Effects of hot air assisted radio frequency intermittent drying with tempering on the physicochemical properties of rough rice

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Abstract: Hot Air Assisted Radio Frequency (HARF) drying with multistage tempering was applied for post-harvest treatment of rough rice. The effects of HARF drying were explored about various parameters such as electrode gap (100, 110, 120 mm), material temperature (50, 55, 60°C) and air velocity (0.5, 1.5, 2.5 m/s) along with Hot Air Drying (HAD) on rice quality. In this study, optimal HARF drying condition was recorded at electrode gap of 110 mm, temperature of 60°C and hot air velocity of 2.5 m/s. After milling, the Head Rice Yield (HRY), broken percentage, chalkiness, length to width (*L/W*) radio, percentage of unsound kernels, fatty acid value and degree of freshness were estimated. Results indicated that RF heating significantly enhanced HRY and degree of freshness while reducing the broken percentage up to 16.21%, 36.48% and 26.45% respectively, as compared to HAD. Yellowness, length to width ratio and fatty acid value of HAD and HARF dried samples were statistically not significant ($P>0.05$), while chalkiness of HARF dried rice was slightly higher than HAD samples. The research findings are critical for application of HARF drying on industrial scale to improve the quality of rice.

Keywords: drying; radio frequency; rough rice; head rice yield; fatty acid value; degree of freshness

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0 Introduction

Paddy (*Oryza sativa* L.) is a major grain crop in the world and half of the people worldwide used milled paddy, that is, rice as staple food[1]. Total post-harvest losses for rough rice at the producer level have been estimated approximately 2.71 percent of total production[2]. After harvesting, rough rice must be dried to achieve safety moisture content of 13%-14% on wet basis (w.b.) for long-term storage in order to maintain the quality and prevent microorganism growth[3-5].

Rough rice has husk (protective outer layer), bran, aleurone layer, embryo and starchy endosperm. Milling is a complex stage in the processing of rough rice that involves removing husk and bran layer as well as improves quality of rice. Drying process of rough rice has been proved to have great influence on quality of rice which is critical, particularly for commercial purposes.

Sun drying and Hot Air Drying (HAD) are commonly used drying methods for rough rice. The main drawbacks of these drying methods are long drying time and low product quality[6]. Some novel heating methods have also been used, including Infrared Radiation (IR), Microwave (MW) and ohmic heating. These emerging heating technologies provide numerous advantages, however, they lead to non-uniform heating or shallow heat penetration that affects the quality of product[7]. With a great awareness of current technical issues, new methods, techniques and their combinations have been applied to rough rice drying. Radio Frequency (RF) heating is a dielectric technique that uses electromagnetic waves of 1-300 MHz which penetrates into foods and produce internal heat[8]. As compared to MW and IR, RF is gaining momentum for drying agricultural products due to its advantages of rapid and volumetric heating, larger penetration depth, higher energy efficiency and more stable product temperature[9]. The effect of volumetric heating accelerates the drying rate by heating materials faster and more uniformly as well as preserving the dried material quality. It has been reported that some researchers have successfully used numerous RF-based hybrid techniques to dry grains, vegetables, nuts and fruits such as corn seeds[10], potato flour[11], apple slices[12], kiwifruits[13] and so on.

Moreover, intermittent drying is a method which can be used to change drying conditions with time by sequentially performing drying and tempering[14-16]. Tempering is considered as a main procedure for those materials easy to

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produce stress cracks during drying process, such as rough rice and corn, so as to obtain moisture and temperature equilibrium to reduce crack ratio[3, 15, 17]. Ng et al.[18] studied the effect of tempering temperature on the drying-tempering characteristics of rough rice and found that 60°C was the optimal temperature for minimizing rice fissure ratio and increasing HRY of rice which is similar with the results of Cnossen et al.[19] and Aquerreta et al.[20]. Tempering has clearly showed improvement in the final characteristics of rice, particularly in its fissure properties[21].

Up till now, RF-based hybrid techniques have been used for controlling insects in rough rice and its byproducts[22], as an efficient alternative to chemical fumigation without exerting significant influences on quality of rough rice[23]. However, still there are very limit number of researches on the HARF drying behavior of freshly harvested and high moisture rough rice, which has been usually subjected to HAD with tempering as well as their effect on quality of rice. The main purpose of this work was to investigate the effects of HAD and HARF drying on physicochemical properties (freshness and fatty acid value) and milling qualities (HRY, chalkiness, broken percentage, yellowness, length to width ratio and unsound kernels) for rice. The research findings would be helpful to determine the effect HARF drying on rice quality and improve the industrial scale rice production.

1 Material and Methods

1.1 Materials

Rough rice (*Oryza Sativa* L.) variety Indica harvested in October 2018 in Jiangxi, China (26°38′-27°32′ north latitude and 115°17′-115°56′ east longitude), were collected for experimentation after one day of harvesting. Fresh grains were selected and preserved in plastic bags. Prior to drying, grains were thoroughly mixed and stored in a refrigerator at 2-4°C. Triplicates of 100 grains, 7-10 g each, were selected randomly for measurement of initial moisture content which came out to be 25.5%±0.5% on wet basis by oven drying (DHG-9140A, Yiheng Technical Co., Ltd., Shanghai, China) at 100°C with time interval of (72±1) h according to National Standards of People’s Republic of China[24]. Before drying experiments, rice samples were taken out from refrigerator and (590±5) g samples were used for HAD and HARF drying experiments. These kernels were uniformly distributed over the tray to form a single layer and placed at room temperature (about 25°C) for 3 h to acquire temperature and moisture equilibrium within rice kernels.

1.2 Drying equipment and experimental design

The HARF drying experimental work was conducted in a 6 kW, 27.12 MHz free-running oscillator RF system with two parallel electrodes (COMBI 6-S, Stray field International Limited, Wokingham, UK) as well as a hot air heating unit (DF-1.6-1, Yinniu electromechanical Co., Ltd, Taizhou, China) that provides auxiliary hot air. The framework of this system demonstrated in Fig. 1. Seven fiber optic sensors (UMI8, FISO Technologies Inc., Quebec, Canada) were used to measure temperatures of samples in different locations as shown in Fig. 1. An adjustable fan and heater were used to control the hot air velocity and temperature before being introduced into the RF chamber through an inlet valve. Rough rice samples (constant weight of (590±5) g) were homogeneously distributed on a tray made of polyethylene having a rectangular shape (350 L×250 W, mm^2) with an average depth of 30 mm as shown in Fig. 1. An automatic controlling system was used to control temperature for intermittent HARF drying in RF-machine. According to our preliminary experiment[25], increasing material temperature and air velocity above 60°C and 2.5 m/s caused crack ratio to exceed permissible limit of industrial standard for rice. Therefore, the drying parameters of electrode gap (100, 110 and 120 mm), material temperature (50, 55 and 60°C) and air velocity (0.5, 1.5 and 2.5 m/s) were determined to investigate the effect of HARF drying on the rice quality. The multistage drying and tempering optimum treatment for HARF drying was used with a determined drying versus tempering duration ratio of 1:5 according to preliminary experimental results[25]. During tempering process, the material was loaded into a foam box to avoid heat loss to the environment and for moisture and temperature equilibrium. Considering energy saving, the foam box with rough rice samples was kept at room temperature of 25°C without being heated during tempering period.

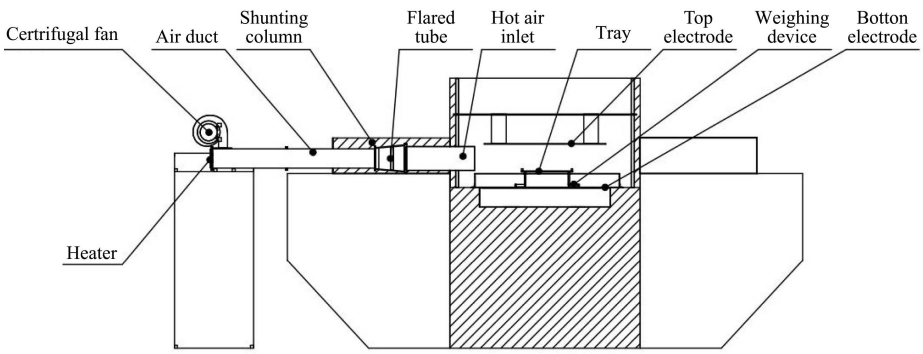


Fig. 1 Schematic diagram of hot air assisted radio frequency (HARF) drying equipment (adapted from[10])

HAD of rice samples with the same weight (constant weight of (590±5) g) in the same tray was conducted in HARF machine with RF off at the same optimized condition of material temperature and hot air velocity used for HARF drying for comparison.

1.3 Drying characteristics

Drying kinetics is typically demonstrated by using drying and drying rate curves, where the moisture ratio is plotted versus time, drying rate is plotted verses moisture content. The Moisture Ratio (MR) expressing the ratio of material moisture compared with the initial moisture was calculated according to Eq. (1).

$$\mathrm{MR} = \frac{M_t}{M_0} \tag{1}$$

Where M_0 is the dry-based initial moisture content, g/g; M_t is the dry-based moisture content at time t, g/g.

Drying Rate (DR) refers to mass of water removed per unit time per unit mass of drying material[26], which is calculated according to Eq. (2).

$$\mathrm{DR} = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \tag{2}$$

According to Eq. (2), t_1 and t_2 are the initial and final drying times, s; M_{t1} and M_{t2} are initial and final moisture content on dry basis at time interval t_1 and t_2, respectively, which are calculated by Eq. (3).

$$M_t = \frac{W_t - W_{ds}}{W_{ds}} \tag{3}$$

Where W_t is the weight at time interval t, g; W_{ds} is absolute dry weight of the material, g.

1.4 Milling of rough rice

Clean dried rough rice was peeled into brown rice using a rice multistage milling (consisting of pre-cleaning, husking, rice separation, polishing and grading) machine (Beijing Orient F & F Technology Development Centre). The brown rice was then polished to produce rice of grade 3 by the multistage milling machine and preserved for measurements of physical and chemical properties[27] as shown in Fig. 2.

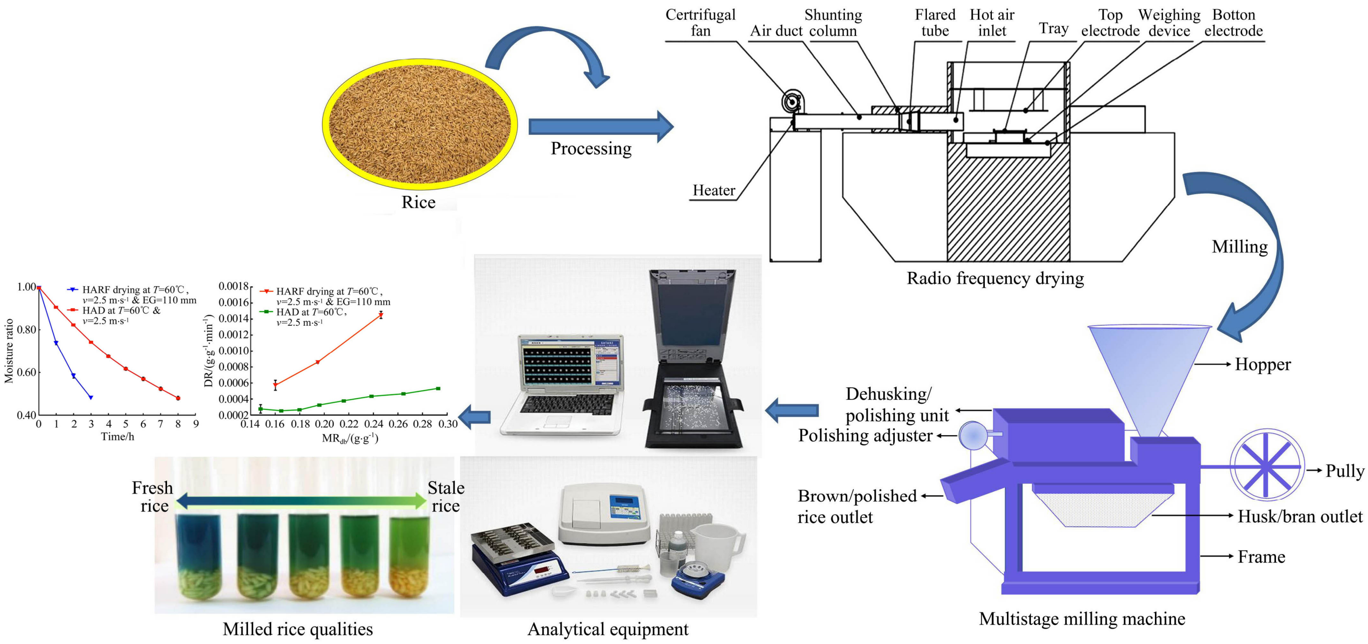


Fig. 2 Test flow chart

1.5 Head rice yield and broken percentage

Head rice is defined as grain that is with a length no less than three-quarters length of the kernel, while broken rice is defined as those with a length less than three-quarters length of the kernel. The head rice yield was determined by dividing the weight of the head rice kernels by the total rice yield using a grain scanner (RSQI10B, Satake Corporation Company, Hiroshima, Japan). The broken percentage of rice was determined by using Eq. (4)[4].

$$\text{Broken percentage (\%)} = 100\% - \text{head rice yield} \tag{4}$$

1.6 Chalkiness

The appearance of the grain is largely determined by its opacity which is mostly classified as the degree of chalkiness. Opaqueness has an overall chalky texture due to an interruption in the grain final filling. The chalky area of rice was determined by using a grain scanner (RSQI10B, Satake Corporation Company, Hiroshima, Japan). Once the rice kernel was scanned, the number of color pixels linked with non-chalky and chalky tissue were identified by a calibration procedure. Chalkiness, that is the percentage of chalky in the total grain area was then obtained[28].

1.7 Yellowness

The color was determined using the CIE (International Commission on Illumination) 1976 (b*) color space. The parameter b* describes the yellow/blue color with positive b* values showing yellowness and negative b* values indicating blueness[29]. Immediately, after the milling, a color analysis was performed and yellowness (b*) of rice samples was measured using a grain scanner (RSQI10B, Satake Corporation Company, Hiroshima, Japan) for rice samples.

1.8 Length to width ratio

The size and shape (length-width ratio) of grain is a stable varietal characteristic. The overall look of rice is vital for consumers. A L/W ratio greater than 3 lies in the range of slender shape. The grain length and width were measured in millimeters (mm)[30]. The rice kernel shape was expressed by its length to breadth ratio. The L/W ratio of rice is defined here as $L/W = L$ (mm)/W (mm), where L is average length of rice (mm) and W is average width of rice (mm). Grain shape

(L/W ratio) was determined using grain scanner (RSQI10B, Satake Corporation Company, Hiroshima, Japan) for rice[31].

1.9 Percentage of unsound kernels

The unsound kernels are whole or broken kernels that were damaged by heat. These were damaged head rice or broken rice with more than one color spots, such as white/whitewash, groats white/clear and red/yellow, or freckles. The grams of unsound kernels were measured among 50 g of rice using a grain scanner (RSQI10B, Satake Corporation Company, Hiroshima, Japan), the percentage of unsound kernels was then calculated by dividing 50 g from the gram of unsound kernels[32].

1.10 Fatty acid value

The fatty acid value was determined using the Chinese National Standard and previous research[33] with some modifications. The modifications were added as follows. The powder samples (10.0 g) were put into a 250 mL stoppered conical flask. After filtration, absolute ethanol (50 mL) was introduced, oscillated for 30 minutes and allowed to stand for 5 min. A 150 mL Erlenmeyer flask was filled with 25 mL of the filtrate and 50 mL of carbon dioxide-free distilled water was added. A magnetic stirrer was started after fixing composite electrode and stir bar. The mixture was then titrated using a standard potassium hydroxide (0.1 mol/mL) ethanol solution for adjusting the pH value to 8.0. The final results were presented in milligrams of potassium hydroxide required to neutralize the fatty acid in 100 g of rice flour (on dry basis)[34].

1.11 Degree of freshness

A solution of pH-adjusted bromothymol blue indicator was prepared and the degree of freshness was determined based on the indicator color change in response to the pH change induced by lipid changes in rice grains. The analysis was carried out by the test tube method with 10 g of sample in a test tube having sufficient chemical solution. After 10 min of reaction, the absorbance of chemical solutions was recorded with a freshness meter (RFDM1B, Satake Corporation Company, Hiroshima, Japan) and expressed as degree of freshness[35].

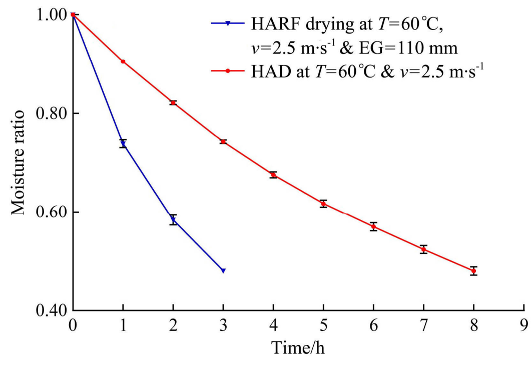
1.12 Statistical Analysis

All experimentations were repeated in triplets. All data was described as the average of three measurements ± standard deviation and evaluated by using statistical software SPSS (Version 24.0, SPSS Inc., Chicago, IL, US). Significance was represented at 5% probability ($P<0.05$) by multiple ANOVA test.

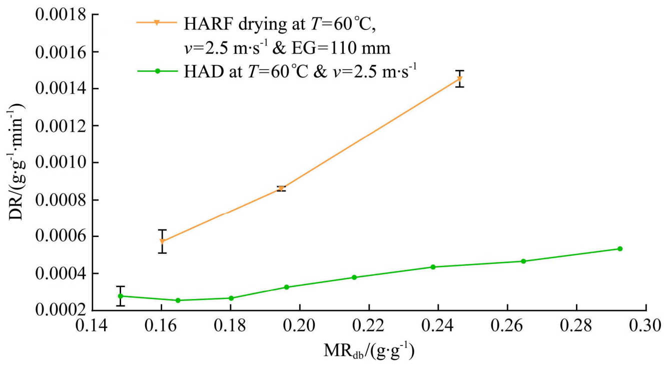
2 Results and discussion

2.1 Drying and drying rate curves of rough rice during HAD and HARF drying processes

A comparison of drying and drying rate curves of HAD and HARF dying at the optimized condition are illustrated in Fig. 3 a and b. Both drying methods exhibited a falling drying rate for rough rice and the drying kinetics can be well fitted by Weibull model and according to our previous study[25]. It was observed that HARF drying has potential to enhance drying rate significantly in the meantime decreasing the crack ratio[25] in comparison with HAD as shown in Fig. 3. The reason is that the volumetric heating characteristics of RF achieved much more uniform heating, resulting in shorter drying time. At the same sample weight, HARF drying required less than half the drying time of HAD. Moreover, optimal HARF drying condition was recorded at electrode gap of 110 mm, temperature of 60°C and hot air velocity of 2.5 m/s.



a. Moisture ratio versus time



b. Drying rate versus moisture content

Note: T-temperature, v-velocity, EG-electrode gap.

Fig. 3 Moisture ratio versus time curves and drying rate versus moisture content curves at optimized condition for hot air drying (HAD) and hot air assisted radio frequency (HARF) drying (adapted from[25])

2.2 Head rice yield and broken percentage

Table 1 illustrates the head rice yield and broken percentage, which are inversely related to each other, of rice dried under various parameters such as electrode gap (100, 110, 120 mm), temperature (50, 55, 60°C) and air velocity (0.5, 1.5, 2.5 m/s) for HARF drying conditions as compared with those of HAD at temperature of 60°C and hot air velocity of 2.5 m/s and control samples. Both HAD and HARF treatments resulted in relatively smaller head rice yield values than the control. With the decrease of electrode gap, that is, increasing RF output power, the HRY decreased, in accordance with the previous findings that greater microwave power density reduced HRY by increasing the broken percentage. This is mainly because of faster heat generation which resulted in internal expansion and faster outward flow of water vapor, leading to formation of cracks in the grain. Lower drying temperature helped maintain higher HRY due to similar reason[4]. Increase of hot air velocity, corresponding to faster water evaporation due to external convection, however, resulted in higher HRY. Thus, lower heat generation rate inside rice kernels and faster moisture evaporation from the surface are helpful in increasing HRY. Moreover, gradual decrease in temperature of grain caused partial gelatinization which had the same effect as accelerating rice aging, leading to increase in HRY[36]. Therefore, HARF drying with the combination of slow heating and cooling, tempering and faster water evaporation from the surface can be used to improve head rice yield quality[37]. Rehal et al.[2] also demonstrated that enhance tempering temperature could reduce the generation of rice fissures. As long as sufficient tempering at a temperature greater than the glass transition temperature is provided, high drying temperatures (up to 60°C) and high moisture removal rates can be used without compromising milling quality[38]. Moreover, HARF dried samples at optimized condition had 16.21% higher HRY while reduced the broken percentage 26.45% as compared to HAD ones. The reason why the high temperature of RF heating did not deteriorate the rice quality could be due to the relatively uniform heating of the rice kernel caused by the RF penetration which resulted in a lower moisture gradient as compared to conventional hot air drying[39].

Table 1 Physicochemical properties of rice for hot air drying (HAD) and hot air assisted radio frequency (HARF) drying under different conditions

Drying methods and conditions			Head rice yield/%	Broken percentage/%	Chalkiness/%	Yellowness	Length to width ratio	Unsound kernels/%	Fatty acid value/(mg·(100 g)$^{-1}$)	Degree of freshness/points
Control			92.25±0.70^{a}	7.75±0.07^{f}	0.35±0.21^{e}	63.33±0.35^{a}	3.86±0.11^{a}	0.22±0.02^{d}	10.60±0.29^{d}	80.33±0.58^{a}
HAD (T=60℃ & v=2.5 m·s^{-1})			62.00±0.42^{e}	38.00±0.42^{b}	2.85±0.21^{c}	12.65±0.21^{d}	3.80±0.00^{abc}	1.42±0.02^{bc}	10.17±0.16^{de}	45.67±0.58^{f}
HARF drying	Electrode gap/mm (T=60℃ & v=2.5 m·s^{-1})	100	55.10±0.42^{f}	44.90±0.42^{a}	3.85±0.71^{a}	30.00±0.28^{c}	3.65±0.07^{de}	2.62±0.12^{a}	13.01±0.12^{c}	50.33±0.57^{de}
		110	72.05±0.64^{d}	27.95±0.64^{c}	3.45±0.21^{ab}	12.50±0.71^{d}	3.70±0.00^{cde}	1.56±0.06^{b}	10.31±0.08^{de}	62.33±0.58^{c}
		120	76.50±0.14^{c}	23.50±0.14^{d}	2.00±0.35^{d}	11.70±0.57^{d}	3.80±0.00^{abc}	1.40±0.28^{bc}	10.00±0.07^{e}	71.67±1.15^{b}
	Temperature/℃ (EG=110 mm & v=2.5 m·s^{-1})	50	78.35±0.21^{b}	21.65±0.21^{e}	2.65±0.21^{c}	30.15±0.35^{c}	3.85±0.07^{ab}	1.48±0.28^{bc}	14.24±0.29^{a}	63.33±4.04^{c}
		55	71.30±0.56^{d}	28.70±0.56^{c}	3.10±0.14^{bc}	11.55±0.07^{d}	3.75±0.07^{bcd}	1.40±0.28^{bc}	13.52±0.26^{b}	61.00±1.00^{c}
		60	72.05±0.64^{d}	27.95±0.64^{c}	3.45±0.21^{ab}	12.50±0.71^{d}	3.70±0.00^{cde}	1.56±0.06^{b}	10.31±0.08^{de}	62.33±0.58^{c}
	Air velocity/(m·s^{-1}) (T=60℃ & EG=110 mm)	0.5	55.80±0.71^{f}	44.20±0.71^{a}	1.70±0.14^{d}	39.35±4.03^{b}	3.60±0.00^{e}	1.36±0.06^{c}	9.95±0.06^{e}	48.67±0.57^{e}
		1.5	62.30±1.98^{e}	37.70±1.98^{b}	3.50±0.14^{ab}	11.90±0.57^{d}	3.70±0.00^{de}	1.40±0.04^{bc}	10.07±0.19^{e}	52.67±0.57^{d}
		2.5	72.05±0.64^{d}	27.95±0.64^{c}	3.45±0.21^{ab}	12.50±0.71^{d}	3.70±0.00^{cde}	1.56±0.06^{b}	10.31±0.08^{de}	62.33±0.58^{c}

Note: *T* represents temperature, *v* represents velocity, and EG represents electrode gap. Different lower case letter indicates that means are significantly different at P = 0.05 among different treatments.

2.3 Milling qualities

2.3.1 Chalkiness

The chalkiness for all rice samples ranged from 0.35% to 3.85% are shown in Table 1. The rice chalkiness decreased with increasing electrode gap while enhanced with increasing temperature and air velocity. The findings revealed that drying temperatures above the glass transition temperature of starch led to chalkiness of rice[40]. Moreover, previous literature has shown that occurrence of chalky kernels at high temperatures is mainly due to inhibition of starch accumulation[41], for chalkiness, opaque white part of rice endosperm, is controlled by starch synthesis and fine structure and arrangement of starch granules[42]. These results suggest that increasing the regularity of starch is critical for controlling chalkiness; mainly larger starch granules have a negative effect on chalkiness reduction[42]. The HARF dried samples at the optimized drying condition of the largest electrode gap corresponding to the lowest RF output power had significantly lower chalkiness as compared to HAD one at the same drying condition.

2.3.2 Yellowness

The yellowness of rice dried with temperature (50, 55, 60°C), electrode gap (100, 110, 120 mm) and air velocity (0.5, 1.5, 2.5 m/s) were evaluated and presented in Table 1. The *b*-value or yellowness of dried rice ranged between 11.55 and 63.33. Fresh samples showed a greater yellowness due to higher moisture content[43]. The yellowness decreased with increase in temperature, electrode gap and air velocity, similar to the results of Bualuang et al.[44]. The color changes could be because of color pigment and moisture removal linked with the Maillard reaction during HARF drying. Different Maillard reactions may occur between the reducing sugar in the heated starch and amino group in the protein during HARF drying, depending on the moisture content and composition of the grain[45]. Moisture of samples remained high for long time during drying process under low drying temperature and air velocity which would increase rate of Maillard reactions resulting in discoloration[46]. The yellowness (b*) of the rice exhibited no significant (P>0.05) difference after HAD and HARF drying. Previous research reported that RF drying associated with volumetric heating rapidly reduces inter-kernel moisture, minimizing rice fissuring, decreasing percentage of discolored grain and preserving rice milling quality[38]. The reason could be that water absorbs electromagnetic energy and generates heat within the agri-foods. When a moist rice grain is introduced to microwave or RF, the rice kernels water molecules are induced to rotate and generate heat which caused higher water removal rate as compared to HAD. Furthermore, microwave or RF heating is capable of preserving the rice original textural structure and color in comparison to conventional oven-drying techniques[47].

2.3.3 Length to width ratio

The length to width ratio for all samples ranged from 3.60 to 3.86 as shown in Table 1. All rice grain samples had slender shape. Previous study showed that moisture gradient occurred between surface and center of rice kernel during drying process[37]. In multistage tempering drying, moisture gradient rapidly increased during drying period and then decreased slowly during tempering, therefore, tempering was important to maintain milling quality of rough rice[39]. Within two hours of tempering, moisture gradients were reduced to less than 5% of their initial value. This decrease in moisture gradient is mainly due to the decrease of rice kernel moisture content with each subsequent drying cycle and reduces crack ratio and shrinkage of rice kernel[48]. The length to width ratio of rice increased with the increasing electrode gap and decreasing temperature, while showed no significant difference under different hot air velocities as shown in Table 1. This demonstrated that length to width ratio decreased with increase in heating rate inside rough rice kernels induced from higher temperature and larger RF output power which resulted in larger shrinkage. Similar results were reported by Shimoyanagi et al.[49] that a larger length to width ratio was observed under lower temperature. Prakash et al.[48] reported that HARF dried sample showed smaller length to width ratio as compared to HAD rice, however, in our research no significant difference was observed on length to width ratio for HAD and HARF dried samples, with control, under optimized condition.

2.3.4 Percentage of unsound kernels

According to Table 1, the percentage of unsound kernels exhibited no significant difference under different drying temperatures of HARF drying, while decreased with increasing electrode gap and decreasing air velocity. Smaller electrode gap corresponding to larger RF output power led to higher heating generation rate, while increased air velocity was correlated with larger moisture evaporation rate causing more damaged grains, therefore resulted in higher percentage of unsound kernels[50]. There was no statistical difference in percentage of unsound kernels between HAD and HARF dried samples at optimized condition. Increased drying time and higher tempering temperatures could reduce the generation of rice fissures according to Tong et al.[38], however, in order to reduce energy consumption, we didn’t heat up the material during tempering period in this research. Influences of tempering temperature on drying rate, rice quality and energy consumption will be further studied.

2.4 Fatty acid value

Fatty acid value in rice were determined before and after HAD and HARF drying as presented in Table 1. Fatty acid value in rice showed no significant change after HAD and HARF drying under optimized condition. Previous finding also evidenced that rice had acceptable quality and were suitable for storage after IR drying[51].

During heat treatment, the fatty acid inside rice kernels was decomposed leading to increase of fatty acid value. The fatty acid value increased with decreasing temperature and electrode gap, while exhibited no significant difference under different hot air velocities. The reason could be that decreasing electrode gap corresponding to increased RF power led to higher heating generation rate which accelerated the oxidative decomposition of fatty acid, resulting in higher fatty acid value. However, at higher temperature, certain lipases were inactivated, slowing down the decomposition of fatty acid leading to reduced fatty acid value[52].

2.5 Degree of freshness

Degree of freshness, a quick indicator of rice quality, increased with increment in electrode gap and velocity, while statistically showed no significant difference under different temperatures as shown in Table 1. The reason is that increasing electrode gap corresponding to lower RF heating generation rate exerted less damage to rice quality. Increasing hot air velocity resulted in faster moisture removal from the surface of rough rice leading to shorter drying time and less damage to rice quality. Previous study also discovered that the prolonged electron beam irradiations deteriorated the quality of cooked rice[22]. HARF dried rice had 36.48% higher degree of freshness as compared to HAD samples at optimized condition as shown in Table 1. According to Table 1, freshness value decreased with increase in fatty acid value. Previous studies also reported similar results that degree of freshness was negatively correlated with fatty acid value (P<0.01), while positively correlated with taste value[53].

3 Conclusions

The experimental results demonstrated that Hot Air Assisted Radio Frequency (HARF) drying not only improved the quality but also maintained the nutrition of rice as compared to Hot Air Drying (HAD). In comparison to HAD, the HARF treatment provides favorable outcome and can effectively enhance head rice yield and degree of freshness up to 16.21% and 36.48% while reducing the broken percentage around 26.45%. Moreover, no significant difference was observed on the yellowness, length to width ratio and fatty acid value of rice after HAD and HARF drying. Drying at high temperature followed by tempering resulted in a higher head rice yield and less breakage due to reduced stress within the rice kernel. A slower rate of water removal and partial gelatinization of starch granules improved overall quality of rice. It can be concluded that HARF drying is a feasible alternative technique for industrial-scale drying application of rough rice with improved milling qualities, including head rice yield, degree of freshness, broken percentage, fatty acid value, length to width ratio and percentage of unsound kernel. It is desirable to conduct future researches to find more physicochemical and the sensory quality of rice after the industrial-scale RF treatment and storage.

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热风辅助射频间歇干燥对稻米理化特性的影响

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摘　要：论文采用热风辅助射频干燥和间歇缓苏技术进行了稻谷产后处理。研究了极板间距（100、110、120 mm）、物料温度（50、55、60°C）、风速（0.5、1.5、2.5 m/s）等参数对稻米品质（整精米产量、破碎率、垩白度、长宽比、不良粒率、脂肪酸值和新鲜度）的影响，获得了最优干燥工艺条件为：极板间距 110 mm、物料温度 60°C、风速 2.5 m/s。研究表明，与热风干燥相比，射频加热提高整精米产量、新鲜度，降低破碎率分别高达 16.21%、36.48%和 26.45%。热风辅助射频干燥和热风干燥样品的黄度、长宽比和脂肪酸值差异不显著（$P > 0.05$），而前者的垩白度略高于后者。研究结果对于工业规模上应用热风辅助射频干燥技术改善稻米品质具有重要的指导意义。

关键词：干燥；射频；稻米；整精米产量；脂肪酸值；新鲜度