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ORIGINAL PAPER

# Improvement in Shelf Life of Rough and Brown Rice Using Infrared Radiation Heating

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**Abstract** The objective of this study was to investigate the effect of infrared (IR) heating and tempering treatments on storage stability of rough and brown rice. Samples of freshly harvested medium grain rice variety M206 with initial moisture content of 25.03±0.21 % (d.b.) were used. They were dried using IR, hot air at 43 °C, and ambient air for comparison. For IR drying, rice were heated to temperature of 60 °C under radiation intensity of 4685 W/m$^2$, followed by 4 h tempering and natural cooling. The dried samples were divided into two portions, which were respectively used as rough and brown rice for storage at 35±1 °C with relative humidity of 65 ±3 % for 10 months. The drying characteristics and milling quality of rice were determined. Free fatty acid, peroxide value, and iodine value were determined to detect any notable degradation of lipids in rough and brown rice during storage. High heating and drying rates of rice were achieved under IR heating. It took only 58 s to heat rough rice to temperature of 60 °C with a corresponding moisture removal of 2.17 percentage points during IR heating. The total moisture removal after natural cooling reached to 3.37 percentage points without additional energy input. IR drying did not show any adverse effects on milling quality of the dried rice. Additionally, it resulted in an effective inactivation of lipase, and consequent improvement in the long-term storage stability of rough and brown rice was achieved under accelerated storage condition. It is concluded that the improvement in rough and brown rice stability during storage can be achieved through drying rough rice using IR heating to temperature of 60 °C followed by tempering for 4 h and natural cooling. IR drying provides a potential to store brown rice instead of rough rice with extended shelf life and reduced cost.

**Keywords** Rice · Drying · Storage · Infrared heating · Shelf life · Milling quality

## Introduction

Rice is cultivated in more than 100 countries with a total production of more than 700 million tons of rough rice (RR) (FAO, 2012). After harvest, rough rice is normally dried using hot air or ambient air and then stored in silo or warehouse for an extended duration to meet the supply need for daily consumption of our society with ensured food safety and quality (Patindol et al. 2005). Most of rough rice is consumed as white (milled) rice. Recently, there is an increasing trend to consume

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brown (unmilled) rice due to its higher nutrition value than that of white rice. Many nutrients are in the rice bran layer, including unsaturated fatty acids, vitamins, dietary minerals, and fibers. When the bran layer is exposed to external environment, enzymatic activity may increase and cause the acceleration of lipid degradation during storage period, which reduces the sensory quality of rice.

It is known that the degradation of lipid in rice kernels caused by enzymatic activity during storage is responsible for many deteriorative changes of rice (Piggott et al. 1991; Shin et al. 1986; Tananuwong and Lertsiri 2010; Tananuwong and Malila 2011; Yoshida et al. 2011; Dautant et al. 2007; Suzuki et al. 1996). To preserve the brown rice from undesirable changes, it is stored at 15 °C or less (Genkawa et al. 2008). Alternatively, brown rice is packaged using different methods including heat-sealed can, bags, and vacuum bags (Sharp and Timme 1986). These measures could effectively minimize the rancidity and maintain stability of brown rice during storage. Whereas, the high cost of these storage methods, including the energy consumption, package materials, and instruments, lead to reduced affordability of the brown rice for consumers. Comparing to storing rough rice, if rice can be stabilized and stored as brown rice form at ambient temperature for a long period, it could save more than 30 % of storage space and reduce by 20 % weight during storage and transportation (Malekian, et al 2000; Thakur and Gupta 2006). It can also eliminate the need in cooling during brown rice storage. Therefore, there is a great need to develop a drying method that can achieve a simultaneous drying and effective inactivation of lipase and extend shelf life of rough and brown rice.

Rice is normally dried with hot air (HA) for high drying rate or ambient air (AA) for high milling quality. However, these methods cannot inactivate the lipase enzyme due to low temperature. Comparatively, infrared (IR) radiation heating has a promising potential to be used to inactivate the lipase enzyme and improve shelf lives of rough and brown rice. Our previous studies (Pan et al. 2008, 2011, Khir et al. 2011, 2014) demonstrated that high drying rate, good milling quality, effective disinfestation and disinfection of rough rice, and effective stabilization of rice bran can be achieved using IR heating with high processing efficiency and low energy consumption.

IR radiation heating offers many advantages compared to conventional drying methods (Pan et al, 2008). 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 (Ginzburg, 1969). Even though the penetration is limited, IR can significantly improve the heat transfer rate at food products, as well as the heat delivered into the products when compared to convective heating. Since IR does not heat up the medium, the temperature of rice grains is not limited by the wet bulb temperature of surrounding air and high heating rate can be achieved for rice grain (Khir et al. 2007). IR has also shown a promising potential as an efficient processing method with high-quality finished food products, including dried fruit, nuts, and grains (Li and Pan 2013; Khir et al. 2011). Many studies have been reported on the investigation and optimization of rice drying by using IR radiation. Pan et al. (2008, 2011) and Khir et al. (2011, 2014) have investigated the infrared drying characteristics, moisture diffusivity, milling quality, and disinfestation effect of rough rice. They reported that IR drying (IRD) could achieve high moisture diffusivity corresponding to high drying rate. Simultaneously, an effective disinfestation could be achieved without milling quality loss. Page model was adequate in describing thin-layer infrared radiation drying of rough rice (Abe and Afzal 1997). However, from previous studies, little is known about the effect of IRD on the storage stability of rough and brown rice. The objectives of this research were to (1) determine the drying characteristics and milling quality of rice dried by using IR heating and investigate the impact of IRD on the storage stability of rough and brown rice; (2) compare the drying characteristics, milling quality, and storage stability of rice dried with IR, HA, and AA; and (3) develop kinetic model for the change of free fatty acid in rough and brown rice during storage.

## Materials and Methods

### Samples

Freshly harvested medium grain rice, variety M206, obtained from Farmers' Rice Cooperative (West Sacramento, CA, USA) was used for conducting this study. The initial moisture content (IMC) of rough rice was 25.03±0.01 % in dry basis (d.b). One hundred twenty kilograms of rice sample was split into three equal portions and prepared for IR drying (IRD), hot air drying (HAD), and ambient air drying (AAD), following the procedures shown in Fig. 1. The dried rice samples (40 kg) obtained from these methods were divided into two portions. One was used as rough rice, and the other one was dehulled to produce brown rice. The rough rice and brown rice samples were stored under accelerated storage conditions (temperature of 35 °C and relative humidity of 65±3 %) for 10 months. All reported moisture contents values are in dry basis (d.b.) as determined by the air oven method (130 °C for 24 h) (ASAE standards, 1995).

### Drying Procedures

#### *Infrared Drying*

A laboratory-scale catalytic IR dryer, developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis,

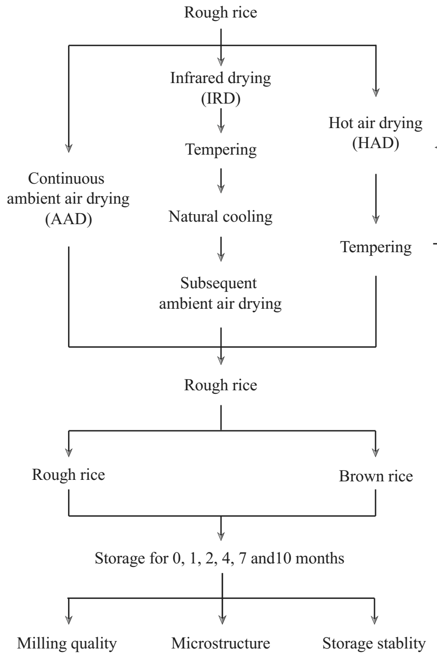


**Fig. 1** Flow diagram of rice drying and storage experimental procedures

was used to dry the rice samples (Fig. 2). The detailed descriptions for the IR dryer are available in our previous publications (Pan et al. 2008, 2011; Khir et al. 2011, 2014).

The rough rice samples as a single layer with a loading rate of 2.06 kg/m$^2$ were heated to temperature of 60±1 °C by using IR under radiation intensity of 4685 W/m$^2$, measured with Ophir thermal excimer absorber head (FL205A, Ophir, Washington, USA). The temperature of heated rice was measured by using a type-T thermocouple (time constant of 0.15 s, Omega Engineering Inc. Stamford, USA) immediately after the heated rice was collected into preheated container with the targeted rice temperature of 60±1 °C (Pan et al., 2008). The mass loss during IR heating and the initial moisture content (MC) were used to calculate the moisture loss during the heating period. The moisture loss was calculated as the difference between the initial MC and the MC after IR heating and is reported as percentage points. After IR heating, the tempering treatment was conducted by keeping heated rice samples in closed containers in an incubator set at temperature of 60 °C for 4 h. After the tempering treatment, the samples were allowed to naturally cool to the room conditions (temperature of 22±1 °C and relative humidity of 43±2 %). The temperatures of the sample reached to room temperature after about 30 min. The mass changes caused by tempering and cooling treatment were recorded at the end of cooling and used to calculate the moisture loss during cooling based on the MCs after the corresponding IR treatment. After cooling, the samples were further dried for 6 h to final MC of 15.92±0.05 % by forced ambient air with temperature of 22±1 °C and relative humidity of 43±2 %.

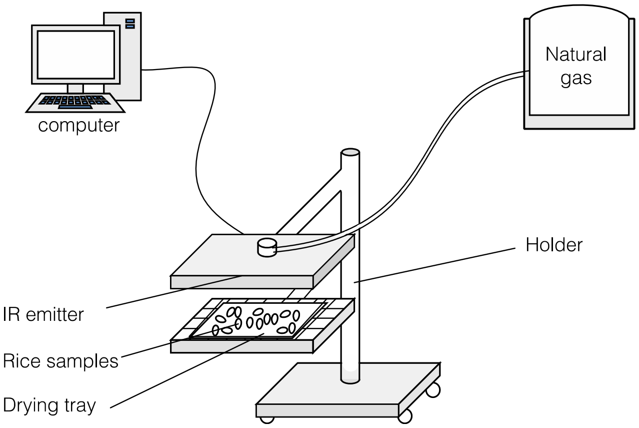


**Fig. 2** Schematic diagram of catalytic infrared dryer set up

### *Hot Air Drying*

A convective dryer made from a wooden box was used to conduct the hot air drying. Dimensions of the wooden box were 1.52 m (length) × 1.22 m (width) × 0.56 m (height). Air was pumped to the dryer by using Dayton air blower (1/6 hp, 124 W at 1050 RPM) at a flow rate of 0.141 m$^3$/s. The dryer had 25 circular openings with diameter of 15.2 cm each. These openings were used to accommodate the rice samples. The samples were placed in cylindrical cardboard containers with a diameter of 17.0 cm and height of 17.5 cm. Each container had fine metallic sieve at the bottom to allow airflow through the rice samples. The air was sucked in by the blower and preheated using an external heater (Cadet Manufacturing, Vancouver, WA, USA). The temperature setting on the heater was adjusted to obtain a temperature of 43±1 °C of drying air. It was measured using Omega type-T thermocouple with a constant time of 0.15 s. Rough rice of 1.5 kg was placed in each container. The velocity of drying air was maintained at 0.10±0.01 m/s. Air velocity was measured using a hot wire anemometer (Solomat MPM500, UK) with an accuracy of 0.01 m/s. The samples were dried from their initial MC to MC of 16.15±0.09 % by following the current drying practice in the rice industry, which uses 43±1 °C air for drying for 20 min followed by a 4-h tempering for each drying pass until the targeted final moisture was achieved.

### *Ambient Air Drying*

The convective dryer described in the previous section was also used to conduct the AAD with same parameters of loading rate and air velocity. The samples were dried from the original moisture contents to 16.13±0.12 % by one single pass without tempering with ambient air at temperature of 22±1 °C and relative humidity of 43±3 %. The drying process was stopped when the rice samples reached the final targeted weight (moisture).

### Storage Study

After drying, half of each dried rough rice samples (20 kg) were placed in paper bags and directly transferred to an incubator for storage, and the other half was dehulled and then stored as brown rice. All rice samples were stored for 10 months at 35±1 °C with relative humidity of 65±3 %. Sampling times for analyzing the milling quality and rice storage stability were set to be at months 0, 1, 2, 4, 7, and 10. The evaluated milling quality indicators were total rice yield (TRY), head rice yield (HRY), and whiteness index (WI). Free fatty acid (FFA) concentration, peroxide value (POV), and iodine value (IV) were investigated to evaluate the effect of the drying method on storage stability.

### *Milling Quality*

Total rice yield (TRY), head rice yield (HRY), and whiteness index (WI) are considered as the most important milling quality indices. They were measured to evaluate the effects of different drying methods on milling quality of rough and brown rice over storage. For rough rice, the samples dried using IRD, HAD, and AAD (400 g each) were dehulled and milled using Yamamoto Husker (FC-2K) and Yamamto Rice Mill (VP-222N, Yamamoto Co. Ltd., Japan). The samples were milled three times to achieve well-milled rice as defined by the Federal Grain Inspection Service (FGIS). The settings of throughput and whitening were 1 and 4 during the first two milling passes and 1 and 5 during the third milling pass (Pan et al 2011). TRY was the percentage of milled rice weight divided by the weight of rough rice before dehulling and milling. HRY was determined with Graincheck (Foss North America, Eden Prairie, MN, USA). The WI was determined by using the whiteness tester (C-300, Kett Electronic Laboratory, Tokyo, Japan). The aforementioned milling procedures for rough rice were also used to mill the brown rice and determine its milling quality indices including TRY, HRY, and WI. All reported data of milling quality indicators are means of three replicates.

### *Storage Stability*

As one of the three main components in rice, lipids are the easiest to be deteriorated during storage. The degradation of lipids in rough and brown rice can impart off flavors by undergoing lipid hydrolysis and subsequent oxidation during storage. FFA concentration is used as an indicator of rice stability (Tao et al., 1993). Also, peroxide per kilogram is the indicator of onset of lipid rancidity of rice (AOCS, 1998). Iodine value, an important index of rice bran oil, indicates the unsaturation of oil. The FFA and POV levels of lower than 10 % and 20 milliequivalent peroxides per kilogram are considered as indicators of stable rice with accepted sensory quality for consumers. Therefore, the FFA concentration and peroxide values (POV) are normally used as indicators of storage stability for rough and brown rice (Villareal et al. 1976). Consequently, FFA and POV were used to detect any notable degradation of lipids in the rough and brown rice samples during storage. After milling procedure, 1000-g rice bran was collected quickly and separated into 10 portions. Each portion and 500 ml n-hexane were placed into 1-L beaker with stirring at 600 rpm on magnetic stirrer (Fisher Scientific, USA) for 2-h oil extraction. Then, the supernatant in the beaker was placed in several 50-ml tubes and centrifuged at 5000 rpm (model: 5804R, Eppendorf, Germany) to separate the hexane solution and the residue of bran. Rotary evaporator (model R, BÜCHI, Switzerland) was applied to collect the oil from the hexane solution. The FFA and POV of extracted bran oil were measured in triplicates according to the AOCS Official Method Ca 5a-40 and AOCS Official Method Cd 8-53. IV was measured following the AOCS Official Method (Cd 1d-92) in triplicates. FFA concentration, calculating as oleic acid, was expressed as a proportion of total lipids.

The kinetics of FFA concentration change of the rice bran oil extracted from the stored rice samples were examined. The exponential model Eq. (1) was applied to simulate the dynamic changes in FFA concentration during the 10-month storage period.

$$y = k\cdot\exp(m\cdot x) \tag{1}$$

where $y$ is the FFA concentration percentage points, and $x$ is the value of storage time, in months. $k$ and $m$ are regression coefficients of the exponential model.

The coefficient of determination ($R^2$) and root mean square errors (RMSE) were used to evaluate the model accuracy for describing the FFA concentration. Lower RMSE and higher $R^2$ values mean better fitness. The RMSE was calculated using Eq. (2):

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{FFAc}_{\mathrm{pre},i}-\mathrm{FFAc}_{\mathrm{exp},i}\right)^2\right]^{\frac{1}{2}} \tag{2}$$

where $\mathrm{FFAc}_{\mathrm{exp},i}$ and $\mathrm{FFAc}_{\mathrm{pre},i}$ are the experimental and the predicted FFA concentration percentage points at observation $i$; $n$ is the number of observations.

### *Microstructure Analysis*

To evaluate the effect of IR on microstructure of rice kernels, scanning electron microscopy (SEM) technique was applied. The whole white rice kernels dried by IRD and AAD were placed in fixative for 24 h in the fridge. The fixative is 2 % formaldehyde, 2.5 % glutaraldehyde, and 2.5 mM $CaCl_2$ in 0.1 M Na cacodylate with a pH of 6.9. The kernels were rinsed three times in 0.1 M Na cacodylate buffer at pH 6.9 and dehydrated in a graded ethanol series: one time with 30, 50, 75, and 95 % and three times with 100 % ethanol. The whole rice kernels were cryofractured in liquid nitrogen followed with critical point drying for the fractured pieces. The dried pieces were examined by using field emission scanning electron microscope (Hitachi, S-4700, Japan).

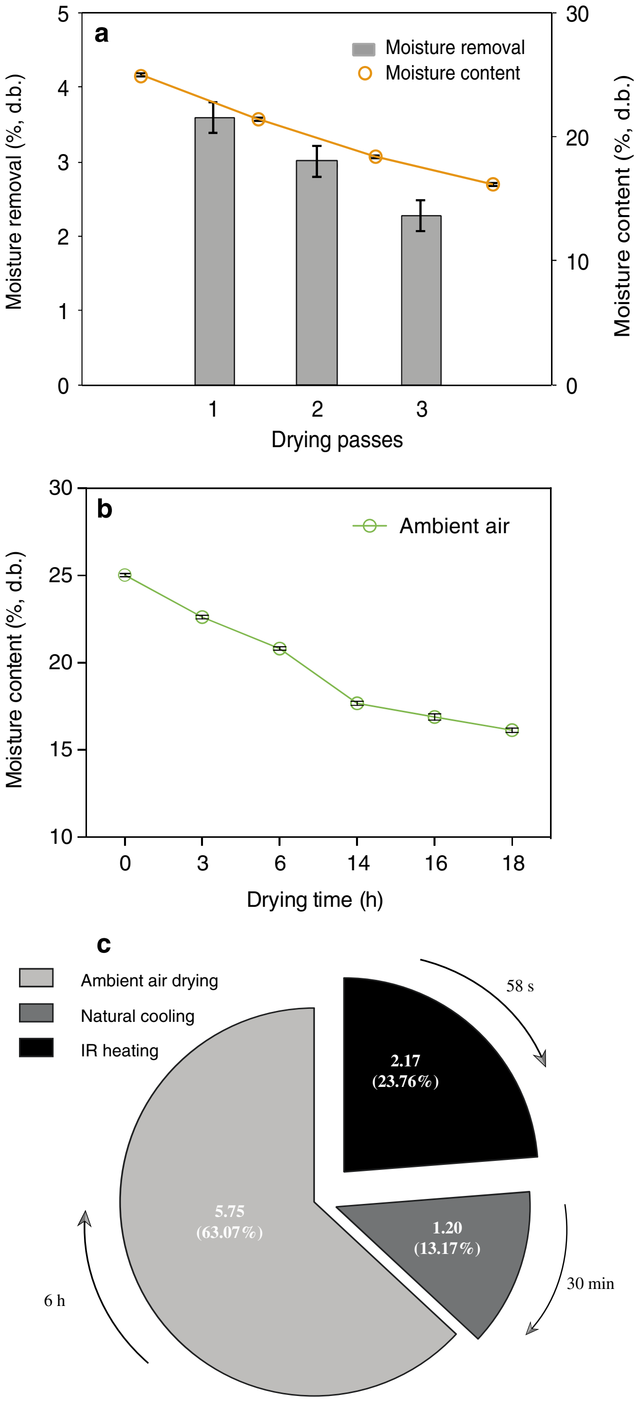
### Statistical Analysis

Data of FFA concentration and rice milling quality were statistically analyzed with PASW 18 (IBM SPSS Statistics, Chicago, IL, USA). Two-way ANOVA with Tukey's multiple comparisons test were applied to compare the data among different drying methods and different storage durations. The regression model for simulating the changes in FFA concentration was implemented with PRISM 6.0 software (GraphPad Software Inc, La Jolla, CA, USA).

## Results and Discussion

### Moisture Removal Under IR Heating

High heating rate and moisture removal were achieved by using IR radiation heating. It took only 58 s to heat rough rice to 60 °C with a corresponding moisture removal of 2.17 percentage points. After tempering and natural cooling, additional 1.20 % point of moisture was removed without any additional energy input. This means that about 23.76 % of total needed moisture removal was removed during IR heating and 13.17 % more was removed during natural cooling without consuming energy. For HAD and AAD, they took 13 h (three drying passes) and 18 h to dry the rough rice from initial MC of 25.03±0.01 % to 16.15±0.09 and 16.13±0.12 %, respectively (Fig. 3). The results showed that high drying rate can be achieved using IRD compared to HAD and AAD. The results also confirmed our previous findings that IRD could obtain high heating and high dry efficiency for rough rice (Pan et al., 2008; Khir et al., 2011).



Total= 100% moisture removal (9.11%, d.b .)

**Fig. 3** Drying characteristics of hot air (**a**), ambient air (**b**), and infrared (**c**) drying for rough rice

### Milled Rice Quality

The milling quality of rough and brown rice after storage for different periods are shown in Table 1. The TRY values increased from 67.12±1.61, 67.74±1.68, and 66.52±1.15 % at month 0 of storage to 68.91±1.37, 68.97±1.41, and 68.50± 1.35 % (rough rice) and 68.16±0.89, 68.13±1.65, 67.80± 0.76 % (brown rice) at month 2 of storage for rice dried with IRD, HAD, and AAD, respectively. The corresponding TRY values at month 10 of storage were 69.39±1.37, 68.97±0.93, and 69.22±1.19 % (rough rice) and 68.91±0.5, 68.83±0.67, and 69.10±0.72 % (brown rice). The HRY values of rice dried with IRD in initial 4 months of storage were slightly higher than those of rice dried with HAD and AAD. HRY values of the samples dried by IRD, HAD, and AAD were 57.94±1.93, 57.78±1.23, and 56.07±1.40 % at month 0 of storage. The corresponding HRY values at month 4 of storage were 59.67± 1.25, 59.15±1.44, and 59.23±1.53 % (rough rice) and 58.87±

**Table 1** Changes in milling quality of rough and brown rice during storage

| Rice category | Drying method | Storage time (month) | Milling quality | | |
|---|---|---|---|---|---|
| | | | TRY (%) | HRY (%) | Whiteness (unit) |
| Rough rice | Infrared drying | 0 | 67.12±1.61 | 57.94±1.93aA | 39.90±0.36aA |
| | | 1 | 68.23±1.64 | 58.69±1.49aA | 40.60±0.28aAB |
| | | 2 | 68.91±1.37 | 59.66±1.02aA | 39.20±0.71aAC |
| | | 4 | 69.05±1.26 | 59.67±1.25aA | 39.45±0.07aAC |
| | | 7 | 69.26±1.16 | 60.81±1.04aA | 35.92±0.50aD |
| | | 10 | 69.39±1.37 | 61.21±1.09aA | 31.08±0.83aE |
| | Hot air drying | 0 | 67.74±1.68 | 57.78±1.23aA | 39.94±0.48aA |
| | | 1 | 67.93±1.35 | 57.98±1.03aA | 40.40±0.28aAB |
| | | 2 | 68.97±1.41 | 58.42±1.39aA | 39.20±0.57aAC |
| | | 4 | 68.68±1.81 | 59.15±1.44aA | 39.30±0.14aAC |
| | | 7 | 68.94±1.43 | 60.93±1.68aA | 36.37±0.23aD |
| | | 10 | 68.97±0.93 | 61.67±1.40aA | 32.18±0.21bE |
| | Ambient air drying | 0 | 66.52±1.15 | 56.07±1.40aA | 38.37±0.46bA |
| | | 1 | 67.83±1.39 | 56.74±1.58aA | 37.95±0.49bAB |
| | | 2 | 68.50±1.35 | 58.00±1.62aAB | 37.15±0.07bB |
| | | 4 | 68.71±1.36 | 59.23±1.53aAB | 35.84±0.49bC |
| | | 7 | 69.10±1.33 | 60.77±1.19aB | 33.57±0.27bD |
| | | 10 | 69.22±1.19 | 61.29±0.93aB | 30.29±0.46aE |
| Brown rice | Infrared drying | 0 | 67.12±1.61 | 57.94±1.93 | 39.90±0.36aA |
| | | 1 | 67.72±0.39 | 58.04±0.55 | 39.73±0.53aA |
| | | 2 | 68.16±0.89 | 58.67±0.53 | 39.53±1.06aA |
| | | 4 | 68.23±0.27 | 58.87±0.33 | 38.52±0.45aA |
| | | 7 | 68.63±0.39 | 58.19±0.97 | 35.45±0.44aB |
| | | 10 | 68.91±0.50 | 58.61±0.49 | 30.87±0.38aC |
| | Hot air drying | 0 | 67.74±1.68 | 57.78±1.23 | 39.94±0.48aA |
| | | 1 | 67.38±0.84 | 58.42±1.17 | 40.19±0.11aA |
| | | 2 | 68.13±1.65 | 58.11±0.76 | 39.54±0.64aAB |
| | | 4 | 68.92±0.66 | 58.44±0.75 | 38.10±0.45aB |
| | | 7 | 68.49±0.64 | 58.2±0.38 | 34.92±0.44aC |
| | | 10 | 68.83±0.67 | 58.99±0.34 | 30.01±0.57aD |
| | Ambient air drying | 0 | 66.52±1.15 | 56.07±1.40 | 38.37±0.46bA |
| | | 1 | 67.63±1.28 | 57.37±0.54 | 37.88±0.77bA |
| | | 2 | 67.80±0.76 | 57.44±0.47 | 36.68±0.29bAB |
| | | 4 | 67.74±0.44 | 57.33±0.9 | 35.72±0.45bB |
| | | 7 | 69.18±0.71 | 57.62±0.55 | 33.25±0.77bC |
| | | 10 | 69.10±0.72 | 58.53±1.29 | 29.59±0.71aD |

Values (means±standard deviation) in each column without letter or followed by the same letter are not significantly different at $P<0.05$. Letters in lowercase and uppercase represent the comparison between different drying methods and different storage durations, respectively

*TRY* total rice yield, *HRY* head rice yield

0.33, 58.44±0.75, and 57.33±0.90 % (brown rice), respectively. The changes in TRY and HRY of the rice dried by HAD and AAD during storage are consistent with those reported by Pearce et al. (2001).

For whiteness, the results showed that the WI values of all milled rice from both rough and brown rice at storage time of zero and 1 month were above 38 units. Compared with the samples dried by AAD, the rice dried by IRD and HAD had higher WI. The decrease in WI for samples dried using AAD may be caused by enzymatic activity. The lipid oxidation and Maillard reaction may lead to the increase value of color indices (b) during the storage (C.E. Park et al. 2012; Kim et al. 2004). After 4 months of storage, there were similar downward trends in WI values of all samples. Besides the lipid oxidation and Maillard reaction, the decrease of whiteness might have some correlation with color leaching from rice bran occurred during the accelerated storage (Lamberts et al. 2006). The pigments exist in rice hull and bran layer can leach out with moisture and transfer to endosperm during long term of storage. Additionally, the changes of milling degree might also affect WI values (Pan et al 2005). During storage, the physicochemical changes of rice bran layer and endosperm might occur and the combination of them would be tighter and firmer. Since the standard milling procedure was used for all samples, those changes made it hard to remove the same amount of rice bran layer from stored rice than fresh rice, which indirectly reduced the whiteness of milled rice. The obtained results clearly demonstrated that high milling quality was achieved by heating the rice to 60 °C using IR followed by tempering and natural cooling, which is in agreement with our earlier results (Pan et al., 2011; Khir et al. 2011).

## Microstructure

The SEM photos of whole and segments transverse sections of dried samples by IRD, HAD, and AAD (Fig. 4) did not show any significant differences. The structures of starch granules in the rice samples were similar. These results indicate that the IR heating has no adverse effect on rice microstructure.

## Storage Stability

### *Free Fatty Acid Concentration*

The concentrations of free fatty acid (FFA) of rough rice and brown rice over the storage period are shown in Fig. 5. For both rough and brown rice, FFA level rose slightly during storage period from month zero to month 1 and there was no significant difference ($P>0.05$) for the rice dried with three different methods. However, after 4 months of storage, FFA concentrations of rough and brown rice samples dried with IRD were significantly ($P<0.05$) lower than those dried with HAD and AAD. The FFA concentrations of fresh rice dried by IRD, HAD, and AAD were 1.81±0.07, 1.81±0.12, and 1.88±0.05 % (calculated as oleic acid), respectively. After 4 months of storage, the FFA concentrations reached to 2.87±0.10, 3.52±0.06, and 4.13±0.05 % for rough rice and 3.90±0.01, 4.90±0.01, and 6.83±0.08 % for brown rice. After 10 months of storage, the corresponding FFA concentrations were 5.12±0.05, 7.84±0.04, and 10.05±0.09 % for rough rice and 6.91±0.07, 9.57±0.04, and 13.16±0.04 % for brown rice.

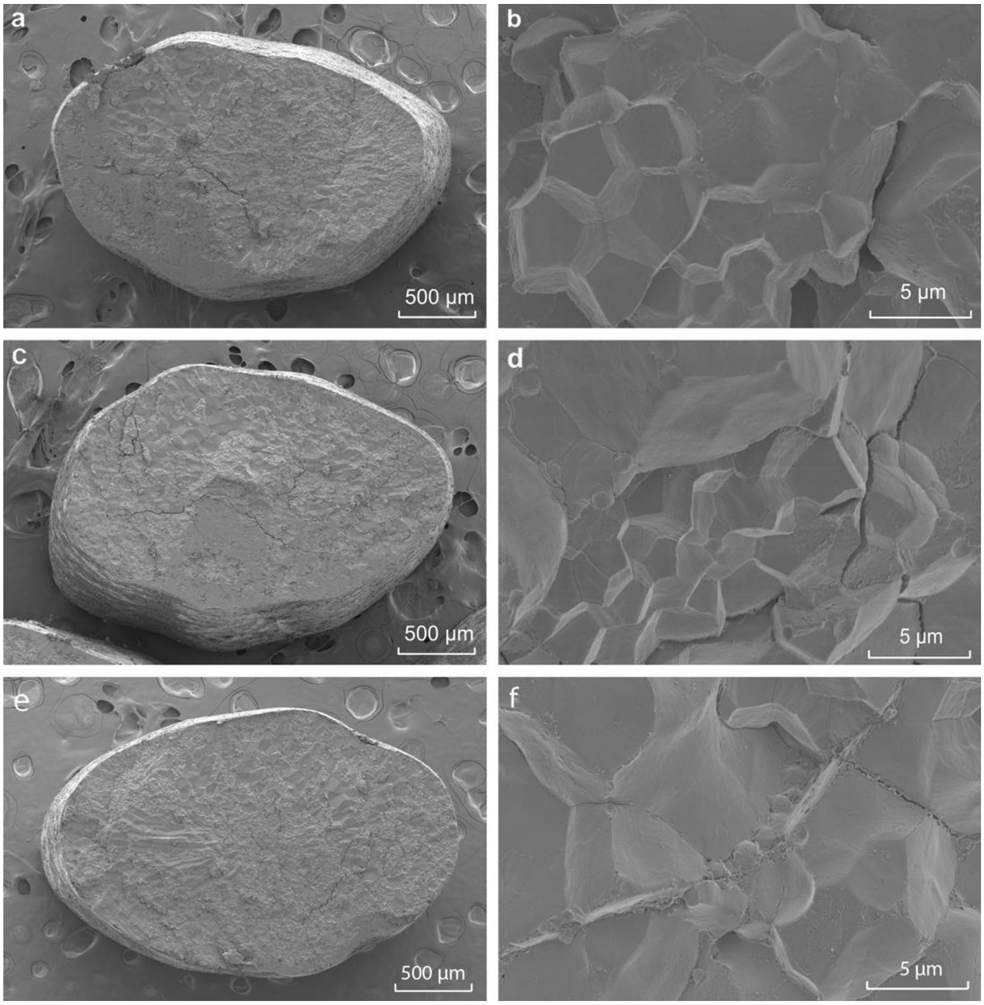


**Fig. 4** Representative scanning electron microgrames of the rice dried with ambient air (**a**, **b**), infrared radiation (**c**, **d**), and hot air (**e**, **f**)

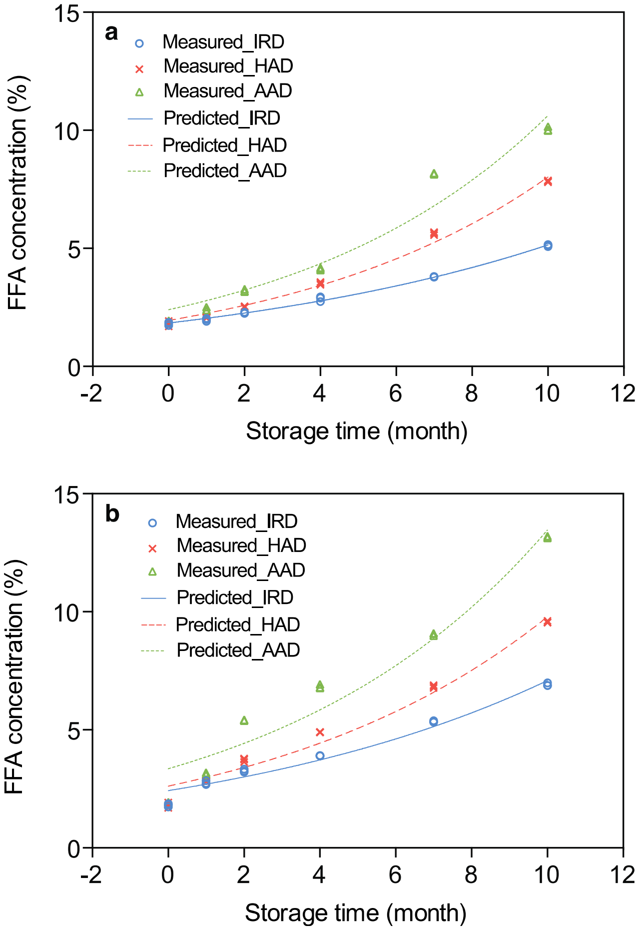


**Fig. 5** Regression of the changes in free fatty acid (*FFA*) concentration of rough (**a**) and brown (**b**) rice during storage

The results showed that rough rice was more stable than brown rice as expected. However, the IRD resulted in an effective stabilization to brown rice and maintained its storage stability during storage even compared to rough rice dried with HAD and AAD. For example, the residual lipase activities of the stored brown rice samples dried by IRD and HAD after 10 months of storage under accelerated conditions were 38.09 and 57.14 %. After stored for 10 months, the FFA concentrations of both rough and brown rice dried by AAD both exceed 10 %. However, the corresponding FFA concentrations of the rice dried by IRD were maintained less than 10 % after 10 months of storage.

There was a strong correlation between the FFA concentration and storage time. The regression models were developed to predict the FFA concentration over the storage time for rice dried with different methods (Table 2). It can be seen that the regression models of each rough rice samples had high $R^2$ (>0.95) with low RMSE. For the brown rice samples, the $R^2$ of each model was lower than the corresponding rough rice samples. Figure 6 presents the residuals of measured FFA concentration value and the predicted values. The residuals of brown rice were slightly higher than those of rough rice samples. However, these differences were in very small range. Consequently, the developed model could be used to simulate the FFA concentration change of rough and brown rice during storage.

**Table 2** Regression analysis of FFA concentration of rough and brown rice during storage

| Categories | Drying methods | *k* | *m* | $R^2$ | RMSE |
|---|---|---|---|---|---|
| Rough rice | Infrared | 1.838 | 0.1029 | 0.9965 | 0.0678 |
| | Hot air | 1.948 | 0.1415 | 0.9908 | 0.1174 |
| | Ambient air | 2.401 | 0.1487 | 0.9523 | 0.2102 |
| Brown rice | Infrared | 2.424 | 0.1072 | 0.9666 | 0.1433 |
| | Hot air | 2.615 | 0.1320 | 0.9725 | 0.1695 |
| | Ambient air | 3.350 | 0.1391 | 0.9441 | 0.2427 |

Based on the developed regression models, the FFA concentration of the stored rough rice dried by IRD was 5.12 % after 10-month storage, compared to 6.8 months for HAD and 5.1 months for AAD dried samples. It means that IRD significantly extend the shelf life of rough rice. Similarly, for stored brown rice, the FFA concentration of IR dried rice was 6.91 %

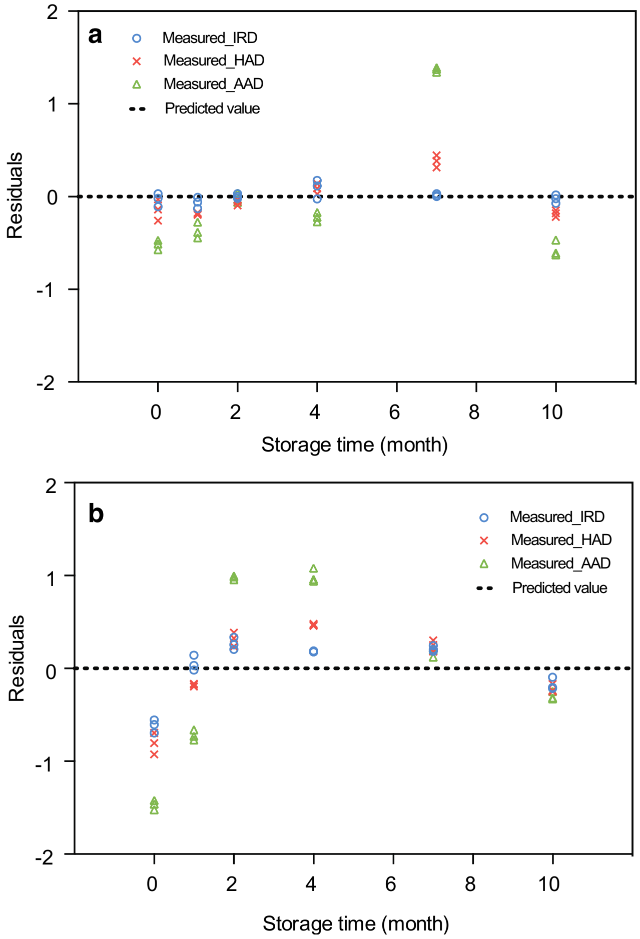


**Fig. 6** Residuals distribution plot of measured and predicted values of FFA concentration of rough (**a**) and brown (**b**) rice during storage

at month 10, same concentration as the brown rice stored for 7.4 and 5.2 months dried by HAD and AAD, respectively. Moreover, even compared with the rough rice samples dried by HAD and AAD, 6.91 % was equal to the FFA concentrations after 8.9 and 7.1 months of storage, respectively. It shows that the lipid hydrolysis of brown rice dried by IRD was reduced to the obvious lower level than the brown rice dried by HAD and AAD, even lower than the corresponding stored rough rice samples. In conclusion, infrared heating resulted in an effective inactivation of lipase, reduced the lipid hydrolysis, achieved consequent improvement in the long-term storage stability, and significantly extended the period of safe storage. The results also clearly demonstrated the potential to store brown rice though IRD instead of rough rice to take all benefits of IR heating.

### *Peroxide Value*

There was no significant difference among peroxide values (POV) for rough rice dried with IRD, HAD, and AAD ($P>0.05$). In general, all the stored rice samples had similar changing trend in POV. POV of all samples increased after the first month and then decreased to the least at month 4. After that, POV increased again at month 7 and became stable till month 10. The dip between month 1 and 4 indicated that the degradation of peroxides was faster than the generation speed of peroxides. The POV increased from 6.05±0.25, 5.72±0.29, and 5.94±0.15 milliequivalent/1000 g at month 0 of storage to 8.38±0.08, 8.64±0.10, and 8.16±0.14 milliequivalent/1000 g at month 1 for rough rice dried using IRD, HAD, and AAD, respectively (Fig. 7a). The corresponding values of brown rice were 12.60±0.01, 12.80±0.05, and 12.61±0.02 milliequivalent/1000 g (Fig. 7b). After 4 months of storage, the peroxide value decreased to 3.89±0.38, 4.44±0.27, and 4.87±0.32 milliequivalent/1000 g for rough rice and 5.86±0.20, 6.09±0.18 and 5.91±0.22 milliequivalent/1000 g for brown rice. After 7 months of storage, the POV of rough and brown rice both reached to the highest. Similar fluctuation of conjugated diene hydroperoxides content of rice during long term of storage was also reported by Sharp (1986). Marmesat et al (2009) proposed that the POV was strongly linearly correlated with the conjugated diene in sunflower oil. Moreover, the activity of lipoxygenase in rice bran fluctuated during 16 weeks of storage (Malekian et al 2000). Therefore, the fluctuation in POV might be due to the instability of the lipoxygenase in rice during storage. From the figure, it is obvious that brown rice samples acquired higher POV than rough rice during the same time period. Apparently, without the barrage of hull, the exposure of brown rice bran layer was more susceptible to oxidation of lipid.

The POV of both rough and brown rice samples were lower than 20 milliequivalent/1000 g rice that is the indicator of onset of lipid rancidity (AOCS, 1998). Part of the peroxides, as the intermediate products of oxidation, could be degraded into the final products and are the source of the stale flavor, like aldehydes, ketones, and acids (Malekian et al. 2000; Suzuki et al. 1996). These low molecule weight compounds were reported to have strong correlations with the generation of rice off-flavor after long term of storage (Ramezanzadeh et al. 1999), which directly made the flavor of cooked rice unacceptable by consumers. In addition, many oxidized products were chromophoric organic matters that may increase the yellowness and decrease the whiteness of cooked rice. Detailed results on cooking and sensory quality of rough and brown rice dried by IRD during storage will be reported in a separate paper.

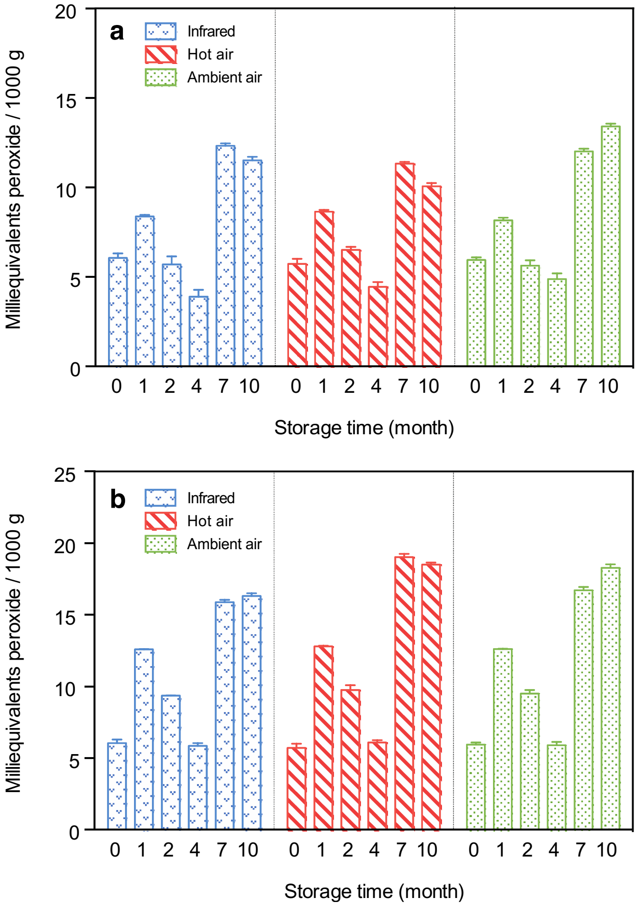


**Fig. 7** Changes in peroxide value (*POV*) of the rough (**a**) and brown rice (**b**) dried by different methods during storage

### *Iodine Value*

As an important oil quality index, iodine value reveals the unsaturated fatty acid amount in oil. All the rice dried by IRD, HAD, and AAD did not have significant difference in iodine value at month 0 ($P>0.05$), followed by a similar steady descend over the storage period. After stored for 10 months, iodine value of rough rice samples decreased from approximately 104 to 98 g $I_2$/100 g and those of brown rice decreased to 93 g $I_2$/100 g (Fig. 8). Therefore, more peroxides might be produced by the oxidation and degradation of unsaturated fatty acid. The results clearly showed that the IR did not increase the iodine value of treated rice immediately or showed any adverse effect on iodine value in prolonged storage even under accelerated storage conditions, which means the IR heating had no negative effects on oxidation of unsaturated fatty acids to saturated fatty acids.

## Conclusions

This study revealed that high drying rate and good milling quality can be achieved by infrared drying compared to hot and ambient drying methods. It took only 58 s during IR heating to achieve surface temperature of 60 °C of rough rice. The corresponding moisture removal during IR heating period was 2.17 percentage points. The total moisture removal after natural cooling reached 3.37 percentage points without additional energy input. There was no adverse effect of IR heating on milled rice quality. Moreover, the results demonstrated that the improvement of rough and brown rice stability during storage could be achieved by heating rough rice using IR under the aforementioned conditions. The IR heating followed by tempering and natural cooling could effectively inactivate lipase and significantly reduce the generation of free fatty acids. It is recommended to use IR to heat rough rice to 60 °C followed by tempering treatment for 4 h for rice drying. This can be an effective approach to achieve high drying efficiency, good milling quality, simultaneously inactivate the lipase, extend the storage stability, and extend the storage lives for both rough and brown rice. The IR drying provides a potential to store brown rice instead of rough rice to take all benefits and extended shelf life from new IR drying method.

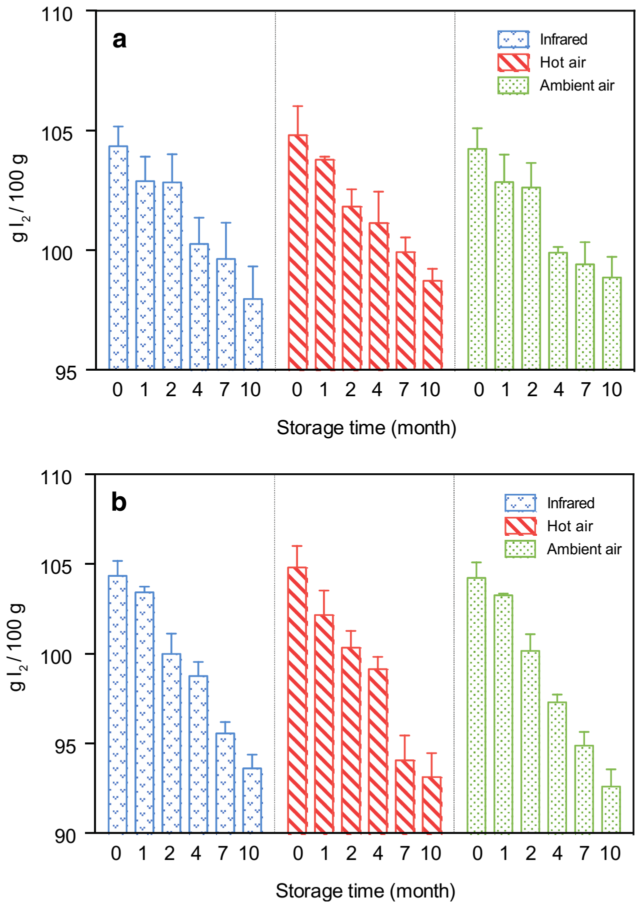


**Fig. 8** Changes in iodine value (*IV*) of the rough (**a**) and brown (**b**) rice dried by different methods during storage

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