16.3 ± 2.5a	14.0 ± 2.5a	30.3 ± 1.8a	3.0 ± 0.1a
RF+ hot air (50 °C)	17.0 ± 3.6a	11.8 ± 4.3a	28.8 ± 3.7a	3.0 ± 0.1a
RF+ sample movement (10 m/h)	16.5 ± 2.7a	13.0 ± 1.8a	29.5 ± 2.1a	3.0 ± 0.1a

Electrode gap was set as 9.5 cm. Same letters in the same column indicate that means had no significant difference ($P = 0.05$)

certain amount of rice was poured into boiling water and boiled till achieving complete gelatinization. Cooked rice was placed on 20-mesh sieve and cooled for 30 min and then measured the mass or volume for calculating the water absorption and expansion rate, respectively. Adhesive strength (mm) was measured according to the Chinese National Standard Method (GB/T 22294-2008).

Sensory Evaluation of Eating Quality of Cooked Rice

Sensory evaluation was conducted based on the Chinese National Standard Method (GB/T 15682-2008). Twenty primary assessors (male/female = 1:1) were selected to do sensory evaluation of rice eating quality. After washing, the rice was cooked in a rice cooker by adding 1.45 times of water (Park et al. 2012). Primary assessors evaluated and graded the cooked rice samples based on its flavor (20), appearance (20), palatability (30), taste (25), and cold rice texture (5), and the sum of scores for each sensory criterion was used to evaluate the sensory quality of the cooked rice.

Statistical Analysis

In this study, mean values and standard deviations were calculated based on three independent replicates for all treatments, and data were analyzed by analysis of variance (ANOVA) using SPSS software (v19.0, SPSS Inc., Chicago, IL, USA). The mean values were separated at a significant level of $P = 0.05$ by conducting Duncan's multiple range test.

Results and Discussions

Influence of Different RF Heating Rates on Fissure Ratio and Broken Rate

In the RF system, bottom electrode was fixed, and different RF heating rates could be obtained by adjusting top electrode to get different electrode gaps, which would affect electric field intensity, thus changing RF heating rate. Table 1 lists the corresponding RF heating rates (°C/min) for milled rice when electrode gap was set as 8.5, 9.0, 9.5, and 10.0 cm, respectively. The heating rate decreased with increasing electrode gap (Zhou et al. 2015), and RF heating curves with different electrode gaps are shown in Fig. 2. The temperature of milled rice samples increased with time almost linearly, and it took about 1.4, 3.6, 4.5, and 6.6 min to raise the sample temperature to 50 °C from room temperature with electrode gap of 8.5, 9.0, 9.5, and 10.0 cm, respectively. Generally, fast heating could increase productivity and throughput but increase the non-uniformity of samples at the same time, so appropriate heating rate should be selected to obtain relatively high throughput with acceptable heating uniformity (Zhou et al. 2015).

In this study, five typical positions inside the cubic plastic container (Fig. 1) were selected to place the fiber optic sensors for measuring temperature changes during RF heating to evaluate RF heating temperature uniformity (Jiao et al. 2016). Figure 3 illustrates the temperature changes at five typical points in milled rice subjected to RF heating with electrode gap of 9.5 cm. After 5-min RF heating, temperature at position #5 was the highest, followed by those at #4, #2, #3, and #1. This trend was also

Table 3 Effect of RF treatment (50 °C, 5 min) on fissure ratio and broken rate of rough, brown, and milled rice

Quality parameters	Rough rice		Brown rice		Milled rice	
	Control	RF	Control	RF	Control	RF
Mild fissure ratio (%)	4.8 ± 0.8a	5.3 ± 1.2a	8.5 ± 1.4a	11.2 ± 1.2b	15.8 ± 1.8a	16.7 ± 1.0a
Serious fissure ratio (%)	4.3 ± 1.0a	5.0 ± 0.9a	4.2 ± 1.5a	5.3 ± 1.2b	9.8 ± 5.3a	10.5 ± 1.4a
Fissure ratio (%)	9.2 ± 1.2a	10.3 ± 1.6a	12.7 ± 1.2a	16.5 ± 1.8b	25.7 ± 6.2a	27.2 ± 1.9a
Broken rate (%)	5.5 ± 0.1a	5.5 ± 0.1a	7.7 ± 0.2a	7.9 ± 0.1a	3.1 ± 0.1a	3.0 ± 0.1a

Different letters in the same raw for different materials indicated that the means were significantly different ($P = 0.05$)

Table 4 Mortality of immature rice weevils in rough, brown, and milled rice after RF treatment (50 °C, 5 min)

Samples	Number of survival rice weevils		
	Rough rice	Brown rice	Milled rice
Samples with infestation but without RF treated	15 ± 4	12 ± 5	22 ± 3
Samples with infestation and RF treated	0	0	0

observed by Jiao et al. (2016). Many studies reported that RF heating had edge and corner heating effect (Alfaifi et al. 2014; Jiao et al. 2015) because of higher electric field intensity in those areas. The temperature difference between the highest point (#5) and the lowest point (#1) was about 6 °C, which was relative good uniformity compared with RF heating of other products, such as dry fruit (Alfaifi et al. 2014), and peanut butter (Jiao et al. 2014). Many studies have investigated the ways to improve RF heating uniformity, such as using polyetherimide (PEI) blocks (Jiao et al. 2014; Jiao et al. 2015; Huang et al. 2016). Therefore, to reduce the influence of non-uniform temperature on insect control and sample quality and to make it easier for taking samples, a small cylindrical-shaped plastic container was used to hold samples, which was placed in the central part of big cubic plastic container filled with same material and subjected to RF treatment in this study.

The influence of RF heating rate on the fissure ratio and broken rate of milled rice is reported in Table 1. For electrode gap of 8.5 and 9.0 cm with relatively higher heating rate, fissure ratio of milled rice increased significantly ($P < 0.05$) after RF treatment. During cooking process, milled rice with higher fissure ratio would make the rice grains starchy and decrease sensory quality. No significant changes of fissure ratio were observed with heating rate less than 5.8 °C/min (9.5 cm electrode gap). All tested heating rates (3.8–19.0 °C/min) had no significant ($P > 0.05$) effects on broken rate, which indicated that broken rate was not sensitive to heating rates. Zhou et al. (2015) successfully developed RF disinfestation treatment protocol for milled rice and improved RF heating uniformity by adding surrounding hot air and sample movement. Table 2 shows the effect of adding hot air and sample movement to the RF treatment on the fissure ratio and broken rate of milled rice. Adding hot air (50 °C) and moving sample (10 m/h) did not cause significant changes on the fissure ratio and broken rate (Table 2), which implied that adding hot air and sample movement were good ways to improve heating uniformity without adverse effect on fissure ratio and broken rate of milled rice. The effects of RF treatment (50 °C, 5 min holding time) on fissure ratio and broken rate of rough, brown, and milled rice are shown in Table 3 (electrode gap was 9.5 cm). There were no significant ($P > 0.05$) changes of fissure ratio and broken rate for both rough and milled rice, but for brown rice, fissure ratio was increased significantly ($P < 0.05$). These results indicated that rough rice and milled rice were more suitable for adding RF disinfestation treatment.

Lethal Effects of RF Treatment on Immature Rice Weevils

Adult rice weevil was reported as the most RF-tolerant (Zhou and Wang 2016a). Zhou et al. (2015) reported that RF heating to 50 °C with 5 min holding time could achieve 100% mortality of adult rice weevil. Therefore, RF heating to 50 °C with 5-min holding time was applied to validate the RF heating effects on immature stage of rice weevil (mainly eggs) in rough, brown, and milled rice, respectively. The mortality results are presented in Table 4. For the artificially infested samples subjected to RF treatment, none of adult rice weevils was detected in rough, brown, and milled rice after 5 weeks of rearing at appropriate conditions. This indicated that RF treatment (50 °C with 5 min holding) could completely control rice weevils including eggs, and this was also an indirect evidence to support that adult rice weevil was the most-RF tolerant stage (Zhou and Wang 2016a).

Effect of RF Disinfestation Treatment on Rice Quality

Nutritive Quality

Protein, fat, amylose contents, and fatty acid value in rough, brown, and milled rice were determined before and after RF

Table 5 Effect of RF treatment (50 °C, 5 min) on nutritive qualities of rough, brown, and milled rice

Nutritive quality	Rough rice		Brown rice		Milled rice	
	Control	RF	Control	RF	Control	RF
Protein content (%)	7.09 ± 0.09a	6.98 ± 0.07a	8.98 ± 0.55a	8.88 ± 0.28a	9.06 ± 0.05a	8.86 ± 0.12a
Fat content (%)	1.83 ± 0.02a	1.72 ± 0.03a	1.81 ± 0.02a	1.79 ± 0.08a	1.53 ± 0.03a	1.48 ± 0.06a
Amylose content (%)	8.99 ± 0.01a	8.33 ± 0.52b	11.29 ± 0.01a	10.40 ± 0.21b	17.28 ± 0.01a	16.36 ± 0.23b
Fatty acid value (mg/100 g)	14.96 ± 0.85a	14.41 ± 0.73a	15.52 ± 0.78a	14.69 ± 0.99a	3.54 ± 0.19a	3.49 ± 0.18a

Different letters in the same raw for different materials indicated that the means were significantly different ($P = 0.05$)

treatments (50 °C, 5 min) in this study, and results are presented in Table 5. For protein, fat, and fatty acid contents in rough, brown, and milled rice, no significant ($P > 0.05$) decreases were observed after RF treatment, but amylose content was slightly decreased after RF treatment in rough, brown, and milled rice (Table 5). Amylose content is considered as one of the most important characteristics for predicting rice cooking and processing behavior and directly related to water absorption, volume expansion, fluffiness, and separability of cooked grains. Cooked rice with low amylose is soft and sticky, while rice with high amylose content is firm and fluffy (Zhou et al. 2002).

Cooking Quality

Effects of RF treatment (50 °C, 5 min) on water absorption, expansion rate, and adhesive strength of milled rice were determined, and the results are reported in Table 6. After RF treatment, although the mean values of water absorption and expansion rate of milled rice were decreased, they were not statistically significant ($P > 0.05$). Expansion rate is closely related to the amylopectin molecular size and structure. Its decrease after RF treatment indicated that the long-chain structure of amylopectin molecular in rice starch was damaged and crystal-ordered structure was destroyed, thus resulting in disintegration and smaller size of starch granules (Li et al. 2012). Adhesive strength can reflect the ability of starch gel formation and gel mobility. Li et al. (2012) found that adhesive strength of rice starch is increased after electron beam irradiation, indicating that electron beam irradiation treatment was effective for improving the cooking quality of rice. In this study, adhesive strength of milled rice was significantly ($P < 0.05$) increased after RF treatment (Table 6), which suggested that RF disinfestation treatment can also improve the cooking quality of rice.

Sensory Evaluation

Sensory quality attributes (flavor, appearance, palatability, taste, and cold rice texture) of cooked rice treated by RF disinfestation treatment were evaluated and compared with that without RF disinfestation treatment (control) (Table 7).

Table 6 Effect of RF treatment (50 °C, 5 min) on the cooking qualities of milled rice

Cooking quality	Control	RF treatment
Water absorption (%)	300.0 ± 1.0a	293.0 ± 1.0b1
Expansion rate (%)	441.0 ± 1.0a	435.0 ± 7.0a
Adhesive strength (mm)	90.0 ± 2.8a	103.2 ± 3.4b

Different letters in the same raw indicated that the means were significantly different ($P = 0.05$)

Table 7 Sensory quality of RF treated (50 °C, 5 min) milled rice

Primary index (score)	Secondary index (score)	Control	RF treatment
Flavor (20)	Flavor purity and intensity (20)	15.6 ± 3.2a	15.3 ± 2.8a
Appearance (20)	Color (7)	5.5 ± 0.9a	5.2 ± 1.1a
	Glossiness (8)	5.8 ± 0.8a	5.6 ± 0.7a
	Integrality (5)	4.5 ± 0.5a	4.2 ± 0.7a
Palatability (30)	Stickiness (10)	8.3 ± 0.5a	7.0 ± 1.7b
	Elasticity (10)	8.0 ± 0.9a	7.0 ± 1.1a
	Texture (10)	8.1 ± 0.8a	7.3 ± 1.4a
Taste (25)	Purity, persistence (25)	19.3 ± 2.2a	18.4 ± 1.9a
Cold rice texture (5)	Cohesiveness, adhesiveness, hardness (5)	4.2 ± 0.5a	3.8 ± 0.4b
Overall (100)		79.5 ± 6.3a	73.9 ± 7.1a

Different letters in the same raw indicated that the means were significantly different ($P = 0.05$)

The results indicated that RF disinfestation treatment had no significant ($P > 0.05$) influence on flavor, appearance, and taste of milled rice, but it had adverse impact on the stickiness and cold rice texture. However, overall sensory quality had no significant ($P > 0.05$) degradation after RF treatment. Li et al. (2012) conducted similar sensory evaluation study to identify the influence of electron beam irradiation effect on quality of cooked rice and found that along with increasing of irradiation dose, overall quality of cooked rice decreased. Generally, the overall score higher than 70 represented that the quality of milled rice is good and appropriate for storage (Li et al. 2012).

Conclusions

This study investigated the possibility of applying RF energy to control insects in milled rice manufacturing process by evaluating the effect of RF heating rate on the fissure ratio and broken rate of milled rice, validating RF heating lethality on immature rice weevils, and investigating the influence of RF disinfestation treatment on cooking and eating quality of milled rice. The results indicated that mild RF heating rate (<5.8 °C/min) had no significantly influence on fissure ratio and broken rate of milled rice; RF treatment (50 °C, 5 min) can completely control immature rice weevils in rough, brown, and milled rice; and even though RF disinfestation treatment (50 °C, 5 min) had no significant influence on overall eating quality based on sensory evaluation, it had influence on the cooking quality (water absorption, adhesive strength) of milled rice. This study suggested that RF disinfestation treatment should be added at the beginning stage (rough rice) or at the ending stage (milled rice) to the currently milled rice industrial production line. More researches should be done to systematically evaluate the treatment effects on cooking and eating quality and to figure out the way to minimize adverse RF treatment effects on quality of milled rice.

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