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Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality

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Abstract

The objective of this study was to investigate the drying characteristics, milling quality, and effectiveness of disinfestation of rough rice under conditions of infrared (IR) radiation heating. Freshly harvested medium grain rice (M202) samples with low (20.6%) and high (25.0%) moisture contents (MCs) were used for this study. Single-layer rough rice samples [non-infested and infested with the adults and eggs of lesser grain borers (*Rhizopertha dominica*) and angoumois grain moths (*Sitotroga cerealella*)] were heated for various durations using a catalytic IR emitter. The effects of the tempering treatment and natural and forced air cooling methods on moisture removal, milling quality and disinfestation were determined. A high heating rate and corresponding high moisture removal were achieved by using IR heating. After heating, tempering increased moisture removal during cooling and improved the milling quality of the rice samples. When 20.6% MC rice was heated by IR for 60 s, the results were a rice temperature of 61.2 °C, 1.7% MC removal during the heating period, and an additional 1.4% MC removal after tempering and natural cooling. In addition, the rice had 1.9% points higher head rice yield than a control sample dried with room air. The heating and tempering treatment also completely killed the tested insects. We concluded that simultaneous drying and disinfestation with high rice milling quality can be achieved by using a catalytic IR emitter to heat rough rice to 60 °C, followed by tempering and slow cooling.

Keywords: Rough rice; Milling quality; Drying; Disinfestation; Infrared; Temperature

1. Introduction

Rough rice is normally harvested at moisture contents (MCs) higher than that required [12–14% (wet basis)] for safe storage. In order to reduce the MC to the safe storage level after harvest, the rough rice is typically dried using convective heated air, which is a slow process because heated air at a relatively low temperature must be used to avoid or minimize lowering the rice milling quality. The convective drying process is normally not able to kill the insects in infested rough rice due to the relatively low air temperature. It would be ideal to develop a drying method that can be used for simultaneous drying and disinfestation of harvested rough rice with high rice milling quality.

When rough rice is dried with heated air, more moisture near the surface of the rice kernel is removed than near the center, which creates a moisture gradient in the rice kernel. A high moisture gradient occurs when a large amount of moisture is removed in a single drying pass and/or a high drying air temperature is used to achieve a high drying rate. The moisture gradient could induce tensile and

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compressive stresses resulting in fissure after cooling and lowering of the head rice yield and milling quality (Ban, 1971; Kunze & Choudhury, 1972; Kunze, 1979). Therefore, current rice drying practice normally uses multiple drying passes, removing a relatively small amount of moisture (2–3%) in each pass by exposing the rice to a relatively low heated air temperature (up to 54 °C for 15–20 min) to minimize the moisture gradient generated during drying (Kunze & Calderwood, 1985). The commercial drying temperature is normally much lower than 54 °C. After each drying pass, the heated rice is tempered by maintaining it for 4–24 h at the heated temperature to allow the moisture inside the rice kernels to equilibrate before it is further dried. However, it was also reported that a reduction in the amount of head rice was influenced by the amount of moisture removed within a time interval, rather than by the temperature of the drying air, which indicated that a certain amount of moisture can be quickly removed at a higher temperature without significantly lowering the head rice yield (Stipe, Wratten, & Miller, 1972).

Based on variations in the thermomechanical properties, such as expansion ratio and specific volume, of starch with MC and temperature, a glass transition hypothesis has been proposed and investigated for rice drying (Perdon, Siebenmorgan, & Mauromoustakos, 2000; Siebenmorgan, Yang, & Sun, 2004). The research results have shown that rough rice can be dried at a higher air temperature (60 °C) in a rubbery state, or above the glass transition temperature, to remove a large amount of moisture in a single pass without reducing the head rice yield (Cnossen, Siebenmorgen, Yang, & Bautista, 2000; Cnossen, Jimenez, & Siebenmorgen, 2003). However, in commercial practice it is difficult to quickly and uniformly heat the rice to a high temperature during convective drying because the rice is not in a single or thin layer and the temperatures of the rice kernels are limited to the wet bulb temperature of the drying air if no secondary heat sources are taken into account (Parrouffe, Dostie, Mujumdar, & Poulin, 1992). However, infrared (IR) radiation heating may provide a solution for achieving fast and relatively uniform heating due to the heat penetration of IR radiation, resulting in quick moisture removal, a reduced moisture gradient in the rice kernels, and improved milling quality.

IR radiation heating offers many advantages over conventional drying methods under similar drying conditions, such as a high heating rate and energy efficiency (Abe & Afzal, 1998; Afzal & Abe, 1997; Bilowicka, 1960; Das, Das, & Bal, 2004a, Das, Das, & Bal, 2004b; Ginzburg, 1969; Masamure et al., 1998; Sharma, Verma, & Pathare, 2005; Zhu, Zou, Chu, & Li, 2002). When it 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, 1969). The penetration could provide more uniform heating in the rice kernel and may reduce the moisture gradient during heating and drying. Also, since IR does not heat up the medium, the temperature of the rice kernel is not limited by the wet bulb temperature of the surrounding air, and the rice kernel can be quickly heated to high temperatures.

The earliest studies using IR for drying rough rice were reported in the early 1960s (Faulkner & Wratten, 1966, 1970; Hall, 1962; Schroeder, 1960, 1961; Schroeder & Rosberg, 1960). A high drying rate was achieved by spreading the rice in a single layer. When IR was used to preheat rough rice to 60 °C, followed by drying with heated air of 49 °C temperature for 2–3 min, approximately 2% MC was removed by each drying pass. However, little detailed information was made available. It has also been reported that it took only 7 min to reduce the MC from 20% to 14.8% (db) using near IR heating, compared to 30 min for hot air drying (Rao, 1983). Recently, medium and far IR sources, with wavelengths of 2–100 μm, have been investigated for drying agricultural products (Arinze, Schoenau, & Bigsby, 1987; Nindo, Kudo, & Bekki, 1995). It was found that the maximum absorption of IR radiation by medium grain rough rice occurred at a wavelength of 2.9 μm (Bekki, 1991). Due to the limited penetration capability of IR, mixing is necessary if the rice is dried in a thick bed, in order to achieve uniform heating of the rice (Nindo et al., 1995). Recently, similar research was conducted with parboiled rice (Das et al., 2004a, 2004b). Since IR can be used to quickly heat rough rice in a single or thin layer to a relatively high temperature, it should be possible to use the sensible heat from the heated rice to remove more moisture during cooling, which could make the overall IR rough rice drying process more energy efficient.

At present, there is a great need to develop alternative environmentally friendly disinfestation methods to replace the typical chemical disinfestation methods, such as methyl bromide fumigation. IR heating has been tested for disinfestation of stored rice and wheat. Tilton and Schroeder (1963) exposed three species of insects commonly found in rice to IR and achieved complete mortality with rice temperatures ranging from 65 °C to 70 °C. It was also reported that adult beetles were killed by IR at 57 °C (Kirkpatrick & Tilton, 1972). Kirkpatrick (1975) found that 93% and 99% of lesser grain borers and rice weevils were killed, respectively, after the wheat was heated to 48.6 °C and tempered for 24 h. Because rough rice could be infested with insects before and after it is harvested, especially rice produced organically, it would be ideal to kill all the insects during drying without needing any additional disinfestation treatments to extend the storage life of the rice. IR heating affords the possibility of performing simultaneous drying and disinfestation for rough rice.

The objectives of this research were (1) to study the drying and milling characteristics of rice with high and low harvest MCs undergoing single-layer heating using catalytic IR, followed by tempering and cooling treatments, and (2) to determine the effective IR heating conditions for disinfestation and the technical feasibility of simultaneous drying and disinfestation.

2. Materials and methods

2.1. Rough rice and infestation methods

Freshly harvested medium grain rice, variety M202, obtained from the Farmers' Rice Cooperative (West Sacramento, CA), was used for conducting the IR drying and disinfestation tests. The MC of rough rice was $25.0 \pm 0.3\%$ (high MC) at the harvest. A rice sample with high MC was divided equally into two portions. One of the portions was slowly dried to $20.6 \pm 0.2\%$ (low MC) with room temperature air ranging from 17 to 20 °C on the floor in 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 slow drying the rice was mixed frequently to ensure uniform drying. It took about 3 d to reach 20.6% MC. Then the rice samples with both low and high MCs were kept in polyethylene bags and sealed to ensure no moisture loss before they were used for the IR drying and disinfestation tests. The rice samples were further divided into 250 g samples with a sample divider at test time. The drying and disinfestation tests were separately conducted using non-infested and infested samples. All reported MCs are averages of three replicates on a wet weight basis and were determined by the air oven method (130 °C for 24 h) (ASAE, 1995).

Four days before the disinfestation tests, each 250 g rice sample was infested with 100 adult lesser grain borers (*R. dominica*) and 50 adult angoumois grain moths (*S. cerealella*), the most common insects in rough rice. These insects were provided by the Entomology Laboratory, Department of Entomology, University of California, Davis, after they were collected from naturally infested rough rice. The rice samples contained both adult insects and their eggs at the time of disinfestation treatment using IR heating.

2.2. Infrared heating treatment

A catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as the IR radiation source. The emitter generated IR radiation energy by catalyzing natural gas to produce heat along with small amounts of water vapor and carbon dioxide as by-products. The dimensions of the emitter were 30×60 cm, and it had a surface temperature of about 650 °C and corresponding peak wavelength of 3.1 μm, assuming a black body. An aluminum box with dimensions of 65 cm (length) $\times$ 37 cm (width) $\times$ 45 cm (height) was installed around the emitter as a wave guide to achieve uniform IR intensity at the rice bed surface. The rice bed was located 5 cm below the bottom edge of the wave guide. The average IR intensity at the rough rice bed surface was 5348 W/m^2, which was measured using an Ophir FL205A thermal excimer absorber head (Ophir, Washington, MA). The drying bed was made with an aluminum plate of 3 mm thickness as its high reflectivity minimized the radiation energy loss through the drying bed. 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. In the drying and disinfestation tests, a 250 g rice sample was placed on the drying bed as a single layer with a corresponding calculated loading of 2 kg/m^2.

2.3. Measurements of rice temperature and moisture removal

Both high and low MC rough rice samples were used for the drying and disinfestation tests. To measure the drying characteristics and the milling quality, 16 non-infested rice samples at initial temperature of 22 ± 1 °C were heated for each of four time durations (15, 40, 60 or 90 s) with an initial drying bed surface temperature of 35 °C. After heating, the rice temperature was measured using a Type T thermocouple – time constant 0.15 s – (Omega Engineering Inc. Stamford, CT) immediately after heated rice was collected into a container. The thermocouple was kept at the center of rice mass until the temperature reading was stabilized, which normally took from 10 to 30 s. The average temperature of four replicates for each treatment is reported.

The rice sample weights were measured via a balance with two-decimal accuracy before and after heating. The weight loss during heating and the initial MC were used to calculate the moisture removal during the heating periods. The moisture removal was calculated as the difference between the initial MC and the MC after treatment and reported as percentage points. The results in figures are expressed as % for simplicity.

During the disinfestation tests, because heating for less than 15 s was too little to kill the insects, 8 infested rice samples were heated for each of the durations of 25, 40, 60 and 90 s. The grain temperature during the 25 s heating was also determined. Control samples for milling quality comparison were produced by drying the high and low MC rough rice samples, using room air at temperature of 22 ± 1 °C and relative humidity of 35–45%, to 13.6% MC. The conditions of room air were the same for all tests, unless otherwise specified.

2.4. Tempering and cooling treatments

In order to study the effects of tempering on moisture loss during cooling, disinfestation, and milling quality, both tempered and non-tempered samples were prepared. Half of the heated rice samples (8 non-infested and 4 infested samples) were tempered, and the rest of the samples were cooled without tempering in the laboratory. The tempering was conducted by keeping the rice samples in closed containers placed in an incubator at the same temperature as the heated rice for 4 h immediately following the heating. The tempered and non-tempered samples were each cooled using natural cooling (slow cooling) or forced air cooling at room temperature as a thin layer (about 1 cm thick). For natural cooling, the thin layer of rice was placed on a laboratory bench for about 30 min. For forced air cooling, the samples were placed on mesh trays and cooled by blowing room air through the bed with an air velocity of 0.1 m/s. The air velocity was measured using a hot wire anemometer (Solomat MPM 500, UK). All forced air cooling samples were cooled for 5 min. After the natural and forced air cooling processes, the difference in temperatures between the rice and the room air temperature was less than 2 °C. The sample weight changes caused by the cooling treatments were recorded at the end of cooling and used to calculate the moisture removal based on the MC after the corresponding IR heating treatments. The cooled samples were stored in polyethylene bags before they were further dried to $13.3 \pm 0.2\%$ MC using room air. Two samples, each of original weight 250 g, from each treatment were combined into one sample with a total weight of more than 400 g for milling quality and disinfestation evaluation, which resulted in two samples being used for each treatment during the tests. The samples were stored in Ziplock bags at room temperature for about 1 month before milling. In order to avoid losing insects during handling, during the disinfestation tests the infested rough rice samples were cooled only with natural cooling after heating or tempering.

2.5. Milling quality and evaluation

The most important rice milling quality indicators are total rice yield (TRY), head rice yield (HRY) and degree of milling. To evaluate the effects of the different treatments, the non-infested rice samples of 400 g each were dehulled and milled using a Yamamoto Husker (FC-2K) and Yamamoto Rice Mill (VP-222 N, Yamamoto Co. Ltd., Japan). The rice samples were milled three times to achieve well-milled rice as defined by the Federal Grain Inspection Service (USDA FGIS, 1994). The settings of throughput and whitening were 1 and 4, respectively, during the first two millings and 1 and 5 during the third milling. The evaluated milling quality indicators included TRY, HRY and whiteness index (WI). The HRY was determined with Graincheck (Foss North America, Eden Prairie, MN). The WI was used to evaluate the whiteness (degree of milling) of the milled rice and was determined by the whiteness tester, C-300 (Kett Electronic Laboratory, Tokyo, Japan). A high index number indicates whiter milled rice. All quality evaluations were conducted at the Farmers' Rice Cooperative (West Sacramento, CA). All reported milling quality indicators are averages of two replicates.

2.6. Effectiveness of disinfestation treatments

After the IR heating or tempering treatments, all naturally cooled, infested rice samples were transferred to glass jars with screened lids to maintain sample moisture and oxygen supply to allow the surviving insects and eggs to emerge. All jars were kept in incubators at $28° \pm 2$ °C with $64 \pm 3\%$ relative humidity (RH) to allow development of the surviving insects and eggs (Kirkpatrick, 1975). The populations of the surviving and emergent live adult insects were visually counted one day after the treatment and then every several days over a 35-day period that covered more than one life cycle of the insects. All adult insects were removed from the rice samples after each examination. The average numbers of live adult insects in the two samples under each treatment at different storage times are reported. Because each sample was obtained by combining two original samples, the original numbers of insects were doubled in each incubated sample.

2.7. Statistical analysis

Data of the rice milling quality were statistically evaluated ($p < 0.05$) in Excel using the t test with the assumption of equal variances. TRY, HRY and WI of IR dried rice and control samples were statistically compared. Because the TRY and HRY of rice dried using IR heating followed by non-tempering or forced air cooling treatment were much lower than the corresponding values of the control samples, only the statistical results of rice dried with IR heating followed by tempering and natural cooling are reported in Figs. 5–7. The values with letter "*a*" were not significantly different from the control samples at $p < 0.05$.

3. Results and discussion

3.1. Rice temperature and moisture removal with different heating durations

After the 20.6% and 25.0% MC rough rice samples were heated for 15, 40, 60, and 90 s, they reached corresponding temperatures of 42.8, 54.3, 61.2, and 69.4 °C, and 42.8, 55.5, 59.1, and 68.0 °C, respectively. The low MC rice samples rose to slightly higher temperatures than the high MC rice samples during the 60 and 90 s heating times, 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 the temperatures of the samples with different initial MC under the same heating duration was 2.2 °C, which was relatively small. Therefore, the average temperatures of low and high MC rice samples at different heating durations are presented in Fig. 1. The increase rate of rice temperature decreased with the increase of heating time because heat loss was increased from heated rice. A high correlation between the average rice temperature and heating time was obtained with a power model as shown in Fig. 1. The model can be used to predict the temperature change for the rice with a known heating time under the tested moisture range and bed temperature.

In our other experiments, the required heating time to reach a specific rice temperature was significantly reduced

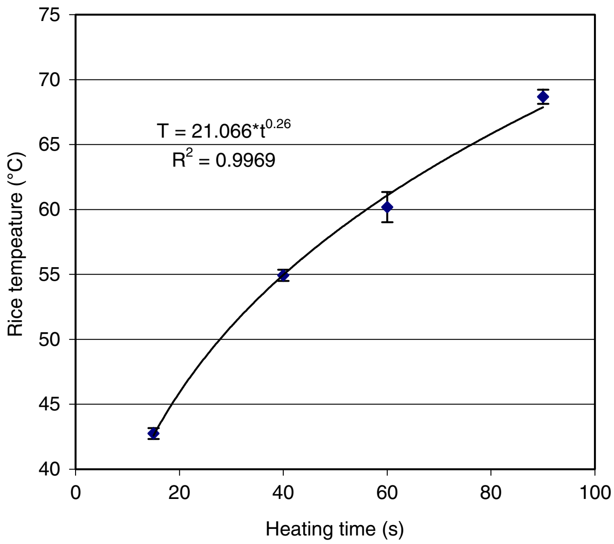

Fig. 1. Relationship between rice temperature and heating time.

when the drying bed temperature was increased by preheating to a higher temperature than the 35 °C used in this study. If it is necessary to reduce the heating time, the method of preheating the drying bed to a relatively high temperature could be considered. Further research is needed to study the effect of preheating temperature on the required heating time, moisture removal, and milling quality of rough rice.

The trend of more moisture removal for the high MC rice samples is clearly shown in Fig. 2, even though the difference between the low and high MC rice samples was relatively small. With 90 s heating (average temperature of 68.7 °C), the moisture removal was 2.8% and 2.5% points for the high and low MC rice samples, respectively. Compared to the low MC rice, at a similar rice temperature, especially at high temperature, the high MC rice had more moisture removal because of less resistance for water transfer in the rice kernel. It is important to note that the average drying rates of the rice samples with initial 25.0% and 20.6% MCs were 2.4%, 1.8%, 1.7%, and 1.7% points per minute at the moisture removal levels of 0.6%, 1.2%, 1.7%, and 2.6% points by each drying pass. The high drying rate at relatively high moisture removal levels by each drying pass, for example, of 1.7% points per minute at 1.7% and 2.6% points MC removal, was much higher than that of the current commercial, conventional heated air drying of 0.1% to 0.2% points per minute, due to the low heated air temperature used (Kunze & Calderwood, 1985). The moisture removal data were very closed to the results from Faulkner and Wratten (1966, 1970) who heated rough rice with IR to 60 °C followed by heated air drying for 2–3 min. The relatively large amount of moisture removal was achieved by using IR heating alone in this study, without counting the moisture removal during cooling.

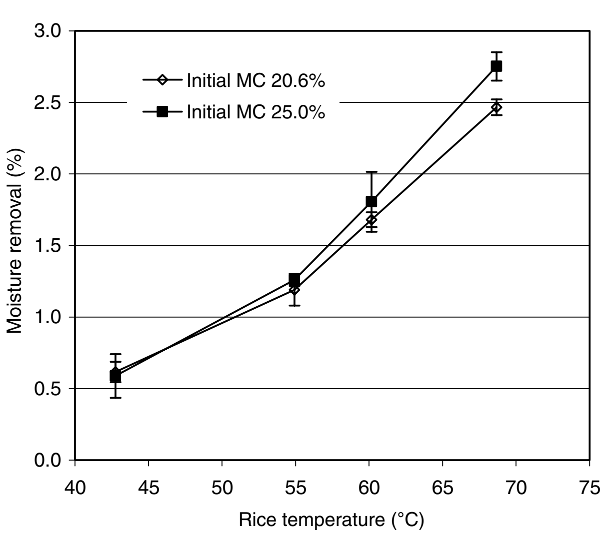

Fig. 2. Measured moisture removal (difference in moisture contents before and after heating) from rice samples with different initial MCs after heating to various temperatures.

3.2. Moisture removal with different tempering and cooling treatments

The clear trends of tempering vs. non-tempering and natural cooling vs. forced air cooling are seen in Fig. 3a and b. For low MC rice, the moisture removals from the tempered rice samples under natural cooling and forced air cooling were 0.6% to 1.3% and 1.1% to 1.9% points, respectively, in the tested temperature range from 42.8 °C to 69.4 °C. In contrast, the non-tempered rice had 0.4% to 0.8% and 0.7% to 0.9% point moisture removals under natural cooling and forced air cooling, respectively. Tempering resulted in 0.2% to 0.5% point higher MC removal than non-tempering, which showed that the tempering treatment significantly improved the moisture removal during cooling compared to non-tempered samples at $p < 0.05$ level. This could be due to the reduced moisture gradient in rice kernel and more moisture near the kernel surface after tempering (Kunze & Calderwood, 1985).

The forced air cooling also removed up to 0.9% points more moisture than natural cooling in the tested temperature range. However, at the high heating temperature of 69.4 °C without tempering, similar moisture removals were achieved with both natural cooling and forced air cooling. This was due to the high moisture gradients after more than 2.5% point moisture removal, and moisture diffusion in the rice kernels became the limiting factor for further improving the drying rate by using an increased drying force of forced air cooling.

The high MC rice had similar moisture removal trends to the low MC rice during cooling, even though more moisture was removed compared to the low MC rice. The tempered rice had moisture removals of 1.6–2.2% points for forced air cooling and 0.8–1.5% points for natural cooling, compared to 1.1–1.3% points for forced air cooling and

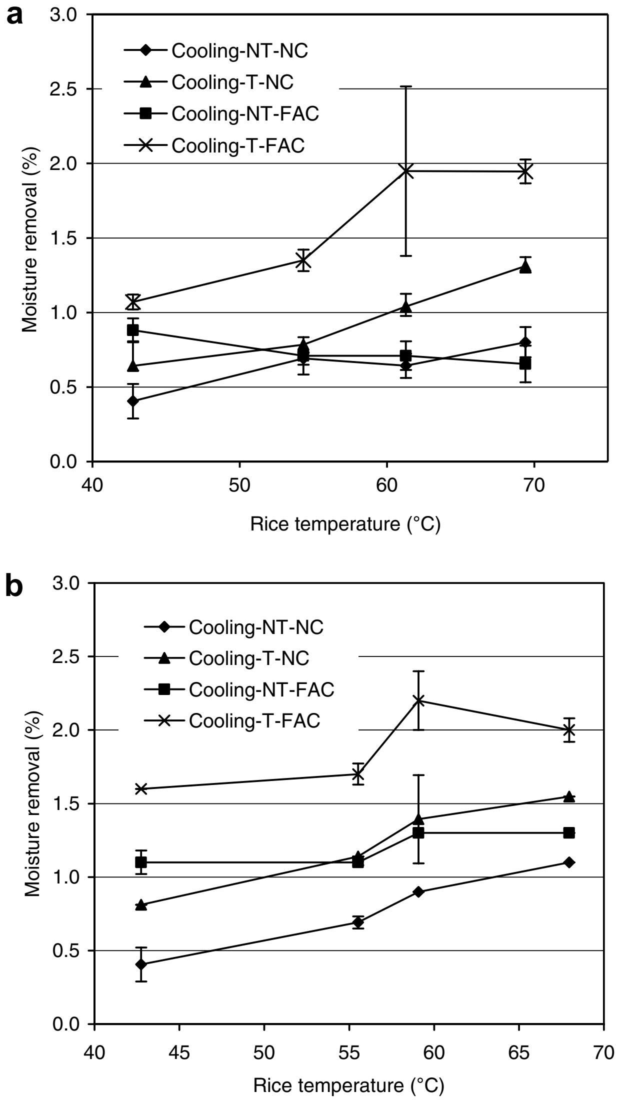

Fig. 3. Moisture removal under different cooling methods with and without tempering for rough rice with initial MC of 20.6% (a) and 25.0% (b). (T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling.)

0.4%–1.1% points for natural cooling of non-tempered rice in the tested temperature range. The tempering treatment resulted 0.4–0.5% and 0.5–0.9% points higher moisture removals than the non-tempering treatment with natural cooling and forced air cooling, respectively. The results indicate that tempering is even more important for high MC rice than low MC rice in order to have high MC removal during cooling.

Based on the above results, the tempering process reduced the moisture gradient in the rice kernels and allowed the moisture to equilibrate before the rice kernels were cooled. Without tempering, there was a significant moisture gradient in the rice kernels and a low MC near the surface, which resulted in less moisture removal during cooling. In general, both a reduced moisture gradient in the tempered rice kernels and forced air cooling increased moisture removal during the cooling process. Therefore, the tempering process is a critical step in increasing moisture removal during cooling. In order to achieve high moisture removal during cooling, a combination of tempering and forced air cooling could be used, even though excess moisture removal could cause rice fissures, lowering the rice milling quality, which would need to be considered.

The trend of total moisture removal at different temperatures with different tempering and cooling treatments was more or less parallel to the moisture removal caused by heating only (Fig. 4a and b). The highest total MC removals from the rice were 1.7–4.4% and 2.2–4.8% points for low and high MC rice samples, respectively, which were achieved with tempering and forced air cooling among the treatments. But the lowest total MC removals generally occurred for rice experiencing no tempering and a natural

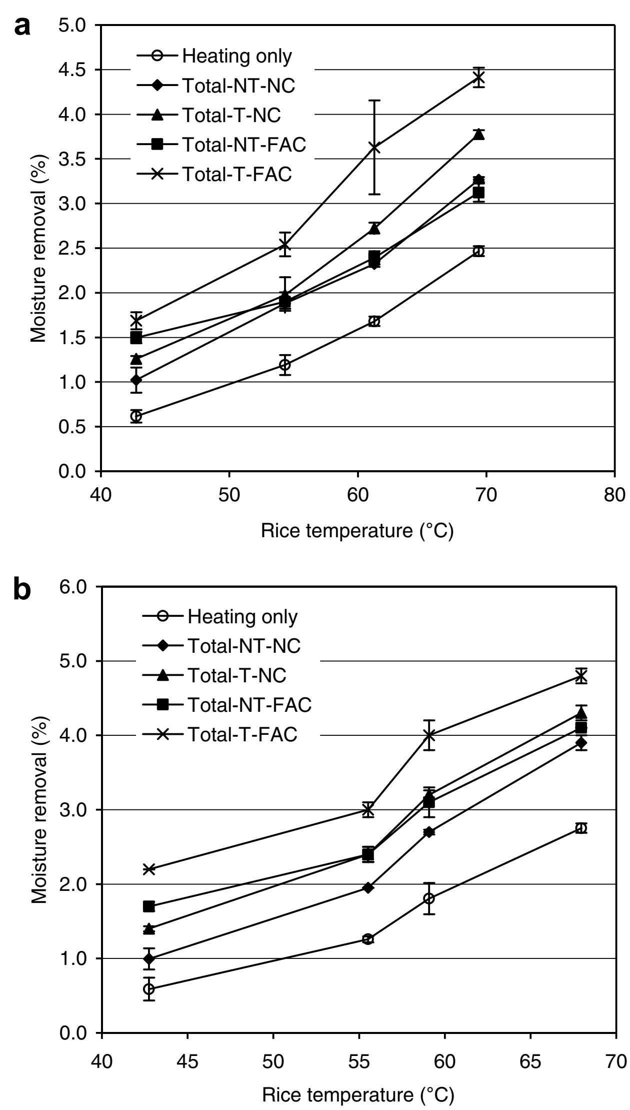

Fig. 4. Total moisture removal under different cooling methods with and without tempering for rough rice with initial MC of 20.6% (a) and 25.0% (b). (T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling.)

cooling treatment. For rice treated with tempering and natural cooling, the total moisture removals were 1.4%, 2.4%, 3.2% and 4.3% points for the high MC rice and 1.3%, 2.0%, 2.7% and 3.8% points for the low MC rice over the tested temperature range. The moisture removals were the second highest among the treatments when the temperatures were above 55 °C. These numbers indicated that 2.7–3.2% points of moisture were removed with 1 min heating followed by tempering and natural cooling. The drying rates were much higher than the 2–3% point moisture removal with 15–20 min heating of the current conventional heated air drying.

For total moisture removal, the moisture removed due to sensible heat during cooling was a very significant portion. For example, 37% and 44% of total moisture removals occurred during cooling when the low and high MC rice samples, respectively, were heated for 60 s (to about 60 °C), followed by tempering and natural cooling. Because no additional heating energy is needed during the cooling, the high moisture removal could further improve the energy efficiency of the IR drying process. The exact amounts of energy saving and consumption still need to be determined in future research.

3.3. Milled rice quality

In general, for both the high and low initial MC rice samples, IR dried rice with tempering followed by natural cooling had similar and higher TRY compared to the controls (Fig. 5a and b). On average, the TRYs of low and high MC rice dried using IR followed by natural cooling were 68.0% and 68.1%, respectively, which were 0.3% and 0.7% points more than the controls. In particular, the rice dried at about 60 °C with natural cooling had the highest TRYs of 68.4% for low MC rice and 68.6% for high MC rice, compared to the controls of 67.7% and 67.4%, respectively. This meant that the TRYs of IR dried rough rice were 0.7% to 1.2% points higher than the controls. However, the samples treated by other methods had much lower TRYs than the controls, especially the rice with low MC dried at high temperature.

Similar trends were also observed for the HRYs (Fig. 6a and b). The low MC rice samples dried using IR with tempering and natural cooling had significantly higher HRY (0.6–1.9% points) than the control, and the highest HRY of 65.2% was obtained at a rice temperature of 61.2 °C. For the high MC rice, the rice dried followed by tempering and natural cooling had the same HRY (63.6%) at 58.8 °C as the control and slightly lower HRY at 42.8 °C and 55.5 °C than the control. All other post-heating treatments resulted in much lower HRYs.

When the WI results of the milled rice were examined, it could be seen that the IR dried rice generally had higher WI values than the controls, especially for the low MC rice, even though the differences between the controls and some of the treated rice samples were not significant (Fig. 7a and b. This indicated that most of the IR dried rice with tem-

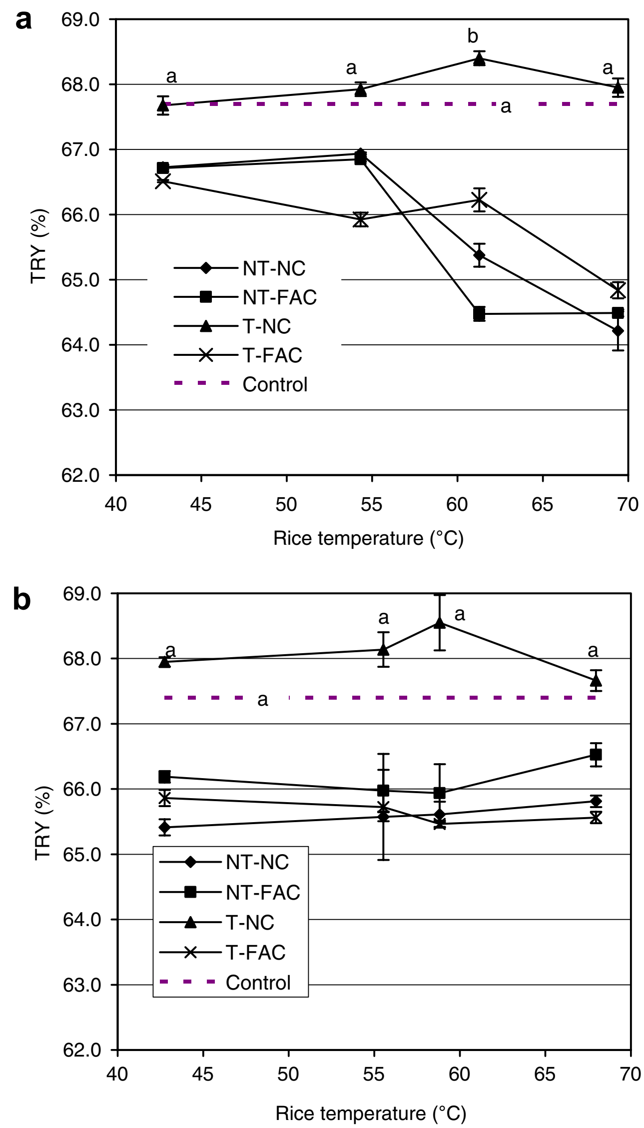

Fig. 5. Total rice yields (TRY) of rough rice with initial MCs of 20.6% (a) and 25.0% (b) under different drying treatments. (T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling; Values with letter "*a*" were not significantly different from the control sample at $p < 0.05$.)

pering followed by natural cooling had a similar milling degree to the control. It seems that there is a trend that WI increased with an increase in the rice drying temperature for the non-tempering treatments, especially for the low MC rice. This could be due to the difference in the hardness of rice subjected to different treatments and/or the contribution of broken kernels to the color, which needs to be further studied.

Based on the milling quality results, it can be concluded that rough rice can be dried using IR followed by tempering and natural cooling to achieve superior rice milling quality. It is recommended that the rice temperature of IR heating be controlled at close to or below 60 °C. This verified the suggestions that rice can be dried at 60 °C in a rubbery state for achieving a relatively large amount of

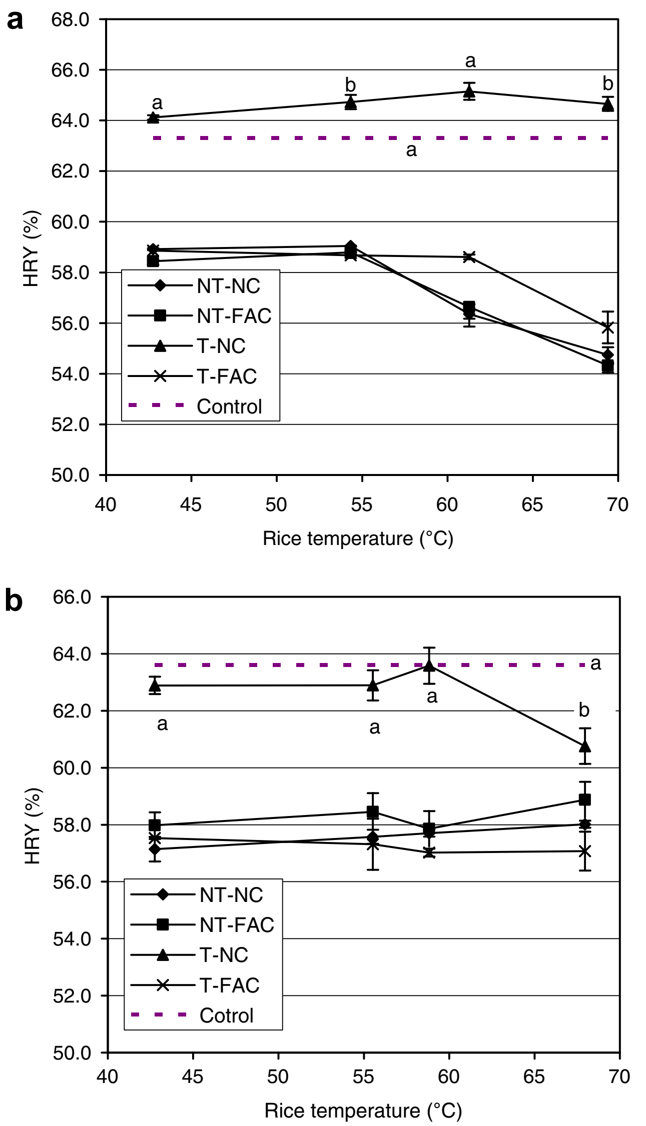

Fig. 6. Head rice yields (HRY) of rice with initial MCs of 20.6% (a) and 25.0% (b) under different drying treatments. (T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling; Values with letter "*a*" were not significantly different from the control sample at $p < 0.05$.)

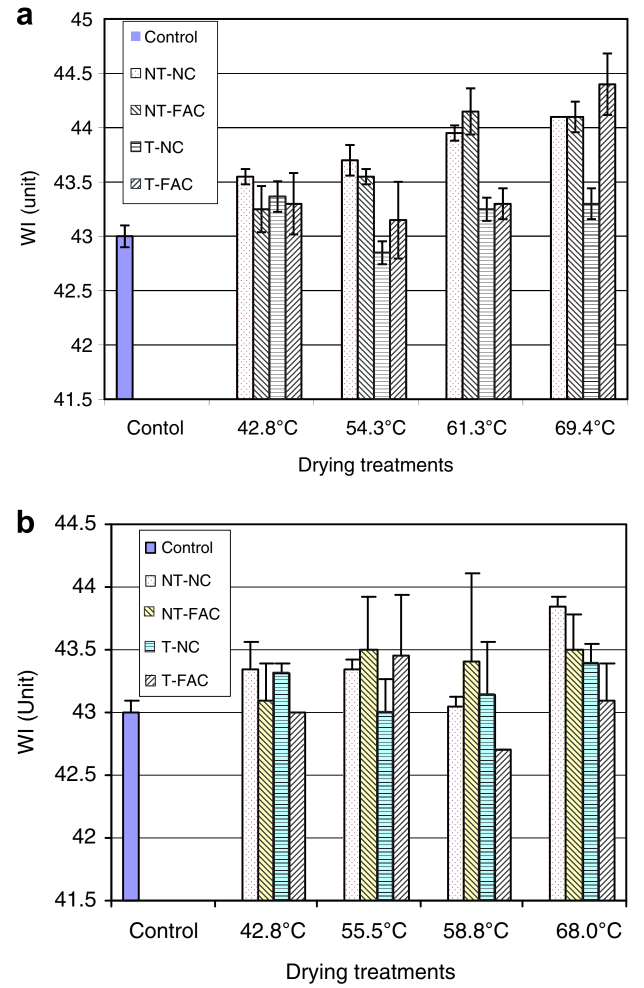

Fig. 7. Whiteness (WI) of milled rice with initial MCs 20.6% (a) and 25.0% (b) under different drying treatments. (T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling.)

moisture removal without lowering rice milling quality (Cnossen et al., 2000; Cnossen et al., 2003). For the current rice drying practice, the drying temperature or heated air temperature is controlled way below 60 °C to avoid creating fissures, lowering the HRY. The reason why the high temperature of IR heating did not damage the rice quality could be due to the relatively uniform heating in the rice kernel resulting from the IR penetration, resulting in a lower moisture gradient compared to conventional heated air drying. The results indicate 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.

This research also showed that the cooling method following the tempering was very important. Rapid cooling using forced air can significantly lower the rice milling quality. Because a relative large amount of moisture was removed during forced air cooling, the cooling might regenerate significant moisture and temperature gradients causing fissures (Ban, 1971; Kunze & Choudhury, 1972; Kunze, 1979). Based on the glass transition hypothesis, the temperature and moisture at the rice surface were lowered first, and the starch reached a glassy state during cooling. At the same time, the temperature and moisture at the centers of the rice kernels were still relatively high, and the starch remained in a rubbery state. The differences in the thermomechanical properties of the starch at different stages would generate stresses and fissures, resulting in breakage during milling and a lower rice milling quality (Perdon et al., 2000; Siebenmorgan et al., 2004). Therefore, controlled slow cooling will be very important for high temperature rice drying. Since the natural cooling effectively preserved the quality, controlled slow cooling could be accomplished by low rates of air flow through a bin of rice.

3.4. Effectiveness in disinfestation

The disinfestation results clearly showed the adult moths were less heat resistant than the adult lesser grain borers (Tables 1 and 2). The 60 and 90 s heating times resulted in the deaths of moths in all stages in the rice with both the initial MCs. Only a few adult moths survived the low temperature treatments. It was also observed that some adult moths developed from the eggs or first-stage larvae during the incubation of the low MC rice that had a 25 s heating treatment. For grain borers, 90 s of heating, regardless of tempering, and 60 s of heating with tempering achieved a near 100% kill rate even though a total of 4 inactive grain borers were found in all the samples under such treatments. With the low temperature treatments, significant numbers of live adult grain borers were discovered during the first week of the incubation, which were believed to be adult grain borers that survived the treatments. The results obtained agreed with reported results that the time to death of the insects was less than 1 min when they were heated to a temperature above 62 °C (Banks & Fields, 1995; Fields & Muir, 1996). Based on the disinfestation

Table 1
Numbers of live moths in the rice samples with different drying treatments[a]

Harvest MC (%)	Heating time (s)	Rice temperature (°C)	Tempering	Days of storage after treatment						
				1[b]	5	8	15	27	32	34
20.6%	90	69.4	Yes	0	0	0	0	0	0	0
	90	69.4	No	0	0	0	0	0	0	0
	60	61.3	Yes	0	0	0	0	0	0	0
	60	61.3	No	0	0	0	0	0	0	0
	40	54.3	Yes	0	0	0	0	0	8	2.5
	40	54.3	No	0.5	0	0	0	0	0	0
	25	49.0	Yes	0	0	0	0	0.5	17.5	3.5
	25	49.0	No	0	0	0	0	0	0.5	0
25.0%	90	68.0	Yes	0	0	0	0	0	0	0
	90	68.0	No	0	0	0	0	0	0	0
	60	59.1	Yes	0	0	0	0	0	0	0
	60	59.1	No	0	0	0	0	0	0	0
	40	55.5	Yes	0.5	0.5	0	0	0	0	0
	40	55.5	No	0	0	0	0	0	0	0
	25	49.0	Yes	1	1	0	0	0	0	0
	25	49.0	No	0	0	0	0	0	0	0

[a] Numbers are the average numbers of moths recovered from two samples at each treatment condition.
[b] Numbers of moths that survived the thermal treatment.

Table 2
Numbers of live grain borers in rice samples with different drying treatments[a]

Harvest MC (%)	Heating time (s)	Rice temperature (°C)	Tempering	Days of storage after treatment						
				1[b]	5	8	15	27	32	34
20.6%	90	69.4	Yes	0	0	0.5	0	0.5	0	0
	90	69.4	No	0	1	0	0	0	0	0
	60	61.3	Yes	0	0	0	0	0	0	0
	60	61.3	No	0	0.5	0	0	0	0	0
	40	54.3	Yes	26	51	1	1	0	0.5	0
	40	54.3	No	0.5	0	0	0	0	0	0
	25	49.0	Yes	45.5	54.5	3.5	1.5	0.5	0	0
	25	49.0	No	50.0	44.5	2	0.5	0.5	0	0
25.0%	90	68.0	Yes	0	0	0	0	0	0	0
	90	68.0	No	0	0	0	0	0	0	0
	60	59.1	Yes	0	0	0	0	0	0	0
	60	59.1	No	2	4.5	0.5	0	0	0	0
	40	55.5	Yes	26	51	1	1.5	0	0.5	0
	40	55.5	No	0	0	0	0	0	0	0
	25	49.0	Yes	58.5	67.5	2.5	1.5	2	0	0
	25	49.0	No	29.5	48.5	0.5	1	1	0	1

[a] Numbers are the average numbers of grain borers recovered from two samples at each treatment condition.
[b] Numbers of grain borers that survived the thermal treatment.

results, it is recommended to heat the rice to 60 °C, followed by tempering, to achieve complete disinfestation of moths and grain borers. Because rice samples heated to 60 °C followed by tempering also had a high rice milling quality, we conclude that IR heating can be used for simultaneous drying and disinfestation of freshly harvested rough rice.

It appeared that non-tempered samples, especially at low temperatures, had fewer insects developing during the incubation than the samples with tempering. This could be due to cooling shock in the non-tempered samples reducing the survival capability of the insects after IR treatment, which needs to further studied.

4. Conclusions

The research showed high rice drying temperatures can be achieved with a relatively short heating time by using a catalytic IR emitter with a single layer of rough rice. The moisture removal during heating increased with an increase in rice temperature. It took only 60 s to achieve a rice temperature of about 60 °C and removal of 1.7% and 1.8% points MC during IR heating alone for the low and high MC rice, respectively. The tempering process after the rapid IR heating and moisture removal is essential to achieve high rice milling quality and improve the amount of moisture removal during cooling. Natural cooling following the tempering treatment can be used to remove a significant amount of moisture while retaining a high rice milling quality. But forced air cooling following heating or tempering could result in lowered rice milling quality, which is not recommended. The recommended conditions for simultaneous drying and disinfestation of freshly harvested rice are a 60 °C rice temperature followed by tempering and slow cooling.

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References

Abe, T., & Afzal, T.M. (1998). Heat and mass transfer characteristics of barley during far infrared radiation drying. *Proceedings of 2nd international workshop on "Control applications in post-harvest and processing technology" (CAPPT'98)*, Budapest, Hungary.

Afzal, T.M., & Abe, T. (1997). Combined convection and far-infrared radiation drying of rough rice. *ASAE Paper No. 9760972*. St. Joseph MI.

Arinze, A., Schoenau, J., & Bigsby, W. (1987). Determination of solar energy absorption and thermal radiative properties of some agricultural products. *Transactions of ASAE, 30*(1), 259–265.

ASAE Standards (1995). *S352.2: 1 Moisture measurements-Unground grain seeds Moisture relationships of grains* (42nd ed.). St. Joseph, MI: ASAE.

Ban, T. (1971). Rice cracking in high rate drying. *Japan Agricultural Research Quarterly, 6*(2), 113–116.

Banks, H. J., & Fields, P. G. (1995). Physical methods for insect control in stored grain ecosystems. In *Stored grain ecosystems* (pp. 353–409). New York, NY: Marcel Dekker, Inc.

Bekki, E. (1991). Rough rice drying with a far-infrared panel heater. *Journal of the Japanese Society of Agricultural Machinery., 53*(1), 55–63.

Bilowicka, E. (1960). *Research concerning the drying of small seeds by infrared radiation. International drying conference*. Warsaw, Poland: Institute of Mechanization and Electrification of Agriculture.

Cnossen, A. G., Siebenmorgen, T. J., Yang, W., & Bautista, R. C. (2000). The glass transaction temperature concept in rice drying and tempering: effect on milling quality. *Transactions of ASAE., 43*(6), 1661–1667.

Cnossen, A. G., Jimenez, M. J., & Siebenmorgen, T. J. (2003). Rice fissuring response to high drying and tempering temperatures. *Journal of Food Engineering, 59*, 61–69.

Das, I., Das, S. K., & Bal, S. (2004a). Determination of mixing index of paddy grains under vibrating conditions. *Journal of Food Process Engineering, 26*(1), 121–133.

Das, I., Das, S. K., & Bal, S. (2004b). Specific energy and quality aspects of infrared (IR) dried parboiled rice. *Journal of Food Engineering, 62*(1), 129–133.

Faulkner, M. D., & Wratten, F. T. (1966). A new system for drying rice. *Rice Journal, 69*(13), 8–10.

Faulkner, M. D., & Wratten, F. T. (1970). The Louisiana State University infrared-preheat rice dryer. 41. In *Proceedings of the 13th Rice Technical Working Group Mtg*. Beaumont, TX: Texas A& M Univ., College Station.

Fields, P. G., & Muir, W. E. (1996). Physical control. In *Integrated management of insects in stored products*. New York, NY: Marcel Dekker, Inc.

Ginzburg, A. S. (1969). *Application of infrared radiation in food processing*. London: Leonard Hill, 174–254.

Hall, C. W. (1962). Theory of infrared drying. *Trans. ASAE, 5*(1), 14–16.

Kirkpatrick, R. L., & Tilton, E. W. (1972). Infrared radiation to control adult stored-product Coleoptera. *Journal of the Georgia Entomology Society, 7*, 73–75.

Kirkpatrick, R. L. (1975). Infrared radiation for control of lesser grain borers and rice weevils in bulk wheat. *Journal of Kansas Entomological Society, 48*(1), 100–104.

Kunze, O. R., & Choudhury, M. S. U. (1972). Moisture adsorption related to the tensile strength of rice. *Cereal Chemistry, 49*(6), 684–696.

Kunze, O. R. (1979). Fissuring of the rice grain after heated air drying. *Transactions of ASAE, 22*(5), 1197–1202, 1207.

Kunze, O. R., & Calderwood, D. L. (1985). Rough rice drying. In *Rice: Chemistry and technology* (pp. 233–263). St. Paul, Minn.: American Association of Cereal Chemists.

Masamure, A., Sado, H., Hoda, T., Shimizu, M., Nabetani, H., Nakajima, M., et al. (1998). Drying of potato by far infrared radiation. *Nippon Shokuhin Kogyo Gakkaishi, 35*(5), 309–314.

Nindo, C. I., Kudo, Y., & Bekki, E. (1995). Test model for studying sum drying of rough rice using far-infrared radiation. *Drying Techology, 13*(1& 2), 225–238.

Parrouffe, J. M., Dostie, M., Mujumdar, A. S., & Poulin, A. S. (1992). Convective transport in infrared drying. In *Proceedings of the 8th international drying symposium* (pp. 695–703). Montreal, Quebec: Elsevier Science.

Perdon, A., Siebenmorgan, T. J., & Mauromoustakos, A. (2000). Glassy state transition and rice drying: Development of a brown rice state diagram. *Cereal Chemistry, 77*(6), 708–713.

Rao, O. N. (1983). Effectiveness of infrared radiation as a source of energy for paddy drying. *Journal of Agricultural Engineering, 20*(2), 71–76.

Schroeder, H. W. (1960). Infrared drying of rough rice. II. Short-grain type: Calrose and Caloro. *Rice Journal, 63*(13), 6–8, 25–27.

Schroeder, H. W., & Rosberg, D. W. (1960). Infrared drying of rough rice. I. Long-grain type. Rexoro and Bluebonnet-50. *Rice Journal, 63*(12), 3–5, 23–27.

Schroeder, H. W. (1961). Infrared drying of rough rice. III. Medium-grain type. Nato and Magnolia. *Rice Journal, 64*(1), 11, 12, 24–27.

Sharma, G. P., Verma, R. C., & Pathare, P. B. (2005). Thin-layer infrared radiation drying of onion slices. *Journal of Food Engineering, 67*(3), 361–366.

Siebenmorgan, T. J., Yang, W., & Sun, Z. (2004). Glass transition temperature of rice kernels determined by dynamic mechanical thermal analysis. *Transactions of ASAE, 47*(3), 835–839.

Stipe, D. R., Wratten, F. T., & Miller, M. F. (1972). Effects of various methods of handling brown rice on milling and other quality parameters. *Louisiana Agricultural Experiment Station Annual Program* Rep., Rice Exp. Stn. 113

Tilton, E. W., & Schroeder, H. W. (1963). Some effects of infrared irradiation on the mortality of immature insects in kernels of rough rice. *Journal of Economic Entomology, 56*, 727–730.

USDA Federal Grain Inspection Service (1994). *Rice Inspection Handbook*. Agricultural Marketing Service. Washington D.C.

Zhu, K., Zou, J., Chu, Z., & Li, X. (2002). Heat and mass transfer of seed drying in a two pass infrared radiation vibrated bed. *Heat Transfer-Asian Research, 3*(12), 141–147.