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Simultaneous Rough Rice Drying and Disinfestation Using Infrared Radiation

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Abstract. *The objective of this study was to investigate the drying characteristics, milling quality, and disinfestation effectiveness of rough rice under infrared (IR) radiation heating. Freshly harvested medium grain rice (M202) samples with low (20.6%) and high (25.0%) moisture contents (MC) 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 infrared emitter. The effects of tempering treatment and natural and forced air cooling methods on moisture removal, milling quality and disinfestation were also determined. High heating rate and corresponding high moisture removal were achieved by using the IR heating. After heating, tempering increased moisture removal during cooling and improved milling quality of the rice samples. For example, 60 s of IR heating of 20.6% MC rice resulted in 61.2°C rice temperature, 1.7 percentage MC removal during the heating period and additional 1.4% MC removal after tempering and natural cooling. The rice also had 1.9 percentage higher head rice yield than control sample dried with room air. The heating and tempering treatment also completely killed the tested insects. However, rice samples without tempering or cooled with forced air after tempering had much lower milling quality than the control. Simultaneous drying and disinfestation with high rice milling quality can be achieved by using the catalytic IR to heat the rough rice to 60°C followed by tempering and slow cooling.*

Keywords. Rough rice, Quality, Drying, Disinfestation, Infrared, Temperature.

Introduction

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

When rough rice is dried with heated air, more moisture near the surface of rice kernel is removed than near the center, which creates a moisture gradient in the rice kernel. High moisture gradient occurs with the drying process having a large amount of moisture removal in a single drying pass and/or high drying air temperature used to achieve high drying rate. The moisture gradient could induce the tensile and compressive stresses resulting in fissure after cooling and lowering head rice yield and milling quality (Ban, 1971; Kunze and Choudhury, 1972; Kunze, 1979). Therefore, the current rice drying practice normally uses multiple drying passes by removing 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 to 20 min to minimize the moisture gradient generated during drying (Kunze and Calderwood, 1985). After each drying pass, the heated rice is tempered by keeping the rice for 4 to 24 h at the heated temperature to allow the moisture inside rice kernel to become equilibrium before it is further dried. However, it was also reported that the reduction 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 certain amount of moisture can be quickly removed with high temperature without significantly lowering the head rice yield (Stipe et al., 1972).

Based on the thermomechanical properties, such as expansion ratio and specific volume, of starch varying with moisture content and temperature, a glass transition hypothesis has been proposed and investigated for rice drying (Perdon et al., 2000; and Siebenmorgen et al., 2004). The research results have shown that rough rice could be dried with high air temperature (60°C) at rubbery state or above glass transition temperature to remove a large amount of moisture in single pass without reducing the head rice yield (Cnossen et al., 2000; Cnossen et al., 2003). However, in commercial practice it is difficult to quickly and uniformly heat the rice to a high temperature in the convective drying because rice is not in 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 et al., 1992). However, infrared (IR) radiation heating may provide a solution for achieving fast and relatively uniform heating due to IR radiation and heat penetration resulting in quick moisture removal with reduced moisture gradient in rice kernels and improved milling quality.

IR radiation heating offers many advantages over conventional drying methods under similar drying conditions, such as high heating rate and energy efficiency (Bilowicka, 1960; Ginzburg, 1969; Masamura et al., 1988; Abe and Afzal, 1997; Afzal and Abe, 1998). When it is used to heat or dry moist materials, the radiation impinges 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 rice kernel and may reduce the moisture gradient during heating and drying. Also, since IR does not heat up the medium, the temperature of rice kernel is not limited by the wet bulb temperature of surrounding air and the rice kernel can be quickly heated to high temperature.

The earliest research using IR for rough rice drying was reported in early 1960s (Schroeder and Rosberg,1960; Schroeder, 1960 and 1961; Hall, 1962; Faulker and Wratten, 1966 and 1970). High drying rate of rice was achieved by spreading the rice in a single layer. When the IR was used to preheat rough rice to 60°C followed by 49°C heated air drying for 2-3 min, approximately 2% MC was removed by each drying pass. However, most of the early research used combustion of natural gas or propane as the radiation source which was a great safety concern in practical drying applications. This problem can now be resolved by using catalytic infrared emitter. It has also been reported that it took only 7 minutes to reduce the moisture content from 20% to 14.8% (db) using near infrared heating compared to 30 minutes used for hot air drying (Rao, 1983). Recently, most IR research for drying agricultural products used medium and far infrared with wavelength of 2-100µm for drying agricultural products (Arinze et al., 1987; Nindo el al., 1995). It was found that the maximum absorption of infrared radiation by medium grain rough rice occurred at a wavelength of 2.9 µm (Bekki, 1991). Due to limited penetration capability of IR, mixing is necessary if rice is dried with thick bed for achieving uniform heating of rice (Nindo et al., 1995). Recently, similar research was conducted with parboiled rice (Das et al., 2003 and 2004). Since the infrared can be used to quickly heat rough rice with single or thin layer to a relatively high temperature, it is 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 more energy efficient. However, no reported research has focused on this possibility.

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 3 species of insects commonly found in rice to IR and achieved complete mortality with rice temperatures ranging from 65°C and 70°C. It was also reported that adult beetles were killed by IR at 57°C (Kirkpatrick and 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 hours. Because rough rice could be infested with insects before and when it is harvested, it is ideal to kill all insects during drying without needing any additional disinfestation treatments for extending the rice storage life. IR heating provides a great possibility to perform simultaneous drying and disinfestation for rough rice.

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

Materials and methods

Rough Rice and Infestation Methods

Freshly harvested medium grain rice, M202, obtained from Farmer's Rice Cooperative (West Sacramento, CA) was used for conducting the IR drying and disinfestation tests. The moisture content of rough rice was 25.0±0.3% (high MC) at the harvest. The rice sample with the high MC was equally divided into two portions. In order to obtain one rough rice sample with low initial MC, the other portion of the sample was slowly dried to 20.6±0.2% (low MC) with room temperature from 17°C 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 rice bed on the floor was less than 5 cm. During the slowing drying the rice was mixed frequently to ensure uniform drying. It took about three days to reach the 20.6% MC. Then the rice samples with both low and high MC 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 the test time. The drying and disinfestation tests were separately conducted using non-infested and infested samples. All reported moisture contents are on wet weight basis and 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 (Rhizopertha dominica), and 50 adult angoumois grain moths (Sitotroga cerealella), the most common insects in rough rice. The insects collected from naturally infested rough rice were emerged at the Entomology Laboratory, Department of Entomology, University of California, Davis. The rice samples contained both adult insects and their eggs at the time of disinfestation treatment using infrared heating.

Infrared Heating Treatment

A catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as infrared 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 dimension of the emitter was 30 x 60 cm with surface temperature at about 730°C and corresponding peak wavelength of 3.6 µm assuming a blackbody. An aluminum box with dimension of 65 cm (length) x 37 cm (width) x 45 cm (height) was installed around the emitter as wave guide to achieve a uniform IR intensity at the rice bed surface. The rice bed was set at 5 cm below the bottom edge of the wave guide. The average IR intensity at the rough rice bed surface was 5348 W/m2, which was measured by using Ophir FL205A Thermal Excimer Absorber Head (Ophir, Washington, MA). The drying bed was made with a 3 mm thick aluminum plate for minimizing the radiation energy loss through the drying bed due to its high reflectively. The reflected radiation energy could also be used to heat the bottom side of rice kernels. A piece of plywood was installed beneath the aluminum plate for reducing 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 corresponding calculated loading rate of 2 kg/m2.

Both high and low MC rough rice samples were used for the drying and disinfestation tests. For measuring the drying characteristics and milling quality, sixteen non-infested rice samples were heated for each of the four time durations, 15, 40, 60 or 90 s with initial drying bed surface temperature of 35°C. The rice sample weights were measured with a balance with two-decimal accuracy before and after heating. The weight loss during heating and the original moisture content were used to calculate the moisture removal during the heating periods. The moisture removal was calculated as the difference between the original MC and the MC after treatment and reported as a percentage point. For disinfestation tests, because the rice temperature under 15 s heating was too low to kill the insects, eight infested rice samples were heated for each of the durations of 25, 40, 60 and 90 s. The grain temperature with 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 to 13.6% from the original moisture contents.

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 numbers 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 rice samples in closed containers placed in an incubator with a temperature as same as the heated rice for 4 h immediately following the heating. For non-infested rice samples, four samples were each cooled using natural cooling (slow cooling) or forced air cooling at room temperature of 20°C to 24°C 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 air velocity of 0.1 m/s. All forced air cooling samples were cooled for 5 min. After the natural and forced air cooling processes, the temperatures of rice samples were close to the room air temperature. 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 moisture contents after corresponding IR heating treatments. The cooled samples were stored in polyethylene bags before they were further dried to 13.3±0.2% MC using room air. Two samples of each original weight of 250 g under each treatment were combined into one sample with a total weight more than 400 g for milling quality and disinfestation evaluation, which resulted in two samples under each treatment for the tests. The samples were stored in Ziplock bags at room temperature for about one month before milling. In order to avoid losing insects during handling, in the disinfestation tests the infested rough rice samples were only cooled with natural cooling after heating or tempering.

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 effect of different treatments, the non-infested rice samples of 400 g each were dehulled and milled by using Yamamoto Husker (FC-2K) and Yamamoto Rice Mill (VP-222N, Yamamoto Co. Ltd., Japan). The rice samples were milled three times to achieve the well milled rice as defined by the Federal Grain Inspection Service (USDA FGIS, 1994). For the first two times, the settings of Throughput and Whitening were 1 and 4, respectively. For the third time, the settings were 1 and 5. The evaluated milling quality indicators included total rice yield, head rice yield, and Whiteness Index (WI). The HRY was determined with Grainchecker (Foss North America, Eden Prairie, MN). The WI was used to evaluate the whiteness (degree of milling) of milled rice and determined with the Whiteness Tester, C-300, (Kett Electronic Laboratory, Tokyo, Japan). High index number indicates whiter milled rice. All quality evaluations were conducted at Farmer’s Rice Cooperative (West Sacramento, CA).

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 surviving insects and eggs to emerge. All jars were kept in incubators at 28°±2°C with 64±3% relative humidity (RH) to allow development of surviving insects and eggs (Kirkpatrick, 1975). The populations of the surviving and emerged live adult insects were visually counted one day after the treatment and then every several days for 35 days 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 combing two original samples, the original numbers of insects were doubled in each incubated sample.

Results and Discussions

Moisture Removals under 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, 69.4°C, and 42.8, 55.5, 59.1, 68.0°C, respectively. The low MC rice samples had slightly higher temperatures than the high MC rice samples at 60 and 90 s heating, which could be due to less energy used for heating the water and a lower evaporative cooling effect in the low MC rice than the high MC rice under the constant radiation heat supply. The maximum difference in temperatures of the samples with different original MC under the same heating duration was 2.2°C. The average temperatures of low and high MC rice samples at different heating durations are presented in fig. 1. A high correlation between the average rice temperature and heating time was obtained with a power model. 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 when the drying bed temperature 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 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.

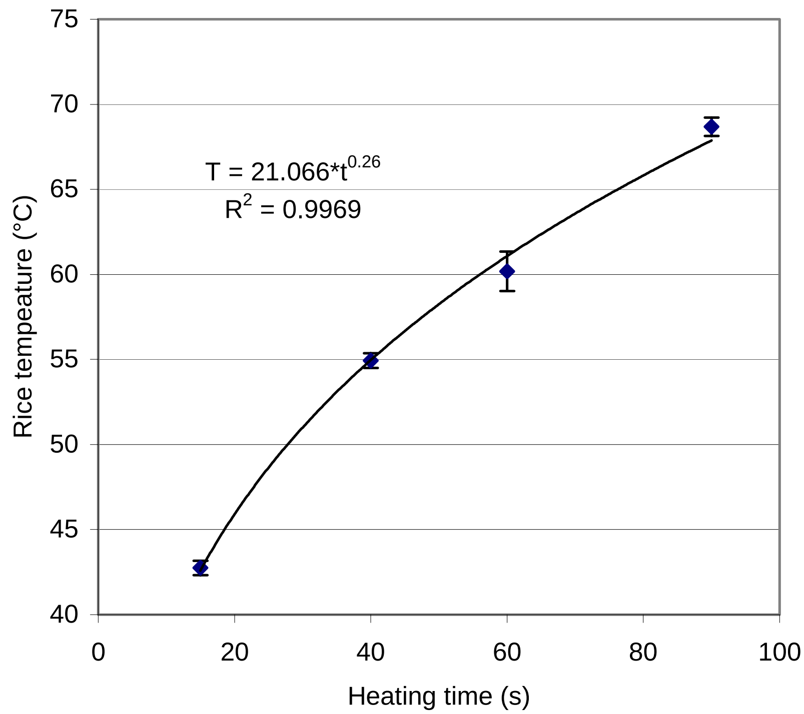

Figure 1. Relationship between rice temperature and heating time

The trend of high moisture removal for the high MC rice samples was clearly shown in fig. 2 even though the difference between the low and high moisture rice samples was relatively small. With 90 s heating (average temperature of 68.7°C), the moisture removal was 2.8 and 2.5 percentage points for the high and low MC rice samples. It is important to notice that the average drying rates of the rice samples with initial 25% and 20.5% MCs were 2.4, 1.8, 1.7, and 1.7 percentage points per minute at the moisture removal levels of 0.6, 1.2, 1.7, and 2.6 percentage points by each drying pass. The high drying rate at relative high moisture removal levels by each drying pass, for example of 1.7 percentage points per min at 1.7 and 2.6 percentage point MC removal, was much higher than that of current commercial, conventional heated air drying of 0.1 to 0.2 percentage points per min due to low heated air temperature used (Kunze and Calderwood, 1985). The high drying rate was achieved by using IR heating alone even without counting the moisture removal during cooling.

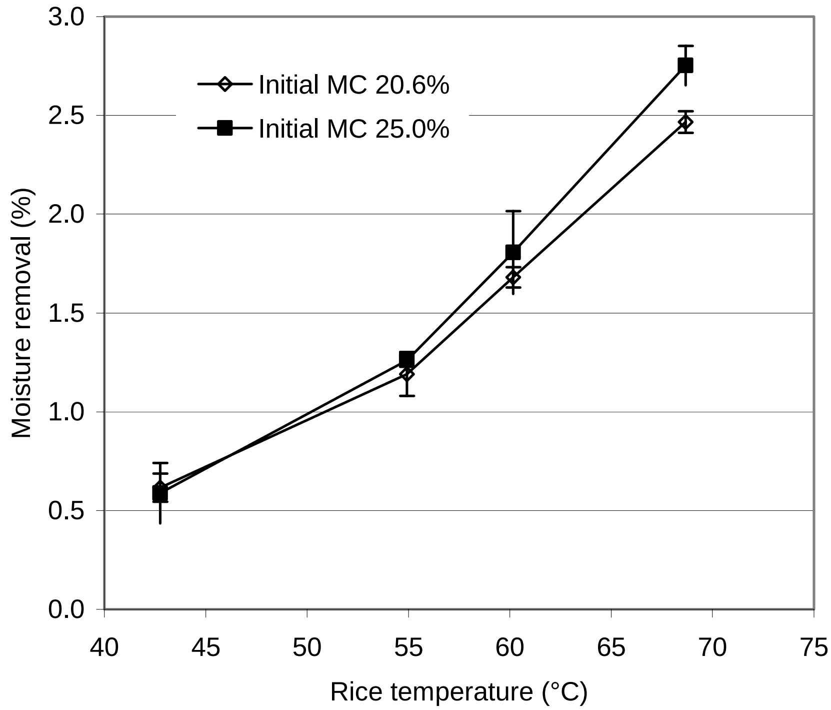

Figure 2. Moisture removals of rice samples with different initial moisture contents after heated to various temperatures

Moisture Removals under Different Tempering and Cooling Treatments

The clear trends of tempering vs. non-tempering and natural cooling vs. forced air cooling are seen in figs. 3 and 4. For low MC rice, the moisture removals of tempered rice samples under natural cooling and forced air cooling were 0.6 to 1.3 and 1.1 to 1.9 percentage points, respectively, in the tested temperature range from 42.8°C to 69.4°C. In contrast, the non-tempering rice had 0.4 to 0.8 and 0.7 – 0.9 percentage point moisture removals under natural cooling and forced air cooling, respectively. The tempering resulted in 0.2 to 0.5 percentage point more MC removals than non-tempering, which showed that tempering treatment significantly improved the moisture removal during cooling compared to non-tempering samples. The forced air cooling also had more moisture removal up to 0.9 percentage points 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 percentage point moisture removal and moisture diffusion in the rice kernels became limited factor for further improving the drying rate by using increased drying force of forced air cooling.

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

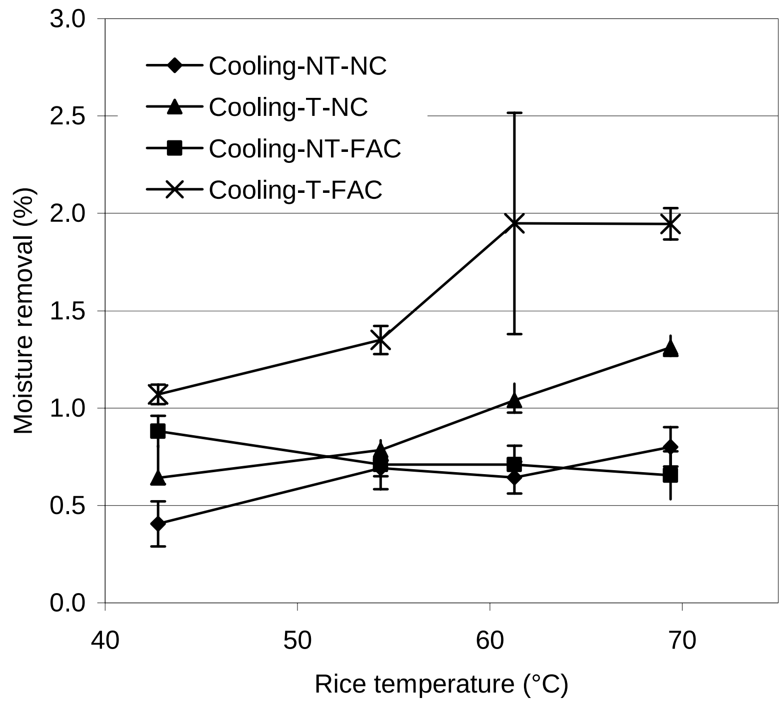

Figure 3. Moisture removal of rice with initial MC of 20.6% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

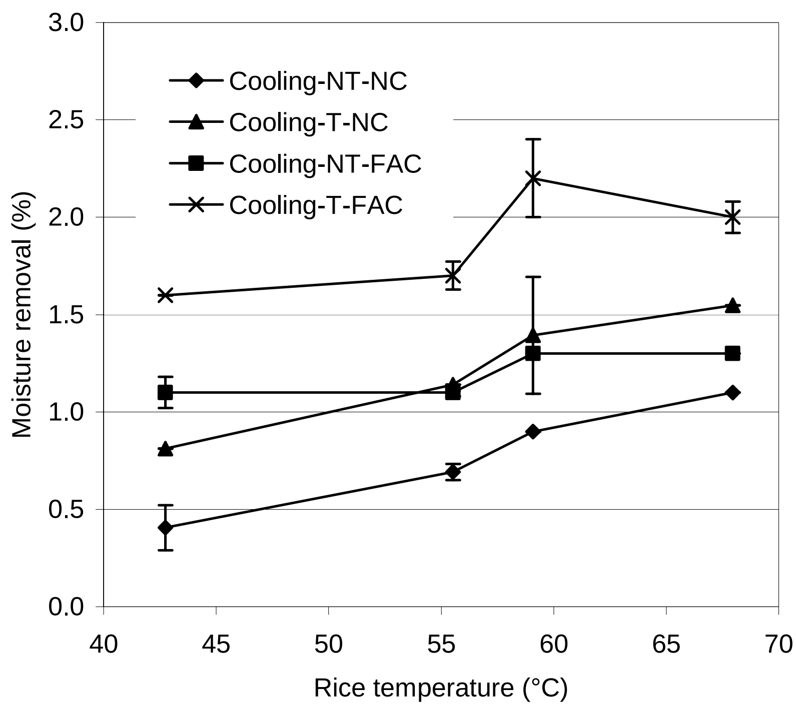

Figure 4. Moisture removal of rice with initial MC of 25.0% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

percentage points for natural cooling compared to 1.1 to 1.3 percentage points for forced air cooling and 0.4 to 1.1 percentage points for natural cooling of non-tempered rice in the tested temperature range. The tempering treatment resulted 0.4 to 0.5 and 0.5 to 0.9 percentage points more moisture removals than the non-tempering treatment under natural cooling and forced air cooling, respectively. The results indicate that tempering is even more important for high MC rice than low MC rice to have high MC removal during cooling.

Based on the above results, the tempering process reduced the moisture gradient in 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 low moisture content near the surface, which resulted in less moisture removal during cooling. In general, both reduced moisture gradient in the tempered rice kernels and forced air cooling increased the moisture removal during the cooling process. Therefore, the tempering process is a critical step to increase the 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 the high moisture removal could cause rice fissures lowering rice milling quality which 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 (figs 5 and 6). The highest total MC removals of rice were 1.7 to 4.4 and 2.2 to 4.8 percentage 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 were generally occurred for rice experienced non-tempering and natural cooling treatment. For rice treated with

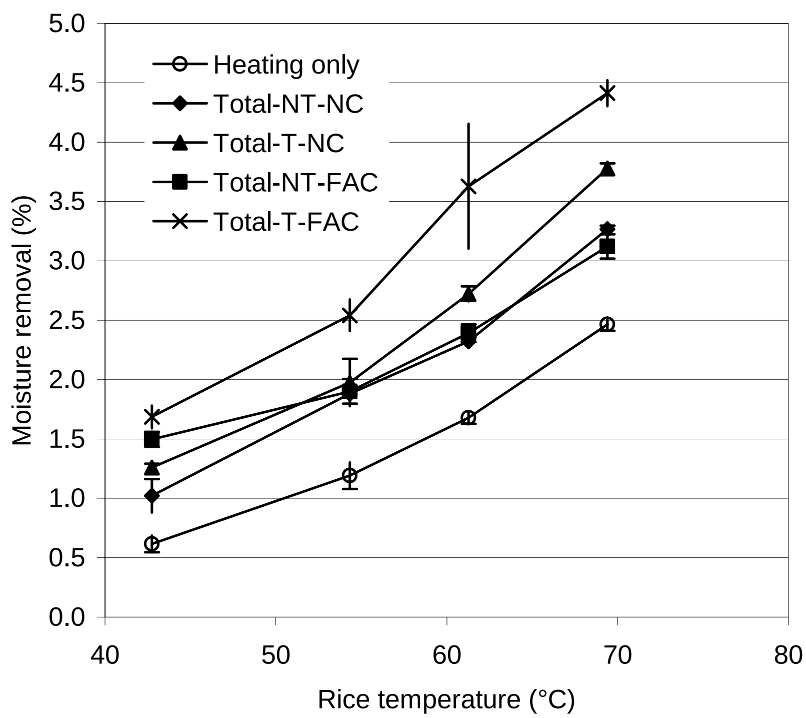

Figure 5. Total moisture removal of rice with initial MC of 20.6% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

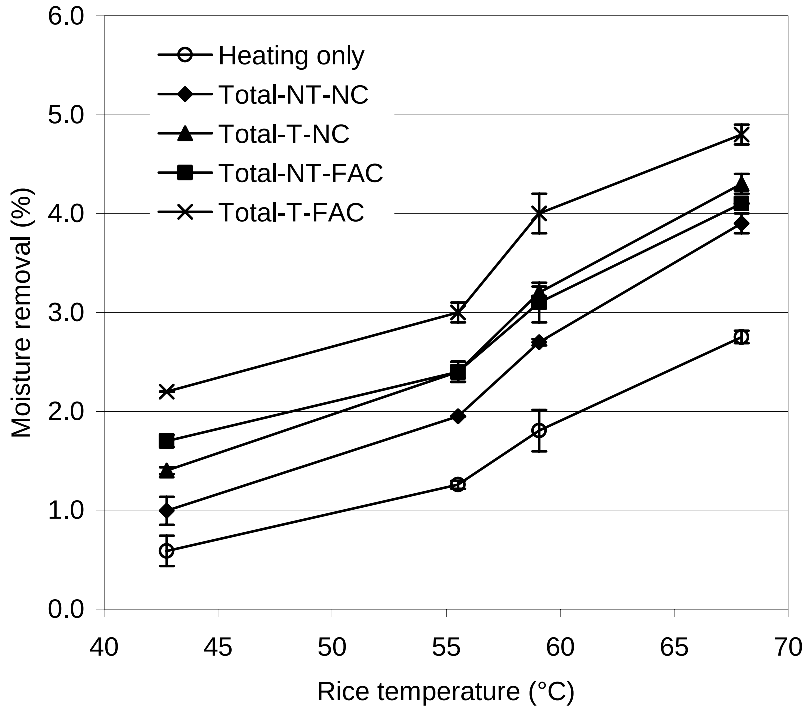

Figure 6. Total moisture removal of rice with initial MC of 25.0% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

tempering and natural cooling, the total moisture removals were 1.4, 2.4, 3.2 and 4.3 percentage points for the high MC rice and 1.3, 2.0, 2.7 and 3.8 percentage points for the low MC rice under 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 to 3.2 percentage point moisture were removed with 1 min heating followed by tempering and natural cooling. The drying rates were much higher than the 2 to 3 percentage point moisture removal with 15 to 20 min heating of the current conventional hot air drying.

Compared to the 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 were heated for 60 s (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.

Milling Quality

In general, for both the high and low initial moisture rice samples, infrared dried rice with tempering followed by natural cooling had similar and higher TRY compared to the control (figs. 7 and 8). On average, the TRYs of low and high MC rice dried by using IR followed with natural cooling were 68.0% and 68.1%, respectively, which were 0.3 and 0.7 percentage points more than the controls. Especially, the rice dried at about 60°C with natural cooling had the highest TRYs of 68.4% for low moisture rice and 68.6% for high moisture 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 to1.2 percentage points more than the control. However, the samples treated with other methods had much lower TRYs than the controls, especially for the rice with the low MC dried under the high temperature.

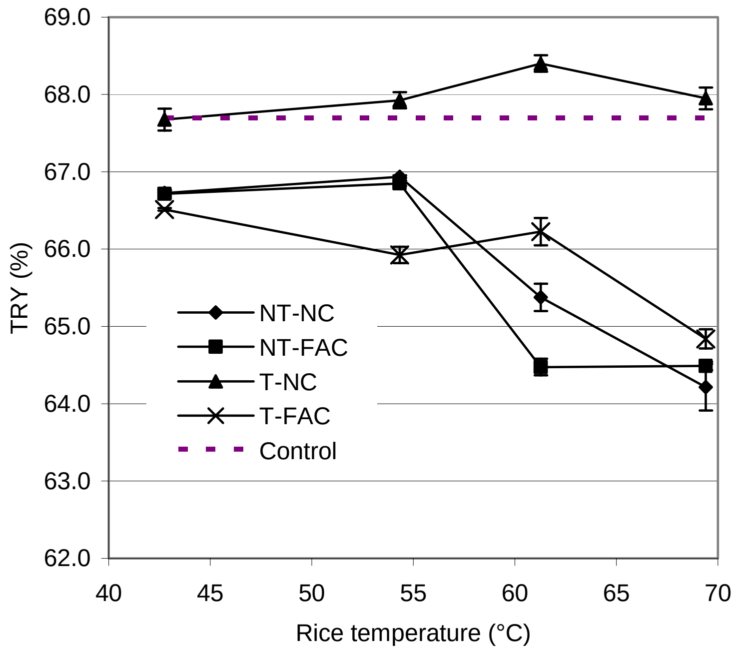

Figure 7.   Total rice yields of rice with 20.6% initial moisture content and different drying treatments
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

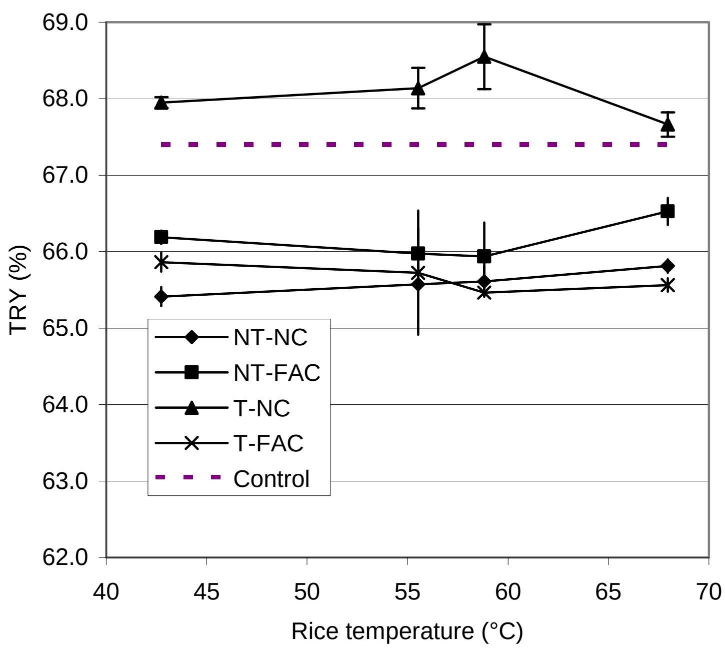

Figure 8.   Total rice yields of rice with 25.0% initial moisture content and different drying treatments

Similar trends were also observed for the HRYs (figs. 9 and 10). The low MC rice samples dried using IR with tempering and natural cooling had significantly higher HRY (0.6 to 1.9

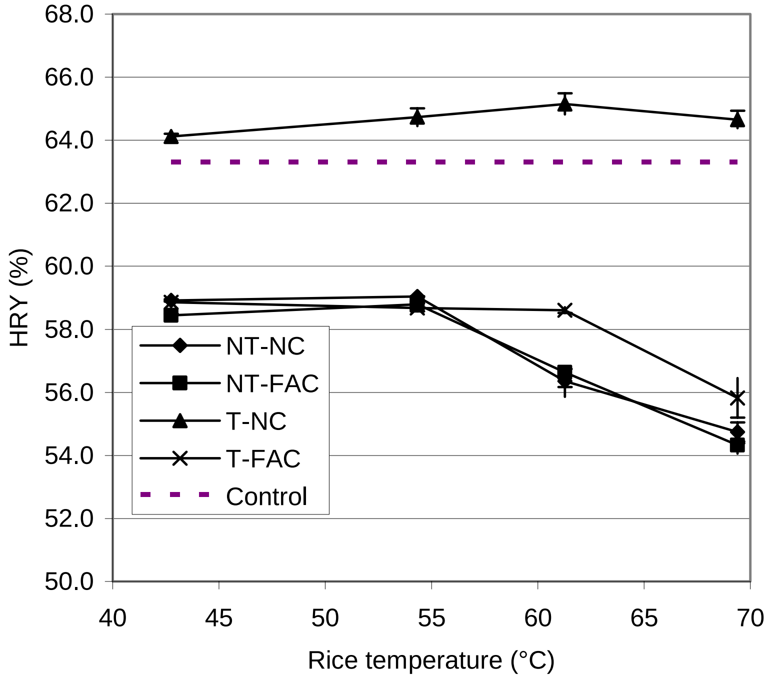

Figure 9. Head rice yields of rice with 20.6% initial moisture content and different drying treatments

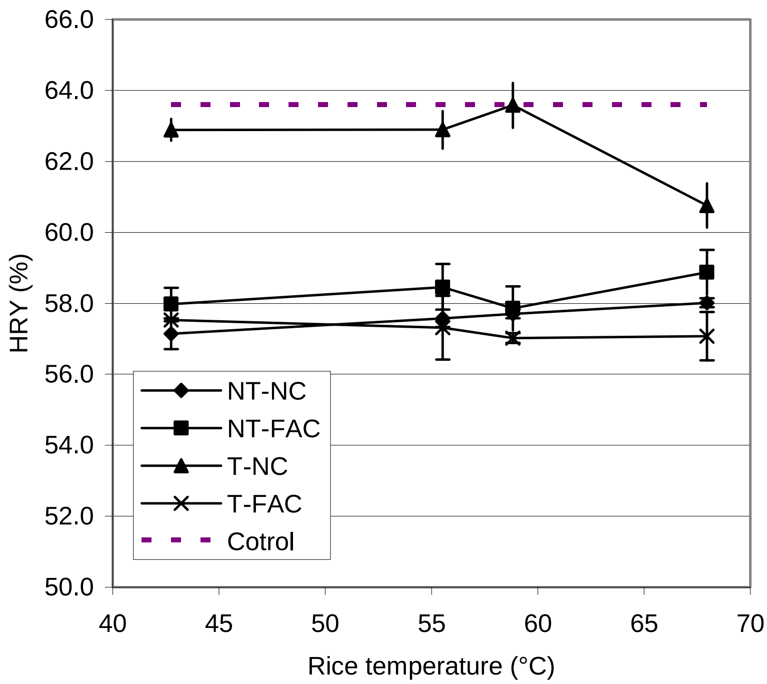

Figure 10. Head rice yields of rice with 25.0% initial moisture content and different drying treatments

percentages) than the control and the highest HRY of 65.2% was obtained with 61.2°C of rice temperature. For the high moisture 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 results of the WI of milled rice were examined, it can 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 the some of the treated rice samples were not significant (figs. 11 and 12). This indicated that most of IR dried rice with tempering followed my natural cooling had a similar milling degree to the control. It seems that there is the trend that WI increased with the increase of the rice drying temperature for the non-tempering treatment, especially for the low MC rice. This could be due to the difference in the hardness of rice with 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 rice can be dried by using IR followed by tempering and natural cooling to achieve superior rice milling quality. It is recommended that the rice temperature of IR heating is controlled at close or below 60°C. For the current rice drying practice, the drying temperature or heated air temperature is controlled away below the 60°C to avoid creating fissures lowering HRY. The reason that the high temperature of IR heating did not damage 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 indicate 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 for minimizing the moisture gradient. When a large amount of moisture is removed during IR heating, tempering is very important to reestablish the moisture equilibrium in rice kernels.

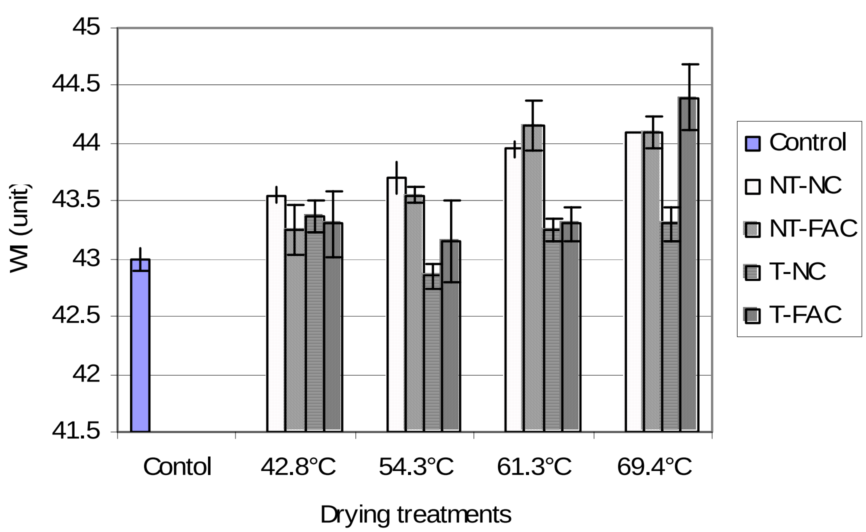

Figure 11. Degree of milling rice with 20.6% initial moisture content and different drying treatments

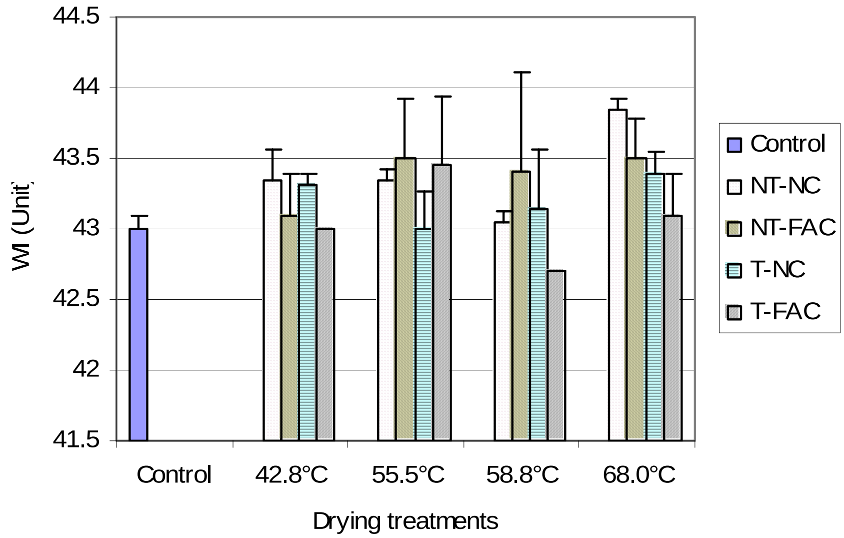

Figure 12. Degree of milling of rice with 25.0% initial moisture content and different drying treatments

This research also showed that the cooling method following the tempering was also very important. The rapid cooling by 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. Also, based on the glass transition hypothesis, the temperature and moisture at the rice surface were lowered first and starch reached glassy state during cooling. At the same time the center temperature and moisture of rice kernel were still relatively high and starch was remained at rubbery state. The differences in thermomechanical properties of starch at different stages would generate stress and fissure resulting in breakage in milling and lowered rice milling quality. 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 to cause cooling.

Effectiveness in Disinfestation

The disinfestation results clearly showed adult beetles were more heat resistant than the adult moths (tables 1 and 2). The 60 and 90 s heating killed moths in all stages in the rice with both the initial MCs. Only a few of adult moths survived the at the low temperature treatments. It was also observed some adult moths developed from the eggs or 1st-stage larvae during the incubation for the low MC rice with 25 s heating treatment. For beetles, the 90 s heating regardless of tempering or non-tempering and 60s heating with tempering achieved near 100% kill even though total 4 inactive beetles were found in all samples under such treatments. With the low temperature treatments, significant numbers of live adult beetles were discovered during the first week of the incubation, which were believed to be the adult beetles survived the treatments. The obtained results agreed with the reported results that the death time of insects was less than 1 min if they are heated to temperature above 62°C (Banks and Fields 1995, Fields and Muir 1996). Based on the disinfestation results, it is recommended to heat rice to 60°C followed by tempering to achieve complete disinfestation of moths and beetles. Because the 60°C rice temperature followed by tempering also had high rice milling quality, it is

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 insects recovered from two samples at each treatment condition
[b] Numbers of insects that survived the thermal treatment

Table 2. Numbers of live beetles 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 insects recovered from two samples at each treatment condition
[b] Numbers of insects that survived the thermal treatment

concluded that IR heating can be used for simultaneous drying and disinfestation for freshly harvested rough rice.

It also appeared that non-tempered samples, especially at low temperatures, had fewer insects developed during the incubation than the samples without tempering. This could be due to the cooling shock of the non-tempering reduced the surviving capability of the insects after the IR treatment, which needs to further studied.

Conclusions

The research showed high rice drying temperature can be achieved with a relatively short heating time by using catalytic IR emitter with single-layer of rough rice. The moisture removal during heating increased with an increase in rice temperature. It took only 60 s to achieved about 60°C rice temperature and removed 1.7 and 1.8 percentage point MC during 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. The natural cooling following the tempering treatment can be used to remove a significant amount of moisture with high rice milling quality. But the 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 were 60°C rice temperature followed by tempering and natural cooling.

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