DRYING CHARACTERISTICS AND QUALITY OF ROUGH RICE UNDER INFRARED RADIATION HEATING

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ABSTRACT. *Infrared (IR) radiation heating could provide a high heating rate and rapid moisture removal for rough rice drying. The objective of this research was to investigate the effect of the drying bed thickness on drying characteristics and quality of rough rice subjected to IR heating. Samples of freshly harvested medium grain rice (M202 variety) with 20.5% and 23.8% (w.b.) moisture contents were used for this study. They were dried with two different radiation intensities (4685 and 5348 W m^{-2}) and exposure times of 15, 30, 40, 60, 90, and 120 s for each drying bed thickness. The three tested drying bed thicknesses were single layer, 5 mm, and 10 mm. After IR drying, the samples were tempered for 4 h followed by natural cooling. The drying rate, moisture removal, and temperature of the rice were determined. The rice temperatures after the IR heating were in the range of 35.9°C to 71.4°C. The heating and drying rates decreased with the increase of bed thickness. Up to 2.2% of moisture was removed during natural cooling after tempering, without additional energy input. IR heating under tested conditions did not have adverse effects on rice sensory and milling quality, including total rice yield, head rice yield, and degree of milling of the dried rice. We concluded that a high heating rate, fast drying, and good rice quality can be achieved by IR heating of rough rice to about 60°C followed by tempering and natural cooling with a tested bed thickness up to 10 mm.*

Keywords. *Bed thickness, Drying, Infrared, Quality, Rough rice.*

Rough rice drying is a critical post-harvest handling process and has a direct effect on milling rice quality, subsequent handling processes, and commercial value of a rice crop. Rough rice is normally harvested at moisture contents (MCs) higher than the 14% or less (wet basis) required for safe storage. It is typically dried using heated air, which is a slow process because only relatively low air temperatures can be used to avoid reducing rice milling quality. The heated air warms the outer layer of the rice kernel first and causes the moisture to evaporate from the kernel surface into the drying air. As the moisture is removed from the outer layers of the grain, a moisture gradient is established within the kernel. This gradient causes stresses in the grain, causing the rice kernel to fissure after drying (Ban, 1971; Kunze and Choudhury, 1972; Kunze, 1979). Therefore, to minimize the moisture gradient generated during conventional rice drying, multiple drying passes are typically used. The multiple drying normally removes a relatively small amount of moisture (2% to 3%) in each drying pass by exposing the rough rice to relatively low heated air temperature (Kunze and Calderwood, 2004).

With the increase in rice production due to high-yielding varieties and rapid harvesting and transport capabilities, it is important to develop methods for drying with high energy efficiency that result in rice of high quality. Infrared (IR) drying has been investigated as a potential method for obtaining high-quality dried foodstuffs, including fruits, vegetables, and grains (Abe and Afzal, 1997; Afzal and Abe, 1998, 2000; Hebbar and Rostagi, 2001; Zhu et al., 2002). IR radiation drying is fundamentally different from convective drying because the material is dried directly by absorption of IR energy rather than transfer of heat from the air (Bal et al., 1970). IR energy is transferred from the heating element to the product surface without heating the surrounding air. The radiation impinges on the exposed material, penetrates it, and is converted to sensible heat. The penetration capability depends on the properties of the treated material and the temperature of the radiator. The depth of penetration in dried potato could be up to 7.8 mm (Ginzburg, 1969). The penetration could provide more uniform heating in individual rice kernels and may reduce the moisture gradient during heating and drying. In addition, since IR does not heat the medium, the temperature of a rice kernel would not be limited by the wet bulb temperature of the surrounding air and would become high in a short timeframe.

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The earliest research using IR for drying rough rice was reported in early 1960s (Schroeder and Rosberg, 1960; Schroeder, 1960, 1961; Hall, 1962; Faulker and Wratten, 1966, 1970). A high drying rate of rice was achieved by spreading the rice in a single layer. When IR was used to preheat the rough rice to 60°C followed by 49°C heated air drying for 2 to 3 min, approximately 2% MC was removed during each drying pass. It has also been reported that only 7 min were required to reduce the MC from 20% to 14.8% (d.b.) using near-IR heating, compared to 30 min for hot-air drying (Rao, 1983). Most researchers have used medium and far IR with wavelengths of 2 to 100 µm for drying agricultural products (Arinze et al., 1987; Nindo el al., 1995). Bekki (1991) found that the maximum absorption of IR radiation by medium-grain rough rice occurred at a wavelength of 2.9 µm.

We found (Pan et al., 2008) that IR can be used to heat rough rice in a single layer quickly to a relatively high temperature. The sensible heat from the heated rice was then used to remove more moisture during cooling, which made the overall IR rough rice drying more energy efficient. Additionally, we found that simultaneous drying and disinfestation using IR could be achieved without any adverse effects on milled rice quality. Due to the limited penetration capability of IR, it is important to understand the effects of rice drying bed thickness on heating and drying rates and rice quality. However, no reported research has focused on this aspect. The objectives of this research were to: (1) determine the effects of drying bed thickness on heating and drying rates of rice under different IR heating times, (2) delineate the characteristics of moisture removal with tempering and natural air cooling, (3) investigate milling and sensory quality of rice dried with IR under selected conditions, and (4) determine effective IR drying conditions that can achieve high heating and drying rates with desired rice quality.

Materials and Methods

Rough Rice and Control Samples

Freshly harvested medium grain rice variety M202, obtained from Farmer's Rice Cooperative (West Sacramento, Cal.), was used for conducting the IR drying tests. The MC of the rough rice was 23.8% ±0.3% (high MC) at harvest. The rice sample with high MC was equally divided into two portions. In order to obtain one rough rice sample with low initial MC, one portion of the samples was slowly dried to 20.5% ±0.2% (low MC) with room temperature of 19°C ±1°C on the floor of the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The thickness of the rice bed on the floor was less than 5 cm. During the slow drying, the rice was mixed frequently to ensure uniform drying. It took about 45 h to reach 20.5% MC. The rice samples with 20.5% and 23.8% MC were then placed in polyethylene bags and sealed to ensure no moisture loss before they were used for the IR drying tests. The rice samples were further divided into 500 g samples with a sample divider (Boerner-sampler, Huffman Manufacturing, Inc., Chicago, Ill.) at test time. Control samples were prepared by drying the samples with original MCs of 20.5% and 23.8% using ambient air at 0.1 m s^{-1} to final MC of 13% ±0.2%. All reported MCs are on wet weight basis as determined by the air oven method (130°C for 24 h) (*ASAE Standards*, 1995).

IR Drying Device

A laboratory-scale IR dryer was developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The IR dryer consisted of two main components: an IR emitter and a drying tray. The catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as the IR radiation source. The emitter generates IR radiation energy by catalyzing natural gas to produce heat along with small amounts of water vapor and carbon dioxide as byproducts. The emitter has dimensions of 30 × 60 cm and a surface temperature of about 650°C with a corresponding peak wavelength of 3.1 µm under assumption of the emitter as a black body. An aluminum box with dimensions of 65 cm (length) × 37 cm (width) × 45 cm (height) was installed around the emitter as waveguide to achieve uniform IR intensity at the rice bed surface. The rice bed was located at 5 and 10 cm below the bottom edge of the waveguide with corresponding average IR intensities of 4685 and 5348 W m^{-2} at the rice bed surface. The radiation intensity was measured using an Ophir thermal excimer absorber head (FL205A, Ophir, Washington, Mass.). The drying tray was made of 3 mm thick aluminum plate. Its high reflectivity minimized the radiation energy loss through the aluminum plate. The reflected radiation energy could also be used to heat the bottom side of the rice kernels. A piece of plywood was installed beneath the aluminum plate to reduce the energy loss through conduction.

Experimental Design and IR Radiation Drying Procedures

Rice samples were dried under the following conditions (table 1). The rice samples with the two initial moisture contents (IMCs) were heated for six durations (15, 30, 40, 60, 90, and 120 s) under IR radiation intensity of 5348 W m^{-2} and for four heating durations (40, 60, 90, and 120 s) under IR radiation intensity of 4685 W m^{-2}. All tests were replicated three times at each condition. For the drying test, a 500 g rice sample was placed on the drying tray so as to achieve single layer (2 mm), 5 mm, or 10 mm bed thickness, with corresponding loading rates of 2.5, 4.5, and 6.5 kg m^{-2}, respectively. The initial drying tray temperature was 35°C.

To determine drying characteristics under different heating conditions, the rice temperature and moisture loss were measured at the end of each heating period. After heating, the rice temperature was measured using a type-T thermocouple (time constant of 0.15 s, Omega Engineering, Inc., Stamford, Conn.) immediately after the heated rice was collected into a preheated container with the targeted rice temperature (Pan et al., 2008). The thermocouple was kept at the center of the rice mass until the temperature reading was stabilized, which normally took 10 to 30 s. The average temperature of three

Table 1. Experimental design of rice drying study.

Initial MC (% w.b.)	Drying Bed Thickness	Heating Time (s)			
20.5	Single layer	15	40	60	90
	5 mm	30	60	90	120
	10 mm	30	60	90	120
23.8	Single layer	15	40	60	90
	5 mm	30	60	90	120
	10 mm	30	60	90	120

replicates for each treatment is reported. The rice sample masses were measured via a balance with two-decimal accuracy before and after heating. The mass loss during heating and the IMC were used to calculate the moisture removal during the heating periods. The moisture removal was calculated as the difference between the IMC and the MC after treatment and is reported as percentage points.

Tempering and Natural Cooling Procedures

In order to study the effects of tempering on moisture loss during cooling and milling quality, both tempering and natural cooling treatments were conducted. The tempering was conducted by keeping rice samples in closed containers placed in an incubator with a temperature the same as the heated rice for 4 h immediately following the IR heating (Pan et al., 2008). After the tempering treatment, rice samples spread as a thin layer (about 1 cm thick) were cooled using a natural cooling method (room temperature of 23°C ±1°C). The temperatures of the rice samples were close to ambient temperature after 35 min of cooling. The mass changes caused by the cooling treatment were recorded at the end of cooling and used to calculate the moisture removal based on the MCs after the corresponding IR heating treatment. The cooled samples were stored in polyethylene bags for one day before they were further dried to 13.5% ±0.2% MC using ambient air. The samples were stored in ziplock bags at room temperature for about one month before milling.

Milling Quality and Evaluation

The most important rice milling quality indicators are total rice yield (TRY), head rice yield (HRY), and degree of milling. The rice samples of 400 g were dehulled and milled using a Yamamoto husker (FC-2K) and a Yamamoto rice mill (VP-222N, Yamamoto Co. Ltd., Japan). They were milled three times to achieve well-milled rice as defined by the Federal Grain Inspection Service (USDA-FGIS, 1994). For the first two millings, the settings of throughput and whitening were 1 and 4, respectively. For the third milling, the corresponding settings were 1 and 5. The HRY was determined using a Grainchecker (Foss North America, Eden Prairie, Minn.). The whiteness index (WI) was used to evaluate the degree of milling of the rice as determined using a 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.

Preparation of Rice Samples for Sensory Evaluation

Procedures described earlier in the Rough Rice and Control Samples section were followed to obtain samples of 20% ±0.1% (low MC) from the harvested rice with 25.1% ±0.2% (high MC). Rice samples were dried at the optimum IR drying conditions that achieved high milling quality. The samples were heated as a single layer using the IR dryer for 1 min to achieve a temperature of 60°C under the radiation intensity of 5348 W m^{-2}. After IR heating, the samples were tempered and naturally cooled to ambient temperature using the procedures described in the Milling Quality and Evaluation section. Control samples were prepared by drying the samples with original MCs of 20% and 25.1% using ambient air at 0.1 m s^{-1} to final MC of 13% ±0.1%. One week in advance, the samples were milled three times to achieve well-milled rice as defined by the Federal Grain Inspection Service (USDA-FGIS, 1994) and shipped to the USDA-ARS Southern Regional Research Center in New Orleans, Louisiana, for sensory analyses.

Portions of white rice (300 g) were rinsed by immersing the rice in cold water (1:3 rice-to-water ratio) followed by straining to remove excess water. After rinsing, the samples were transferred to pre-weighed rice cooker insert bowls, and water was added to provide a rice-to-water weight ratio of 1:1.5. The rice was then cooked in a 5-cup rice cooker-steamer (Panasonic SR-W10G HP) to completion, followed by a 10 min holding period. Samples were taken from the cooker as described by Champagne et al. (1999). Cooking was staggered so that samples were analyzed at 20 min intervals.

Sensory Quality Evaluation

The sensory quality of IR-dried and control rice was evaluated by six trained panelists (Meilgaard et al., 1999). The rice flavor lexicon, based on the work of Goodwin et al. (1996), included 12 unique flavor attributes that were determined by smelling and tasting the samples (table 2). The intensities were scored based on a universal scale for all foods (Meilgaard et al., 1999) with the maximum rating for rice flavor attributes being generally about 5. The lexicon for rice texture used by the panel was based on that developed by Lyon et al. (1999) and Goodwin et al. (1996) and is described in table 3. The sensory texture profile included 14 sensory attributes that described rice texture at different phases of sensory evaluation, beginning with the feel of the rice when it was first placed in the mouth and ending with mouthfeel characteristics after the rice was swallowed. Flavor evaluations were conducted on control and IR-dried rice samples with

Table 2. Descriptive sensory analysis attributes and definitions used to evaluate cooked rice flavor and taste.

Attribute	Definition
Sewer/animal	An immediate and distinct pungent aromatic in the flavor characterized as sulfur-like and generic animal. The animal aromatic in the flavor can sometimes be identified as “piggy”.
Grain/starchy	A general term used to describe the aromatics in the flavor associated with grains such as corn, oats, and wheat. It is an overall grainy impression characterized as sweet, brown, sometimes dusty, and sometimes generic nutty or starchy.
Hay-like/musty	A dry, dusty, slightly brown aroma/flavor with a possible trace of musty.
Popcorn	A dry, dusty, slightly toasted and slightly sweet aromatic in the flavor that can be specifically identified as popcorn.
Corn	The sweet aromatics of the combination of corn kernels, corn milk, and corn germ found in canned yellow creamed-style corn.
Sweet aromatic	A sweet impression, such as cotton candy, caramel, or sweet fruity that may appear in the aroma and or aromatics.
Water-like/metallic	Aromatics and mouthfeel of the minerals and metals commonly associated with tap water. This excludes any chlorine aromatics that may be perceived.
Sweet taste	Basic sweet taste associated with sugar.

Table 3. Descriptive sensory attributes and definitions used to evaluate cooked rice texture.

Phases/Attributes	Definition
Phase I	Place 6 or 7 grains of rice in mouth behind front teeth. Press tongue over surface and evaluate
Initial starchy coating	Amount of paste-like thickness perceived on the product before mixing with saliva (three passes)
Slickness	Maximum ease of passing tongue over the rice surface when saliva starts to mix with sample
Roughness	Amount of irregularities in the surface of the product
Stickiness to lips	Degree to which kernels adhere to lips
Stickiness between grains	Degree to which the kernels adhere to each other
Phase II	Place 1/2 teaspoon of rice in mouth. Evaluate before or at first bite
Springiness	Degree grains return to original shape after partial compression
Cohesiveness	Degree to which the grains deform rather than crumble, crack, or break when biting with incisors
Hardness	Force required to bite through the sample with the incisors
Phase III	Evaluate during chew
Cohesiveness of mass	Maximum degree to which the sample holds together in a mass while chewing
Uniformity of bite	Evenness of force throughout bites to chew
Moisture absorption	Amount of saliva absorbed by sample during chewing
Phase IV	Evaluate after swallow
Residual loose particles	Amount of loose particles in mouth
Toothpack/toothstick	Amount of product adhering in/on the teeth

IMC 12.4% ±0.2% in duplicate in a preliminary study. Texture was evaluated on control and IR-dried rice samples with IMC of 20.0% and 25.1% three times in separate sessions. The details of the procedure followed for presenting samples to panelists at each session were described by Champagne et al. (1999).

Statistical Analysis

Data on rice temperatures and milling quality were statistically analyzed with Sigma State software (version 2.0, Jandel Corp., San Rafael ,Cal.) using one-way RM ANOVA and multiple comparisons to compare treatments for significant differences ($p < 0.05$). Sensory evaluation data were analyzed by Proc Mixed using the Analyst Option (SAS Institute, Inc., Cary, N.C.) to compare the six treatments. Least square (LS) means with Tukey's adjustment method was used to compare treatment means. Significance was reported at $p < 0.05$ for all data.

Results and Discussion

Effect of Heating Time, Radiation Intensity, and Bed Thickness on Rice Temperature

The rice sample temperatures obtained during different heating durations at different IMCs, radiation intensities, and drying bed thicknesses are shown in figures 1 and 2. In general, the rice temperature increased with increase in heating duration and radiation intensity under the same IMC and drying bed thickness. For example, when the rice samples with IMC of 20.5% were heated at radiation intensity of 5348 W m^{-2} in single-layer, 5 mm, and 10 mm drying bed thicknesses, the temperatures of the rice were 61.8°C, 53.4°C, and 46.2°C for 60 s heating and 69.4°C, 60.2°C, and 53.4°C for 90 s heating, respectively (fig. 1a). Similarly, the rice temperatures were 60.6°C, 50.6°C, and 46.0°C for 60 s heating and 67.5°C, 59.1°C, and 52.3°C for 90 s heating for rice samples with IMC of 23.8% in single-layer, 5 mm, and 10 mm drying bed thicknesses, respectively (fig. 1a). A similar trend of the rice sample temperatures was observed when the rice samples were heated under radiation intensity of 4658 W m^{-2} (fig. 1b).

In addition, when the radiation intensity increased from 4658 to 5348 W m^{-2}, the rice temperatures increased by 9.1°C, 5.1°C, and 6.5°C for rice samples with IMC of 20.5% heated for 60 s with single-layer, 5 mm, and 10 mm drying bed thicknesses, respectively.

It was also found that the heating rate decreased with increase of the drying bed thickness due to increased mass. However, the decrease in the heating rate was not proportional, which could be due to less energy loss during heating for a thicker bed. For example, the rice samples with IMC of

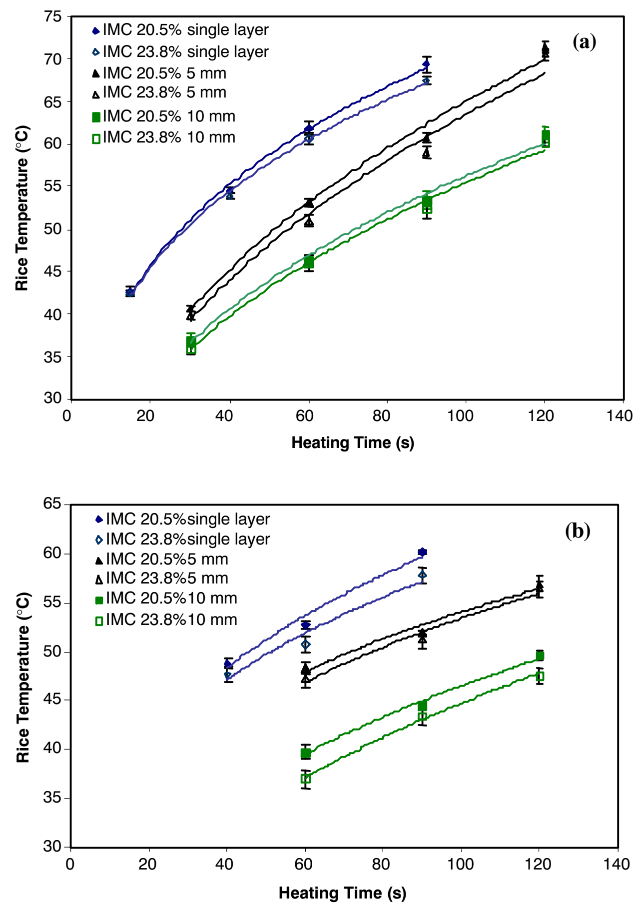

Figure 1. Relationship between rice temperatures and heating time at drying bed thickness and initial moisture contents under radiation intensity of (a) 5348 W m^{-2} and (b) 4658 W m^{-2}.

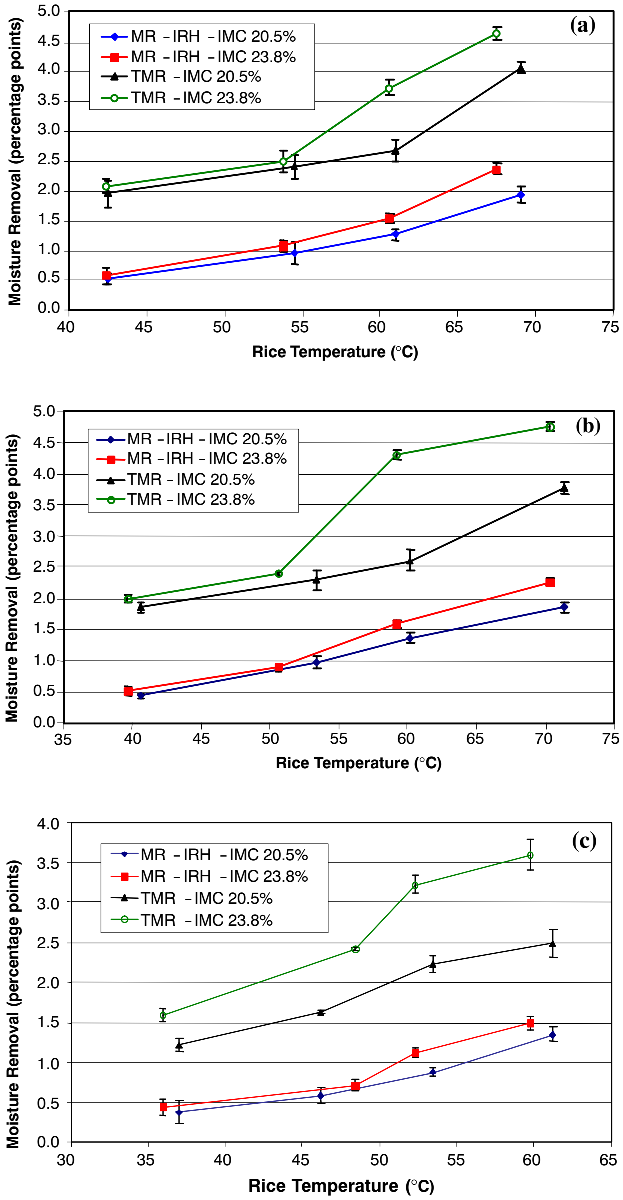

Figure 2. Moisture removal of rice with initial moisture contents (MCs) of 20.5% and 23.8% caused by infrared heating and cooling after tempering treatment with (a) single-layer, (b) 5 mm, and (c) 10 mm drying bed thicknesses under radiation intensity of 5348 W m^{-2} (MR = moisture removal, IRH = infrared heating, TMR = total moisture removal).

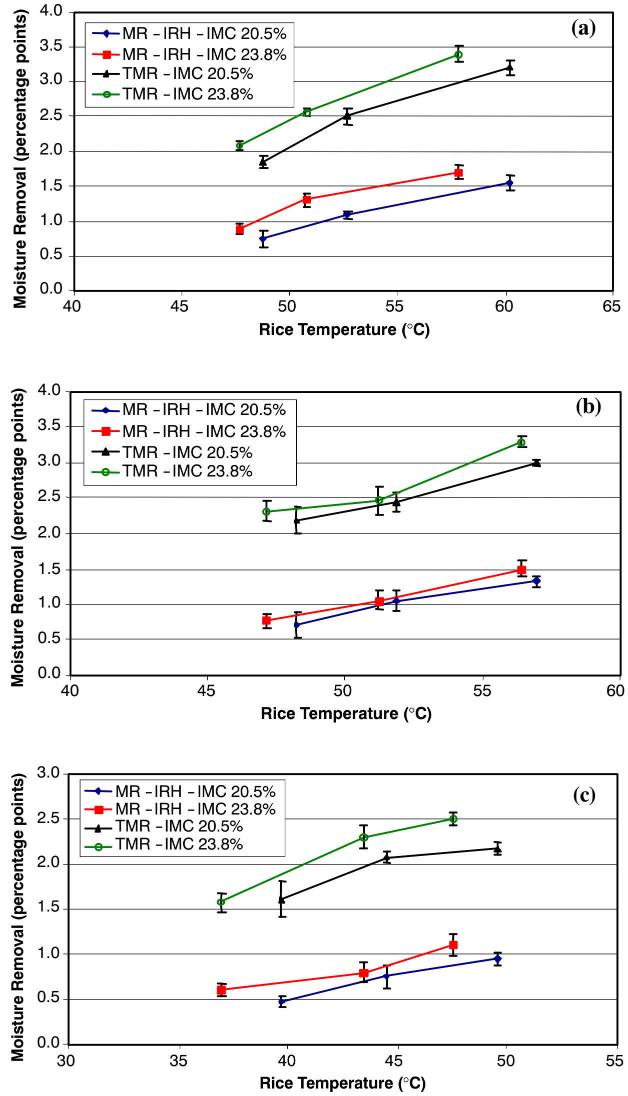

Figure 3. Moisture removal of rice with initial MCs of 20.5% and 23.8% caused by infrared heating and cooling after tempering treatment with (a) single-layer, (b) 5 mm, and (c) 10 mm drying bed thicknesses under radiation intensity of 4685 W m^{-2} (MR = moisture removal, IRH = infrared heating, TMR = total moisture removal).

20.6% and single-layer, 5 mm, and 10 mm drying bed thicknesses under radiation intensity of 5348 W m^{-2} reached a similar temperature (corresponding temperatures of 61.8°C, 60.2°C, and 61.2°C) with corresponding heating times of 60, 90, and 120 s. It can be seen that doubled thickness (from 5 to 10 mm) did not require doubled heating time to reach temperatures of 60°C to 61°C, which could mainly due to less heat loss and better heat penetration through the rice bed. This means that a relatively high heating rate could still be achieved during the short time by increasing the drying bed thickness up to 10 mm. The required uniform temperature distribution through the drying bed was achieved by preheating the drying bed to 35°C in this study.

In general, there was no significant differences between the low and high MC rice temperatures; however, the low MC rice samples had slightly higher temperatures than the high MC rice samples, especially at 60, 90, and 120 s heating time, which could be due to less energy being used for heating the water and a lower evaporative cooling effect in the low MC rice than in the high MC rice with the constant radiation heat supply. The maximum difference in temperatures of the samples with different original MC under the same heating duration was only 2.8°C.

Moisture Removal Under Different Drying Treatments

The moisture removal for rice samples with IMC of 20.5% and 23.8% during IR heating and after tempering and cooling treatment with different drying bed thicknesses and radiation intensities are shown in figures 2 and 3. The rice moisture removal during IR heating increased with the increased heating time and radiation intensity under a specific drying bed thickness and IMC. The moisture removal increase resulted from the increased rice temperature due to more energy being absorbed by the rice kernels with longer heating time and higher radiation intensity and caused more water evaporation compared to a shorter heating time and low radiation intensity. When rice samples with different depths were heated to a similar temperature, the moisture removal during heating was similar, indicating that depth up to 10 mm was not a limiting factor for moisture removal. Therefore, moisture removal mainly depended on the rice temperature. For example, when the rice samples with IMC of 20.5% were heated under radiation intensity of 5348 W m^{-2} to 61.0°C, 60.2°C, and 61.2°C for single-layer, 5 mm, and 10 mm drying bed thicknesses, the corresponding moisture removals during IR heating were 1.3, 1.4, and 1.3 percentage points, respectively. The corresponding total moisture removals, after tempering and cooling treatments, were 2.7, 2.6, and 2.5 percentage points. The same trend was noticed under low radiation intensity heating. When the rice samples with IMC of 20.5% were heated under radiation intensity of 4685 W m^{-2} to 48.8°C, 48.3°C, and 49.6°C for single-layer, 5 mm, and 10 mm drying bed thicknesses, the corresponding moisture removals during IR heating were 0.7, 0.7, and 0.8 percentage points, respectively. The corresponding total moisture removals, after tempering and cooling treatments, were 2.0, 2.2, and 2.2 percentage points.

It was also found that rice moisture removal increased with increase in IMC under the same radiation intensity and drying bed thickness. For example, when the rice samples with IMC of 20.5% were heated under radiation intensity of 5348 W m^{-2} to 60°C ±1°C, the moisture removal during IR heating was 1.3, 1.4, and 1.3 percentage points for single-layer, 5 mm, and 10 mm drying bed thicknesses, respectively. The corresponding total moisture removals, after tempering and cooling treatments, were 2.7, 2.6, and 2.5 percentage points. When the rice samples with IMC of 23.8% were heated under radiation intensity of 5348 W m^{-2} to 60°C ±1°C, the moisture removals during IR heating were 1.5, 1.6, and 1.5 percentage points for single-layer, 5 mm, and 10 mm drying bed thicknesses, respectively. The corresponding total moisture removals, after tempering and cooling treatments, were 3.7, 4.2, and 3.6 percentage points.

The results indicated that a high drying rate was achieved during IR heating with different drying bed thicknesses. For example, the drying rates of rice samples with IMC of 20.5% were 1.3, 0.9, and 0.7 percentage points per min during heating for single-layer, 5 mm, and 10 mm drying bed thicknesses and heating time of 60 s. Similarly, when the IMC was increased to 23.8%, the drying rates of rice samples were 1.5, 1.1, and 0.8 percentage points per min. Therefore, it is important to note that a high drying rate was achieved by using IR heating alone, even without counting the moisture removal during tempering and cooling, compared to conventional heated-air drying of 0.1 to 0.2 percentage points per min due to the low air temperature used (Kunze and Calderwood, 2004).

Rice Milling Quality

In general, for all of the rice samples with IMCs of 20.5% and 23.8%, high TRY and HRY were achieved for single-layer, 5 mm, and 10 mm drying bed thicknesses by heating the rice samples to about 60°C compared to the controls (tables 4 and 5). On average, the TRYs of the rice samples with IMC of 20.5% heated to 61°C, 60.2°C, and 61.2°C and corresponding total moisture removals of 2.7, 2.6, and 2.5 percentage points were 69.2%, 69.4%, and 69.2% for single-layer, and 5 mm, and 10 mm drying bed thicknesses, respectively . This means that the TRYs of IR dried rough rice were 0.65, 0.88, and 0.59 percentage points higher than the controls (table 4).

The TRYs of the rice samples with IMC of 23.8% heated to 60.6°C, 59.1°C, and 60.3°C and corresponding total moisture removals of 3.7, 4.2, and 3.6 percentage points were 68.9%, 69.3%, and 68.9% for single-layer, 5 mm, and 10 mm drying bed thicknesses, respectively, which were 1.08, 1.43, and 1.06 percentage points higher than the controls (table 5). This means that high moisture removal and high TRY could

Table 4. Quality of milled rice dried with different conditions with initial moisture content of 20.5%.

Heating Time (s)	Rice Temp. (°C)	Total Moisture Removal (%)	DBT and Control[a]	Milled Rice Quality[b] TRY	HRY	WI
--	--	--	Control	68.61 a	64.11 a	41.90 a
15	42.6	2.0	Single-layer	68.39 ab	64.45 a	41.50 a
30	40.6	1.9	5 mm	68.11 bc	62.67 b	41.80 a
30	37.0	1.2	10 mm	67.78 cd	62.84 b	41.60 a
--	--	--	Control	68.61 a	64.11 a	41.90 a
40	54.5	2.4	Single-layer	68.68 a	64.71 b	41.67 a
60	53.4	2.3	5 mm	68.38 a	62.91 c	41.80 a
60	46.2	1.6	10 mm	68.42 a	63.97 a	41.60 a
--	--	--	Control	68.61 a	64.11 a	41.90 a
60	61.0	2.7	Single-layer	69.26 b	65.63 b	41.60 a
90	60.2	2.6	5 mm	69.49 bc	65.05 b	42.06 a
90	53.4	2.2	10 mm	68.82 ab	65.40 b	41.60 a
--	--	--	Control	68.61 a	64.11 a	41.90 a
90	69.1	4.1	Single-layer	68.51 a	63.52 a	41.80 a
120	71.4	3.8	5 mm	67.91 b	62.77 b	42.00 a
120	61.2	2.5	10 mm	69.20 c	65.17 c	41.70 a

[a] DBT = drying bed thickness, Control = ambient air drying.
[b] TRY = total rice yield, HRY = head rice yield, and WI = whiteness index. Values from the control, single-layer, 5 mm, and 10 mm in each category followed by different letters are significantly different at $p < 0.05$.

Table 5. Quality of milled rice under different drying conditions with initial moisture content of 23.8%.

Heating Time (s)	Rice Temp. (°C)	Total Moisture Removal (%)	DBT and Control[a]	Milled Rice Quality[b] TRY	HRY	WI
--	--	--	Control	67.90 a	63.40 a	41.80 a
15	42.4	2.1	Single-layer	68.12 a	61.55 b	41.50 a
30	39.7	2.0	5 mm	68.03 a	61.50 b	41.50 a
30	35.9	1.6	10 mm	67.70 a	60.32 c	41.50 a
--	--	--	Control	67.90 a	63.40 a	41.80 a
40	53.8	2.5	Single-layer	68.42 b	62.18 b	41.40 a
60	50.6	2.4	5 mm	68.26 b	62.25 b	41.80 a
60	48.4	2.4	10 mm	68.24 b	61.53 b	41.50 a
--	--	--	Control	67.90 a	63.40 ad	41.80 a
60	60.6	3.7	Single-layer	68.98 bc	63.95 abc	41.60 a
90	59.1	4.2	5 mm	69.33 b	64.36 c	41.70 a
90	52.3	3.2	10 mm	68.80 c	63.06 d	41.60 a
--	--	--	Control	67.90 a	63.40 a	41.80 a
90	67.5	4.6	Single-layer	68.39 b	62.19 b	41.80 a
120	70.3	4.8	5 mm	67.92 a	60.85 c	41.80 a
120	60.3	3.6	10 mm	68.96 c	63.30 a	41.70 a

[a] DBT = drying bed thickness, Control = ambient air drying.
[b] TRY = total rice yield, HRY = head rice yield, and WI = whiteness index. Values from the control, single-layer, 5 mm, and 10 mm in each category followed by different letters are significantly different at $p < 0.05$.

Table 6. Comparison of sensory flavor and texture attributes of IR treated rice and control.

Flavor Attributes	Initial MC 20% Control	Initial MC 20% Treated	Texture Attributes	Initial MC 20% Control	Initial MC 20% Treated	Initial MC 25.1% Control	Initial MC 25.1% Treated
Sewer animal	1.0 a	0.9 a	Initial starchy coating	2.2 a	2.2 a	2.1 a	1.9 a
Floral	0.0 a	0.0 a	Slickness	6.9 a	7.3 a	7.2 a	7.9 a
Grain/starchy	3.4 a	3.5 a	Roughness	5.6 a	5.4 a	5.1 a	5.0 a
Hay-like musty	0.6 a	0.5 a	Stickiness to lips	10.2 a	9.5 b	9.0 b	8.7 c
Popcorn	0.3 a	0.5 a	Stickiness between grains	5.6 a	5.2 a	5.8 a	5.0 a
Corn	0.8 a	1.0 a	Springiness	4.0 a	4.0 a	4.3 a	4.0 a
Alfalfa	0.0 a	0.3 a	Hardness	5.3 a	5.4 a	5.6 a	5.9 a
Dairy	0.9 a	0.5 a	Cohesiveness	5.8 a	5.7 a	5.7 a	6.0 a
Sweet aromatic	0.4 a	0.4 a	Uniformity of bite	6.9 a	7.5 a	7.3 a	7.2 a
Water-like metallic	0.8 a	1.1 a	Cohesiveness of mass	5.8 a	6.0 ac	6.8 b	6.3 c
Sweet taste	1.3 a	1.2 a	Moisture absorption	5.3 b	5.2 b	5.4 ab	5.2 b
Sour	0.3 a	0.3 a	Residuals	4.7 a	4.8 a	4.7 a	4.8 a
Astringent	1.0 a	1.2 a	Tooth pack	4.1 a	4.0 a	4.0 a	4.0 a

Values in each row followed by the same letter indicated no significant difference at $p < 0.05$.

be achieved using IR heating followed by tempering and cooling.

Similar trends were also observed for the HRYs .The low MC rice samples dried using IR with tempering and natural cooling had significantly higher HRY (by 1.52, 0.94, and 1.06 percentage points) than the control when the rice samples were heated to about 60°C in single-layer, 5 mm, and 10 mm drying bed thicknesses, respectively (table 4). For the rice samples with IMC of 23.8% and temperature about 60°C, there was no significant difference between HRYs of rice dried rice and the control (table 5).

A comparison of whitening index (WI) values showed no significant differences between the IR-dried rice under different drying bed thicknesses and the control (tables 4 and 5). For all the rice samples dried under different drying bed thicknesses, heating times, and radiation intensities, the WI values were more than 41.5 units. However, it seems that there is a trend that WI increased with the increase of the rice drying temperature. This could be due to the difference in the hardness of rice with different treatments and/or the contribution of broken kernels to the overall color, which needs to be further studied.

Based on the milling quality results, it can be concluded that high moisture removal and milling quality could be achieved by heating the rice samples to about 60°C followed by tempering and natural cooling. This is in agreement with the suggestions that rice can be dried at 60°C in a rubbery state for achieving a relatively large amount of moisture removal without lowering rice milling quality (Cnossen et al., 2000; Cnossen et al., 2003). The reason that the high temperature of IR heating did not lower the rice quality could be due to the relative uniform heating in the rice kernel resulting from the IR penetration, which had less moisture gradient compared to conventional heated-air drying. The results also indicate that rice milling quality may not be compromised with a relatively large amount of moisture removal in a single drying pass with high drying rate if the rice can be heated quickly and uniformly to minimize the moisture gradient. In addition, tempering treatment followed by natural cooling plays an essential role in preserving rice quality. When a large amount of moisture is removed during IR heating, tempering is very important to re-establish the moisture equilibrium in rice kernels. Moreover, based on the glass transition phenomenon, the temperature and moisture at the rice surface were lowered first, and the starch reached the glassy state during cooling. At the same time, the center temperature and moisture of the rice kernels were still relatively high, and the starch remained in the rubbery state. The differences in thermomechanical properties of starch at different stages would generate stress and fissures, resulting in breakage during milling and lowered rice milling quality. Therefore, tempering and natural cooling would be very important for high-temperature rice drying. Since the tempering and natural cooling effectively preserved rice quality, controlled slow cooling could be accomplished by low rates of airflow through a bin of rice.

Sensory Quality

The results of sensory analyses are shown in table 6. The sensory quality of IR-dried rice under optimum IR drying conditions was compared to ambient air dried rice (control). No significant differences in flavor were observed between the control and IR-dried samples. In a comparison of texture, stickiness to lips was significantly higher in control rice than in that with low IMC dried with IR. Significantly lower cohesiveness of mass was exhibited by rice samples with high IMC dried with IR when compared to the control. No other textural attributes differed significantly between the control and IR-dried rice samples. These results are in agreement with previous results for hot-air drying reported by Champagne et al. (1997). They reported no increasing or decreasing trends in flavor attribute intensities at drying temperatures ranging from 18°C to 60°C. In the same study, Champagne et al. (1998) reported no effect of these drying conditions on the instrumental texture characteristics of the cooked rice, with the exception of cohesiveness, which was found to be lower in rice dried at lower temperature than in rice dried at higher temperature.

Based on the above results, IR drying treatments during which rice attained maximum temperatures up to 60°C, followed by tempering and natural cooling, appeared to have no adverse effects on sensory quality. Moreover, it is important to note that these IR drying conditions maintain high milling quality of rough rice.

Conclusions

This research showed that a high heating rate and rapid moisture removal for drying of freshly harvested rice can be achieved with a relatively short heating time by using a catalytic IR emitter with different drying bed thicknesses. When the drying bed thicknesses were single-layer, 5 mm, and 10 mm, only 60, 90, and 120 s were required to achieve about 60°C rice temperature, and this heating resulted in 1.3, 1.4, and 1.3 percentage points of moisture removal for the low MC rice and 1.5, 1.6, and 1.5 percentage points of moisture removal for the high MC rice. The corresponding total moisture removals, after tempering and natural cooling treatments, were 2.7, 2.6, and 2.5 for the low MC rice and 3.7, 4.2, and 3.6 percentage points for the high MC rice.

The tempering process after the rapid IR heating and moisture removal is essential to achieve high rice milling quality and to improve the amount of moisture removal during cooling. The natural cooling following the tempering treatment can be used to remove a significant amount of moisture and achieve high rice quality without additional energy input. In addition, IR heating under the tested conditions had no adverse effects on sensory quality. The recommended conditions for drying of freshly harvested rice are 60°C rice temperature followed by tempering and natural cooling at drying bed thickness up to 10 mm.

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