Simultaneous Rough Rice Drying and Rice Bran Stabilization Using Infrared
Radiation Heating

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Abstract

The objective of this study was to develop a new rice drying method using IR heating followed by tempering. Freshly harvested medium grain rice (M206) samples with different initial moisture contents (IMCs) were used in this study. The samples were dried for one- and two-passes using a catalytic IR emitter to reach rice surface temperature of 60 °C. After IR heating, the samples were tempered in an incubator at 60 °C for different durations ranging from 1 to 5 h. The effects of new drying method on moisture removal, milling quality, and shelf life of rice bran were evaluated. High heating and drying rates and good milling quality of rough rice were achieved. It took only 55 s to heat the rice samples to 60 °C. For one-pass drying and 4 h tempering treatment, the total moisture removals were 3.33, 3.78 and 5.89 g moisture/100g dry solid for samples with initial moisture contents of 20.06, 25.53 and 32.50 g moisture/100g dry solid, respectively. IR heating did not generate adverse effects on milling quality of rough rice. Importantly, the storage stability of rice bran from the new drying method was extended to 38 days compared 7 days from current drying practice.

Keywords: Rough rice, Rice Bran, Drying, Infrared, Stabilization, Tempering, Milling quality.

1. Introduction

Rice bran, an important by-product of rice milling, constitutes 8-10% of the weight of brown rice. It contains valuable components such as proteins, vitamins and essential minerals and has 15-22% of edible oil with high nutritional and functional characteristics (Luh, 1980). The antioxidants in the rice bran also showed effect in lowering cholesterol in humans (Carvalho, 2006). Despite of its high nutrition value rice bran is underutilized and frequently wasted, except it is used for producing oil. In general, utilization of rice bran is severely restricted by the activity of endogenous enzymes, such as lipase, which can hydrolyze the triglyceride into glycerol and free fatty acids (FFAs). When rice is milled, bran is scoured and lipase is exposed to the oxygen in air, then the oxidation starts, resulting in the deterioration of the oil quality and forming off flavor (Luh, 1980). It takes only less than one week to make the FFAs in the oil exceed 10%, and then the rice bran oil is no longer suitable for human consumption (Desikachar, 1977; Qian et al., 2014). In order to better utilize the rice bran from rice milling process, the oil must be extracted quickly after milling process to control FFAs at a low level. However, this practice may not be feasible due to restriction of facility and production schedule (Randall, 1985). Therefore, it is a normal practice that the bran undergoes a stabilization process to inactivate the potent lipase enzyme immediately after milling to extend storage time at ambient conditions for controlling the FFAs concentration at a low level (less than 10%) before oil extraction.

Many approaches on the stabilization of rice bran have been investigated and reported,

such as chemical methods (Prabhakar and Venkatesh, 1986), heat methods (Rao Lakkakula et al., 2004), extrusion (Sayre et al., 1985) and microwave treatment (Tao et al., 1993). The most common method used in rice industry is extrusion even though it is an energy intensive process. The rice bran stabilization depends on temperature, duration of heat treatment, moisture content, PH, and other parameters (Luh, 1980; Tao et al., 1993). Hot air heating could be used, but it may not be able to heat the bran quickly to the needed temperature with desired uniformity (Kim et al., 1987; Pacheco de Delahaye et al., 2005). The severe and non-uniform heating could damage valuable components and also result in high energy consumption. Moreover, these stabilization processes are typically operated right after rice milling, which may not be feasible for certain rice mills.

Freshly harvested rough rice is subjected to drying to reduce the MC to the safe storage level (14.9 g moisture/100g dry solid). At present, the hot air drying at a low air temperature (about 43°C or ambient air) is typically used in the rice industry to minimize the fissure of rice caused by high heat. The low drying temperature extends the required drying time and cannot inactivate the enzymes in the rice bran. Therefore, it is ideal to develop alternative techniques that can simultaneously achieve drying of rough rice and stabilization of rice bran.

Infrared (IR) radiation heating offers many advantages compared to conventional drying methods (Sharma et al., 2005 and Das et al., 2004). It may offer a promising potential in achieving efficient drying and simultaneously inactivating the lipase in rice bran without affecting the rice quality. When IR is used to heat or dry moist

materials, the radiation impinges on the exposed material and penetrates it, and then the radiation energy is converted into heat (Ginzburg, 2002). The penetration could provide more uniform heating in the rice kernel and may reduce the moisture gradient during heating and drying. Also, the rice can be quickly heated to high temperatures in a short time. Our previously consecutive studies have confirmed that high moisture diffusivity corresponding to high drying rate for rough rice can be achieved by using infrared (IR) heating to 60 °C followed by tempering treatment for 4 h and natural cooling. Simultaneously, effective disinfestation and disinfection have also been achieved without compromising milling quality. Extended shelf life of both rough and brown were also achieved (Pan et al., 2008 and 2011; Khir et al., 2011 and 2014, Wang et al., 2014; Ding et al. 2015 and 2016). Accordingly, drying using IR heating followed by tempering treatment may be an effective approach to achieve stabilized rice bran and extend its shelf life after milling without additional stabilization process. However, there is no literature published about the effects of IR heating and tempering treatment under one- and two-pass drying processes on drying characteristics, milling quality and shelf life of rice bran. Therefore, the objectives of this research were to (1) investigate the effects of IR heating and tempering treatment on the drying characteristics and milling quality of rough rice under one- and two-pass drying; (2) determine the effect of new drying method on the FFA concentration of rice bran oil over different storage periods; and (3) investigate the kinetics of lipase enzyme inactivation under IR heating and tempering treatments.

2. Materials and methods

2.1. Samples

Freshly harvested medium grain rice, variety M206, obtained from the Farmers' Rice Cooperative (West Sacramento, CA), was used for conducting this research. The initial moisture content (IMC) of rough rice at harvest was 32.51 ± 0.09 g moisture/100g dry solid. In order to obtain rice samples with different (IMCs), the rice sample with the high MC was equally divided into three portions. Two portions were spread evenly on the floor in the thickness of 5cm and slowly dried to MC of 25.54 ± 0.11 and 20.07 ± 0.04 g moisture/100g dry solid under ambient conditions of temperature of $21 \pm 1^\circ\text{C}$ and relative humidity (RH) of $42 \pm 3\%$. During drying, the rice was mixed frequently to ensure to be uniformly dried. Finally, the rice samples with different IMCs of 20.07 ± 0.04 , 25.54 ± 0.11 and 32.51 ± 0.09 g moisture/100g dry solid were kept in polyethylene bags and sealed till they were used for IR drying and stabilization tests. All reported MCs are determined by the air oven method (130°C , 24 h) and reported on dry basis (d.b) (ASAE Standards, 1995).

2.2. IR heating

The rough rice samples with different IMCs were heated using IR device developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis, California, USA. The detailed descriptions for IR unit were mentioned in our previous publications (Pan et al., 2008 and 2011; Khir et al., 2011 and 2014). The samples of a single layer with loading rate of 2 kg/m^2 were heated for one and two drying passes under radiation intensity of 5000 W/m^2 . They were heated for 55s to reach surface temperature of 60°C during

each drying pass. The temperature of 60 °C was determined based on previous findings (Pan et al., 2008 and 2011; Khir et al., 2011 and 2014) that indicated that the high drying rate corresponding to good milling quality could be achieved by heating rough rice to aforementioned temperature level using IR. The temperature was measured by a Type T thermocouple (Omega Engineering Inc. Stamford, CT) immediately after samples were heated. The thermocouple was kept at the center of rough rice in a container until the temperature reading was stabilized, which took from 10 to 30s. The rice sample masses were measured by a balance with two-decimal accuracy before and after IR heating. The mass loss during heating and IMC were used to calculate the moisture removal during the IR heating durations. The moisture loss was calculated as the difference between the IMC and the MC after IR heating and is reported as g moisture/100g dry solid.

2.3. Tempering and cooling treatments

After IR heating, the tempering and cooling treatments were conducted. The tempering treatment was conducted by keeping the samples in closed container placed in an incubator set at 60 °C for various durations (1, 2, 3, 4 and 5h). After tempering treatment, the samples were cooled under ambient conditions at temperature of $21\pm1^{\circ}\text{C}$ and RH of $42\pm3\%$. They reached to the ambient temperature after 1h. Then after tempering and cooling treatments the samples were further dried to MC of 14.94 g moisture/100g dry solid using the ambient air.

For the two-pass drying, after infrared heating followed by tempering and cooling treatment as the first pass, the rough rice with initial high MC was left in the room

temperature overnight. The samples were heated using IR to the surface temperature to 60 °C again, and then followed by tempering for different durations ranging from 0-5h. The mass changes caused by tempering and cooling treatment were recorded at the end of cooling and used to calculate the moisture loss based on the MCs after the corresponding IR treatment.

2.4. Evaluation of milling quality

The indicators of rice milling quality including, total rice yield (TRY), head rice yield (HRY) and whiteness index (WI) were evaluated. The treated and untreated rice samples were dehulled and milled using a Yamamoto Husker (FC-2K) and Yamamoto Rice Mill (VP-222N, Yamamoto Co. Ltd., Japan). The samples were milled three times to achieve well-milled rice as defined by the Federal Grain Inspection Service (USDA, 1994). The setting of throughput and whitening were 1 and 4, respectively, during the first two milling passes and 1 and 5 during the third milling pass.

TRY, HRY and WI were used to evaluate the effects of IR heating and tempering treatments on milling quality. The HRY was determined with Graincheck (Foss North America, Eden Prairie, MN). The WI was determined by the whiteness tester (C-300, Kett Electronic Laboratory, Tokyo, Japan). A higher index number indicates whiter milled rice. All reported milling quality indicators are averages of three replicates.

2.5. Measurement of FFAs concentration

The FFA concentration of oil from rice bran obtained by milling the rough rice samples were determined and compared to those of untreated samples (control). The treated and untreated rice bran samples were packed in plastic ziplock bags and stored

for 38 days at temperature of 20 ± 1 °C and RH of $46 \pm 3\%$. To measure FFA concentration, rice bran samples of 2 g was mixed with 40 mL hexane and shaken for 1h at 20 °C at 3 x g. The mixture was then centrifuged for 6 min at 1192 x g using centrifugation (Eppendorf 5810 R, Germany). The amount of extracted oil was then measured gravimetrically. The concentration of total FFAs in rice bran oil (RBO), which expressed as oleic acid percentage, was evaluated according to alcoholic alkali titration method. After extraction and evaporation of hexane, 3 cm³ ethanol with 5 g/L phenolphthalein was added to the extracted oil. The mixture was stirred sufficiently and then titrated by 20 mol/L aqueous NaOH. During the titration, the mixture was vigorously shaken until the first permanent pink color appeared (Pourali et al., 2009).

The total FFAs percentage was calculated using equation (1).

$$FFA\% = \frac{V_{NaOH} \cdot N_{NaOH} \cdot 282.5}{10 \cdot m_{oil}} \times 100\% \quad (1)$$

where FFA% was FFA percentage in RBO (g/ 100 g RBO), V_{NaOH} was amount of titrant (cm³), N_{NaOH} was normality of titrant (mmol/cm³), 282.5 was oleic acid molecular weight and m_{oil} was RBO weight (g). All the procedures mentioned above are illustrated in Figure 1.

2.6. Kinetics of lipase-catalyzed reaction

The lipase-catalyzed reaction was determined by formation of FFAs in RBO. The lipase reaction kinetic was described by the following model: (Levenspiel, 1999; Pourali et al., 2009) and equation (2) was applied.

$$r_{FFA} = \frac{dC}{dt} = \frac{k_1 C}{k_2 C - 1} \quad (2)$$

where C is total FFAs concentration (g/100g RBO), t is storage time (day), and k_1 (day⁻¹) and k_2 (100g RBO/g FFAs) are kinetic parameters of FFAs formation. Integration of equation (2) under the initial condition of $C = C_0$ at $t = 0$ gives the following equation (3):

$$\frac{\ln(A+1)}{t} = \frac{k_2 C_0 A}{t} - k_1 \quad (3),$$

where A is defined as equation (4):

$$A = \frac{C - C_0}{C_0} \quad (4)$$

By plotting of $(\ln(A+1)) t^{-1}$ versus At^{-1} , kinetic parameters (k_1 and k_2) can be determined for the FFAs formation reaction in the stored rice bran under temperature of $20 \pm 1^\circ\text{C}$.

2.7. Statistical analysis

The obtained data were statistically analyzed using PASS software (IBM Chicago, IL). The significant differences at ($P < 0.05$) of the t-test with the assumption of equal variances was applied to compare milling quality indicators, including, TRY, HRY and WI under the tested conditions. In addition, multiple comparisons were applied to compare FFA concentrations for significant differences at $P < 0.05$.

3. Results and discussion

3.1. Moisture removal under IR heating and tempering treatment

As expected, high heating and moisture removal were achieved using IR heating. It took only 55s to heat rough rice to surface temperature of 60°C with corresponding

moisture removal of 1.75, 2.19 and 2.91 g moisture/100g dry solid for the rice samples with IMCs of 20.06, 25.53 and 32.50 g moisture/100g dry solid, respectively, as shown in Figure 2 (a, b and c). After IR heating, the tempering treatment significantly improved the moisture removal during natural cooling. For one-pass drying, the moisture removal during natural cooling increased with the increase of tempering time. The moisture removal after natural cooling increased from 0.81, 1.50 and 2.20 g moisture/100g dry solid to 1.50, 1.40 and 2.60 g moisture/100g dry solid by increasing tempering time from 1h to 4 h for the samples with IMCs of 20.06, 25.53 and 32.50 g moisture/100g dry solid, respectively. The corresponding total moisture removals were 2.56, 3.70, 5.10 g moisture/100g dry solid, and 3.33, 3.78, 5.89 g moisture/100g dry solid. It is important to notice that a considerable moisture removal was achieved by conducting tempering treatment and natural cooling without any energy consumption. After 4h of tempering, about 49.87%, 38.88%, and 47.27% of total moisture removal were achieved during natural cooling of the samples with IMCs of 20.06, 25.53 and 32.50 g moisture/100g dry solid, respectively. While the total moisture removal reached to 12.27 g moisture/100g dry solid, under two-pass drying and tempering treatment of more than 3h for samples with IMCs of 32.5 g moisture/100g dry solid as shown in Fig. 3. Thus, the tempering process reduced the moisture gradient in rice kernels and allowed the moisture to equilibrate before the rice kernels were cooled. Therefore, the tempering process is a critical step to increase the moisture removal during cooling of the rough rice. These results are in agreement with those we reported before (Pan et al., 2008; Khir et al., 2011; Ding et al. 2015).

This confirms that IR heating followed by tempering and natural cooling could achieve high heating and high drying efficiency for rough rice.

3.2. Milling quality

Milling quality indicators, including TRY, HRY, and WI under different IR and tempering treatments for rough rice samples with different IMCs are shown in Tables 1 and 2. In general, IR heating followed by tempering treatment led to improve TRY and HRY for samples with different IMCs compared to the controls. For example, the average of TRYs for rough rice heated using IR to 60 °C followed by tempering treatment for 4 h were 66.59%, 67.63% and 66.03% which were 3.77%, 5.06% and 1.02% significantly higher than those of the controls for samples with IMCs of 25.53, 32.50 g moisture/100g dry solid under one-pass drying and 32.50 g moisture/100g dry solid two-pass drying, respectively. The corresponding HRYs were 51.61%, and 49.80%, 50.89%. The TRY and HRY of samples with low MC of 20.06 g moisture/100g dry solid were slightly lower than those of controls. However, there is no significant difference between the tested samples and the controls.

When the color results of milled rice were examined, it was observed that the WI of the treated samples was less than that of the control. This may be due to storing rice for a long time before conducting the experiments. During the storage, color leaching from the hull and bran layer into the endosperm layer of rice might have occurred. This is similar to what we have observed before, which could be caused by the less degree of milling (Ding et al. 2015 and 2016).

Based on the milling quality results, it can be seen that using IR heating followed by

tempering treatments to dry rough rice led to achieve high moisture removal corresponding to good rice milling quality. The reason why the high temperature of IR heating did not damage the milled rice quality could be due to the relatively uniform heating in the rice kernel resulting in a lower moisture gradient compared to conventional hot air drying. Additionally, the results indicated that the rice milling quality may not be compromised with a relatively large amount of moisture removal in a single drying pass with a high drying rate if the rice can be heated quickly and uniformly, minimizing the moisture gradient. When a large amount of moisture is removed during IR heating, tempering is very important to re-establish the moisture equilibrium in the rice kernels. Moreover, it is important to notice that by applying two-pass drying approach, high moisture removal could be achieved without compromising the rough rice quality.

3.3. Effectiveness of enzyme inactivation

To evaluate the effectiveness of IR heating on inactivation of lipase enzyme, the FFA concentrations were determined for rice bran samples produced from milling of rough rice samples with different initial MCs treated with IR followed by tempering treatments and stored for different durations (Fig 4). It can be seen that the concentration of FFAs increased in the course of storage time under all tested conditions. However, concentration profiles of treated samples and the control are different. For untreated samples (control), the FFA concentration increased sharply to more than 10% during less than seven days of storage. This means that FFAs formed as a result of hydrolysis reaction in the rice bran and lipase enzyme catalyzed this

reaction to proceed rapidly. Thus untreated rice bran cannot be utilized for edible oil production after one week from the date of rice milling based on industrial practice. The FFA results from air dried rice are in agreement with those reported by Pourali et al. (2009). This confirms the necessity to inactivate the lipase enzyme that responsible for rice bran degradation and instability.

For samples treated with IR followed by tempering treatment for more than three hours, the FFA concentration increased gradually to 10% after 17, 19 and 30 days of storage for samples with initial MC of 20.06, 25.53 and 32.5 g moisture/100g dry solid (Fig 4 a, b and c). Moreover, for two-pass treatment, the FFA concentration reached 10% after 38 days for rough rice samples with initial MC of 32.5 g moisture/100g dry solid treated with IR followed by tempering treatment for 4 hours during each drying pass (Fig. 5). This means that the IR heating followed by tempering treatments has a destructive effect on lipase activity. The lipase activity declined with increase of tempering time and initial moisture content of the rough rice. Thus tempering treatment is one of essential part of the new drying process to inactivate the enzyme and extend the storage satiability of rice bran. The integrated IR drying and tempering treatment, particularly for high initial moisture rice, created an effective moist heat-treatment for lipase inactivation. It has been reported that the heat resistance of lipase depends on temperature, treatment time, and moisture content. The moisture content is a critical parameter. The higher the moisture content, the lower the heat resistance of lipase (Luh, 1980; Randall, 1985). Additionally, our previous study (Wang et al., 2014) has revealed that an increase in moisture content of

rough rice improved disinfection effect of IR heating followed by tempering treatment. High moisture of rough rice created a wet and warm environment during tempering treatment and effectively denature the portion of *A. flavus* spores. Since the lipase enzyme is protein, a similar effect could take place.

It is important to notice that the rough rice is typically harvested at moisture content ranging from 25.0 to 32.0 g moisture/100g dry solid (Mutters and Thompson, 2006). This means the heating of freshly harvested rough rice to 60 °C using IR followed by tempering treatment for three hours or longer can be an effective approach to inactivate the lipase and extend the storage stability of rice bran for up to 38 days after milling. At the same time, high drying rate and good milling quality can be simultaneously achieved for rough rice. These results are in agreement with those we reported before (Pan et al., 2008 and 2011; Khir et al., 2011 and 2014, Wang et al., 2014; Ding et al. 2015 and 2016). These findings indicate the promising potential of this technology to be applied in the commercial scale in the rice industry.

3.4. Kinetics of FFAs formation

The formation of FFAs plays an important role to create deteriorative changes and affect the quality of RBO. Consequently, application of an accurate kinetic model to understand and predict the FFAs formation could be a useful to determine RBO rancidity rate and feasibility of full utilization of rice bran. To further describe the effect of IR heating and tempering treatments on the inactivation of lipase in rice bran and estimate the storage time which FFAs concentration is kept below 10%, the kinetic of FFAs formation was investigated for the one- and two-pass dryings for rice

samples with different IMCs. The kinetics of FFAs formation were determined by regression relationships of kinetic data. The slope determined by the k_2 and k_1 values was represented by intercept. Based on the k_1 and k_2 , the storage time required to reach to 10% of FAA was estimated.

In Table 3, it can be seen that there is a good agreement between the experimental and kinetics data according to the high R^2 value for treated and control samples under one- and two-pass dryings. The values of k_1 and k_2 of controls were significantly higher than those of treated samples. When the tempering time increased, the k_1 and k_2 values decreased, which suggested that the lipase activity was reduced. For example, by increasing the tempering time for 1 h to 5 h, the k_1 and k_2 values of samples with IMC of 25.54 g moisture/100g dry solid decreased from 0.2022 day⁻¹ and 0.5412 (100 g RBO/g FFAs) to 0.0834 day⁻¹ and 0.4736 (100 g RBO/g FFAs) for the one-pass drying samples. Moreover, with increasing in initial moisture content, the lipase activity reduced further under one- and two-pass dryings. At 4 h of tempering time, the k_1 and k_2 values decreased from 0.149 day⁻¹ and 0.511 (100 g RBO/g FFAs) of rice samples with IMC of 20.02 g moisture/100g dry solid to 0.036 day⁻¹ and 0.3680 (100 g RBO/g FFAs) for samples with IMC of 32.54 g moisture/100g dry solid. The corresponding values under two-pass drying were 0.023 day⁻¹ and 0.357 (100 g RBO/g FFAs). According to the k_1 and k_2 obtained from the regression, the storage time during which FFA concentration kept under 10% was estimated, which exhibited the similar trend as those of the experimental results. The obtained results showed that the simplified kinetics model can successfully describe and predict the FFAs formation in the course

of rice bran storage. The model can be used by food industries to prepare an accurate manufacturing plan for processing rice bran into edible oil prior to its deterioration.

4. Conclusion

The research showed that high heating rate, drying efficiency and milling quality for rough rice can be achieved by using infrared heating followed by tempering treatment and natural cooling under one- and two-pass drying processes. It took only 55s to heat rough rice to surface temperature of 60 °C. The total moisture removals during IR heating for one-pass drying followed by tempering treatment for 4 h and natural cooling were 3.33, 3.78 and 5.89 g moisture/100g dry solid for samples with IMCs of 20.06, 25.53 and 32.50 g moisture/100g dry solid, respectively. The corresponding total moisture removal reached to 12.27 g moisture/100g dry solid for samples with IMCs of 32.5 g moisture/100g dry solid treated for two-pass drying. TRY and HRY values for rough rice with high initial moisture were higher than those of the control. However, WI values were slightly less than that of the control. Importantly, the IR heating and tempering treatments showed a promising potential to achieve an effective stabilization for rice bran during storage after milling. The IR heating of rough rice to 60 °C followed by tempering treatment for 4 or 5 h resulted in significant reduction in lipase activity, particularly for rice with high initial MC. Consequently, the storage time of stabilized rice bran with FFA concentration less than 10% could be extend to 38 days under two-pass drying compared to 7 days for the control. The results indicate that IR heating can achieve simultaneous drying and effective stabilization for rice bran and provide a more effective way for the

utilization of rice bran without affecting the quality of rice bran oil.

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Abbreviations

IMC initial moisture content, g moisture/100g dry solid,

IR Infrared radiation,

FFA Free fatty acid,

HRY Head rice yield,

MC Moisture content, g moisture/100g dry solid,

RBO Rice bran oil,

TRY Total rice yield,

WI Whiteness index

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Table 1. Total rice yield (TRY) and head rice yield (HRY) of rough rice with initial different IMCs under IR heating and tempering treatment for different durations.

IR heating and tempering duration	Initial moisture content (g 100 g ⁻¹)							
	20.06 (One pass)		25.53 (One pass)		32.50 (One pass)		32.50 (Two passes)	
	TRY	HRY	TRY	HRY	TRY	HRY	TRY	HRY
Control	64.23±0.27 a	49.84±1.47a	62.82±0.16a	50.01±1.34a	62.57±0.40a	49.3±1.24a	65.01±0.07a	49.38±0.47a
IR	63.10±0.28a	48.02±0.96a	66.89±0.72c	50.87±1.21a	66.20±1.37b	49.67±2.24a	66.33±0.62b	48.98±2.16a
1h	63.28±0.31a	48.04±1.43a	65.92±0.88c	50.84±1.01a	67.00±1.00b	49.50±1.20a	66.65±0.43b	50.30±0.75a
2h	63.08±0.22a	48.13±2.39a	66.64±0.93c	52.00±1.56b	67.36±0.27b	49.29±1.36a	65.81±0.51ab	49.99±0.70a
3h	62.30±1.00b	47.60±1.09a	66.63±0.46c	51.41±0.73b	66.81±1.27b	49.81±2.46a	66.25±0.31b	51.39±0.81a
4h	62.15±0.54b	47.99±2.41a	66.59±1.23c	51.61±0.62b	67.63±0.07b	49.80±0.83a	66.03±0.07b	50.89±0.54a
5h	63.53±0.75a	48.11±1.43a	66.74±0.53c	51.54±0.25b	68.14±0.91b	49.02±0.59a	65.85±0.66ab	50.65±2.92a

Values (means ± standard deviation) in each column with different letters are significantly different at p<0.05.

Table 2. Whiteness index (WI) of rough rice with initial different IMCs under IR heating and tempering treatment for different durations.

Infrared and tempering treatments	Initial moisture content (g 100 g ⁻¹)			
	One pass		Two passes	
	20.06	25.53	32.50	32.50
Control	41.03±0.25a	38.93±1.00a	40.67±0.80a	25.63±3.01a
IR	40.53±1.27a	35.10±0.82b	33.33±1.43b	28.33±0.40b
1h	41.47±0.32a	35.00±2.40b	32.10±1.21b	29.10±0.65b
2h	40.10±0.44a	33.30±1.25b	31.03±0.72b	30.05±3.36b
3h	40.80±2.46a	32.23±1.46bc	31.27±1.05b	25.63±3.0a1
4h	40.20±1.51a	33.46±0.68b	30.8±1.39bc	28.33±0.40b
5h	39.83±2.03a	33.23±0.97b	29.27±0.84bc	29.10±0.65b

Values (means ± standard deviation) in each column with different letters are significantly different at p<0.05.

Table 3 Kinetics parameters and estimated storage time for single and multiples IR/tempering treatments for different moisture contents

Drying pass	Initial MC (g 100 g ⁻¹)	Parameters	Control	IR	Tempering duration (h)				
					1	2	3	4	5
One	20.05	R ²	0.9949	0.8365	0.8363	0.8813	0.8830	0.8782	0.8781
		k ₁	0.1354	0.2272	0.1096	0.0484	0.1571	0.1490	0.2417
		k ₂	0.3144	0.4776	0.3558	0.2864	0.5240	0.5110	0.6651
	Estimated storage (day)		6.9	9.3	10.4	12.2	16.8	17.1	18.2
	25.54	R ²	0.9338	0.9312	0.9492	0.9060	0.9130	0.8510	0.8132
		k ₁	0.2600	0.1871	0.2022	0.1439	0.1843	0.1300	0.0834
		k ₂	0.5080	0.4525	0.5412	0.4823	0.5630	0.5080	0.4736
	Estimated storage (day)		9.2	9.5	12.6	14.1	19.3	20.7	23.4
	32.54	R ²	0.8570	0.8523	0.8979	0.7667	0.9245	0.9450	0.9962
		k ₁	0.3829	0.4329	0.4080	0.0979	0.1579	0.0360	0.0358
		k ₂	0.5930	0.7151	0.8055	0.3599	0.5228	0.3680	0.3844
	Estimated storage (day)		7.7	8.8	12.13	13.4	29.6	38.2	41.5
Two	32.54	R ²	0.9456	0.9002	0.6942	0.6942	0.7272	0.8150	0.9811
		k ₁	0.3324	0.0441	0.0583	0.0122	0.0289	0.0230	0.0115
		k ₂	0.5611	0.3244	0.4805	0.3104	0.3693	0.3570	0.2458
	Estimated storage (day)		8.2	24.0	31.5	37.7	39.7	45.4	48.0

Figure Captions

Figure 1. The procedures of IR heating, tempering treatment, and evaluation milling quality and FFA concentration.

Figure 2. Moisture loss under infrared heating and tempering treatments for rough rice with IMC of (A) 20.06; (B) 25.45; (C) 32.45 and (D) 32.45 g moisture/100g dry solid for two-pass drying

Figure 3. Total FFAs concentration (as oleic acid percentage in RBO) in treated rice bran produced from treated rough rice with IMCs of (A)20.06, (B) 25.45,(C) 32.45 and (D) 32.45 g moisture/100g dry solid for two-pass drying

Figure 1. The procedures of IR heating, tempering treatment, and evaluation milling quality and FFA concentration.

(a)

(b)

Figure 2. Moisture loss under infrared heating and tempering treatments for rough rice with IMC of (a) 20.06, (b) 25.45%, and (c) 32.45 g moisture/100g dry solids. ■ IR ■ Tempering, ● Total

Figure 3. Moisture loss under infrared heating and tempering treatment for different durations at one- and two-pass drying for rough rice with IMC of 32.45%. ■ 20.06 g moisture/100g dry solid, □ 25.53 g moisture/100g dry solid, ● 32.50 g moisture/100g dry solid, ○ two passes.

(a)

(b)

(c)

Fig 4. Total FFAs concentration (as oleic acid percentage in RBO) in treated rice bran of rice with different initial MCs, (a) 20.06, (b) 25.53 and (c) 32.50 g moisture/100g dry solid. Control, IR, Tempering -1h, Tempering -2h, Tempering -3h, Tempering -4h, Tempering -5h.

Fig 5. Total FFAs concentration (as oleic acid percentage in RBO) in two-pass treated rice bran of M.C. 32.5050 g moisture/100g dry solid during storage at 20 degree C. ■ Control, □ IR, ● Tempering -1h, ○ Tempering -2h, ▲ Tempering -3h, △ Tempering -4h, ◆ Tempering -5h.