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Quality of Milled Rice from Large-Scale Dried Paddy Rice by Hot Air Combined with Radio Frequency Heating

Karn Chitsuthipakorn [1,*] and Sa-nguansak Thanapornpoonpong [2]

[1] Postharvest Technology Research Center, Faculty of Agriculture, Chiang Mai University, Chiang Mai 50200, Thailand

[2] Department of Plant and Soil Sciences, Faculty of Agriculture, Chiang Mai University, Chiang Mai 50200, Thailand; sa-nguansak.t@cmu.ac.th

* Correspondence: karn_c@cmu.ac.th; Tel.: +66-65-8799-895

Abstract: A scaled-up process for paddy drying was developed using hot air (HA) combined with radio frequency (RF) heating. The study was conducted using hot air (control treatment) arranged in descending order in four temperature levels, namely 80 °C at moisture content of 25–26%, 70 °C at moisture content of 20–25%, 60 °C at moisture content of 17–20%, and 50 °C at moisture content of 13–17%, as well as with hot air combined with radio frequency (HA/RF) at different paddy temperatures (45–60 °C) by adjusting the appropriate RF energy when passing through RF heating chamber, namely HA/RF45, HA/RF50, HA/RF55, and HA/RF60. Each treatment was performed in three replicates and data were statistically analyzed in a randomized complete block design. The quality attributes of paddies affected by the drying process were assessed: fissure percentage, color, milling quality, and sensory evaluation. The drying efficiency showed that the drying time and the specific energy consumption could be decreased by up to 54.44% and 23.17% at HA/RF60 and HA/RF45, respectively. As the RF heating temperature increased, the fissure percentage of brown rice kernels at HA/RF45 and HA was not significantly impacted. Regarding color evaluation, combining RF heating and convective drying at all given conditions could be statistically applied in terms of the b*, WI, and ΔE* value. Considering the milling yield of HA as the baseline, head rice yield was maximized at HA/RF45, while bran yield reached the maximum at HA/RF60. The liking score of cooked rice after it was dried using the HA method was the highest. This study concludes that the HA/RF45 was the most appropriate drying condition, and this may provide preliminary exposure to the industrial drying of paddies.

Keywords: paddy; hot air drying; radio frequency heating; drying efficiency; rice quality

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1. Introduction

Rice production plays an important role in Thailand's economy, with approximately 30 million tons of paddy production harvested per year. The optimum harvest period for the paddy rice variety Hom Mali is 25–35 days after heading at a moisture content level of 18–28% (w.b.) when harvested by a combine harvester [1]. The most commonly used mechanical drying systems in Thailand are the continuous flow dryer and re-circulating batch dryer. There are around 2000 industrial-scale rice mills across the country. The continuous-flow hot air dryer is the most selected method for use at industrial-scale rice mills because of its cost and drying rate. A paddy is dried by hot air (HA) (40–80 °C) to achieve the shortest drying time because the drying time can determine a paddy's daily intake. The shorter the drying time, the more paddies can be bought from farmers, increasing business turnover.

Radio frequency (RF) and microwave (MW) are electromagnetic waves within the frequency ranges of 1–300 MHz [2] and 300 MHz–300 GHz [3], respectively. They have been widely used for drying agricultural products, such as rice [4–7], soybean [8], walnut [9], barley malt [10], macadamia nut [11], tea leaves [3], etc. RF and MW treatments, as a kind of dielectric heating method, involves the generation of heat as a result of the interaction between an electromagnetic field and polarized molecules in the crops that are either of bipolar or ionic nature [12]. In the method of hot air drying combined with RF heating application, the paddy is placed between two electrodes, causing polar molecules in the paddy to rotate and create heat energy throughout the volumetric paddy; moreover, it penetrates products and generates heat inside paddy kernels uniformly and instantly, with no regard for convective or conductive media. The generated heat enhances moisture evaporation from the paddy surface and stimulates moisture migration from the inner to the outer area. The most successful past applications have often combined two or more technologies (RF-HA, etc.). However, the use of hot air (HA) combined with RF heating has not been well studied for paddy drying in recent years, despite great advances in other applications being reported, such as controlling rice weevil in milled rice [13] while maintaining rice physical properties [14], controlling Aspergillus flavus in packed milled rice [15], and aging milled rice [16].

Thus, we looked to the vertical operating prototype that supported an RF heating system from Vearasilp et al. [13] in order to expand the drying process up to the industrial scale. We decided to study a hot air dryer combined with radio frequency heating in an industrial-scale process compared with the conventional hot-air drying method. The specific objectives of the study were (1) to investigate the drying characteristics and kinetics of the method, (2) to observe the rice quality after treatment (including fissure percentage, color, and milling yield), and (3) to evaluate and compare the sensory attributes of cooked rice after treatment with a liking score method.

2. Materials and Methods

2.1. Materials and RF Heating Systems

A total of approximately 9000 kg of freshly harvested paddy rice (var. RD 41) was procured from local farmers in Nakhon Sawan province, Thailand. The initial moisture content was, on average, 25–26% (w.b.) and it was stored in PP-woven bags. Each replication was treated within 4 days after harvest in order to prevent quality deterioration. After treatment, 25 kg paddy samples of each replication were kept for further quality assessment.

A picture of the industrial-scale continuous-flow hot air dryer combined with radio frequency heating used in this study is shown in Figure 1. It mainly consists of a recirculating hot air dryer that can hold up to 450 kg of paddy at a time (QS-500, Quaser Engineering, Pathum Thani, Thailand), a 15 kW, 27.12 MHz RF heating machine (BiO-Q, Yont Phol Dee, Nakhon Sawan, Thailand), and a bucket elevator. The air is circulated through the heating compartment at the front, where three rows of 1000-Watt infrared heaters are installed, by a blower (2 HP/2850 rpm/28 CMM/80 mmAq) stationed at the back of the dryer. The hot air temperature was set and controlled automatically by a sensor and control equipment. The hot air flowed through the paddy in the drying section, carried evaporated water out of the paddy via a blower, and ventilated it out to the exterior environment. There are five temperature sensors (PT100, Primus Thai, Bangkok, Thailand), two relative humidity sensors (RHM, Primus Thai, Bangkok, Thailand) installed in the dryer and one humidity and temperature data logger (EL-USB-2-LCD, Lascar Electronics, MA, USA) for measuring the ambient environment as shown in Figure 2. A fresh paddy was filled into the intake pit and conveyed by bucket elevator into a hot air dryer. To maintain the quality of the milled rice, the hot air temperature was divided into 4 levels. The temperature profiles of the hot air were 80 °C at a moisture content of 25–26%, 70 °C at a moisture content of 20–25%, 60 °C at a moisture content of 17–20%, and 50 °C at a moisture content of 13–17%. Inside the hot air dryer, hot air was blown through the paddy while the paddy was continuously fed from the hopper into a RF heating machine. The paddy was heated to the set temperature (45 °C, 50 °C, 55 °C, 60 °C) with the appropriate RF energy as it passed through the RF heating chamber. The paddy was then discharged from the RF heating machine into the bucket elevator and recirculated to the hopper for hot air drying. This process was carried out continuously and not in batches until the moisture content of the paddy was below 14% (w.b.). A temperature sensor 6 was installed in the RF heating chamber (see Figure 2) to measure the temperature of the paddy after heating. To achieve the different paddy temperatures, the RF energy was adjusted by increasing or decreasing the electrical voltage in a control panel of the machine. The study was designed with a randomized complete block design (RCBD) involving hot air combined with different RF heating temperatures (45, 50, 55, 60 °C) and three replications. The paddy was not used more than once in any treatment or replication.

2.2. Moisture Content Determination

Moisture content determination during drying was performed in triplicate using a rapid capacitance-type moisture meter (Granomat, Pfeuffer GmbH, Kitzingen, Germany) every 30 min to observe the drying-in-process moisture content value, which was reported as mean and standard deviation.

(**a**) (**b**)

Figure 1. Prototype of the industrial-scale continuous-flow hot air dryer combined with radio frequency heating: (**a**) front view; (**b**) side view.

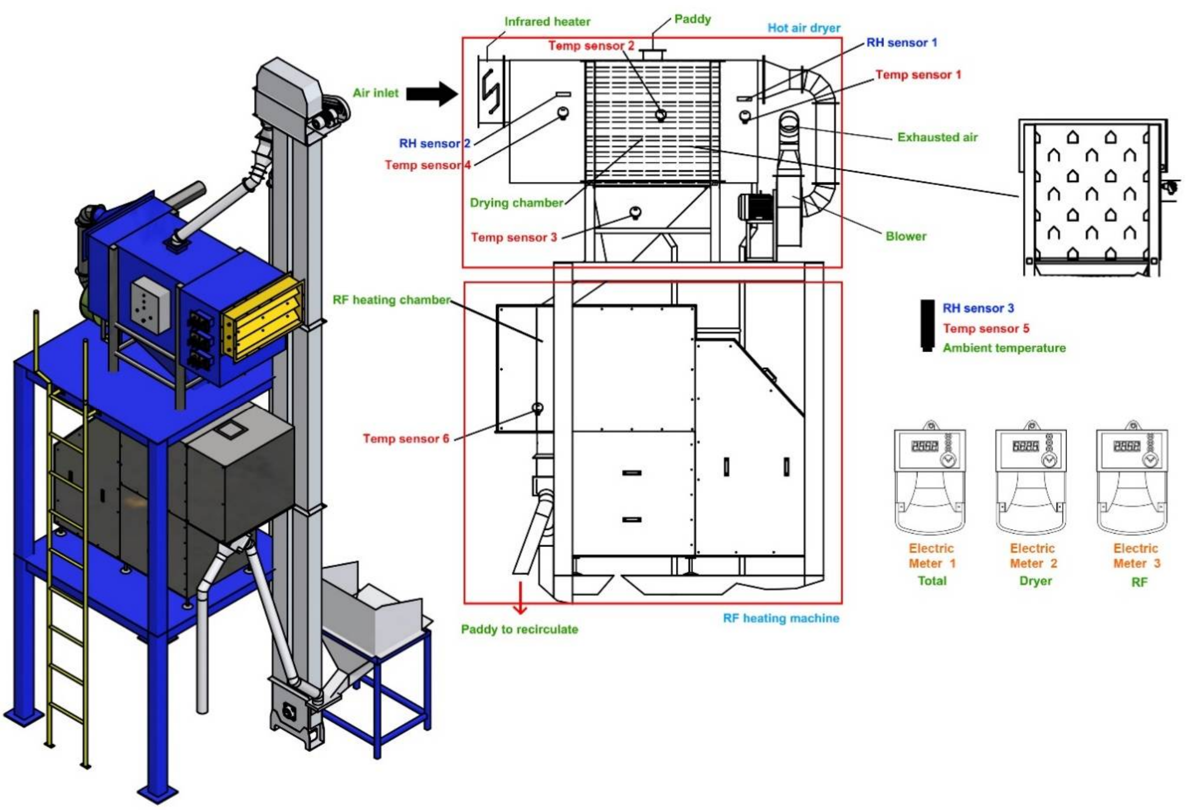


Figure 2. Schematic diagram of the industrial-scale continuous-flow hot air dryer combined with radio frequency heating.

2.3. Fissure Percentage Determination

The samples were then cleaned and dehusked to brown rice. One hundred kernels were randomly collected (approximately 2 g) for each measurement. In each replication, the measurement was repeated three times and was reported as mean and standard deviation. Brown rice samples were laid on a clear translucent plate above a fluorescent bulb and magnifying glass to count fissured kernels by visual inspection [17]. The fissures inside brown rice kernels were observed and recorded with the naked eye with a fissure degree of 0, 1, 2, 3, 4, and 5 or more fissures [18]. The fissure percentage was introduced to quantitatively calculate the proportion of brown rice kernels with different fissure degrees and it was defined as the ratio of brown rice kernels with different fissure degrees to the total amount of selected kernels according to Shen et al. [18]. The calculation method of the fissure percentage is shown in Equation (1).

$$\text{Fissure percentage } (\%) = \frac{N_f}{N_t} \times 100 \tag{1}$$

where N_f is the total amount of brown rice kernels at a certain fissure degree (0, 1, 2, 3, 4, $\geq$5) and N_t is the total amount of the brown rice kernels.

2.4. Milling Quality Determination

Milling quality was determined according to the method described in the Thailand standards for rice [19]. Dried paddy was collected and cleaned by a pre-cleaner machine (0.5 HP, Yont Phol Dee Co., Ltd., Nakhon Sawan, Thailand). A total of 375 g of clean paddy from each replication was collected, divided into 125 g portions, and stored in a plastic zipper bag. The measurement was repeated three times and reported as the mean and standard deviation. After husking two times with a rubber-roll husker machine (0.5 HP, Yont Phol Dee Co., Ltd., Nakhon Sawan, Thailand), the weight of the brown rice was recorded. Then, the brown rice was milled for 20 s by a horizontal friction-type whitener machine (0.5 HP, Yont Phol Dee Co., Ltd., Nakhon Sawan, Thailand). The white rice was obtained, and the weight of white rice was measured once its temperature was approximately equal to ambient temperature. Lastly, broken white rice was graded and removed from head rice by a circular-shaped hole sieve (diameter 2.4 mm) and hand-picking in order to completely separate the broken rice from the head rice. The weight of the head and broken rice was measured. After weight data were collected, the husk, bran, and head rice yield were calculated using Equations (2)–(4).

$$\text{Husk weight percentage } (\%) = \frac{W_{pd} - W_{br}}{W_{pd}} \times 100 \tag{2}$$

$$\text{Bran weight percentage } (\%) = \frac{W_{br} - W_{wr}}{W_{pd}} \times 100 \tag{3}$$

$$\text{Head rice weight percentage } (\%) = \frac{W_{hr}}{W_{pd}} \times 100 \tag{4}$$

where W_{pd} is the weight of rice from each measurement, W_{br} is the weight of brown rice, W_{wr} is the weight of white rice, and W_{hr} is the weight of the head rice yield.

2.5. White Rice Color Determination

A color value of white rice was determined with the CIE (L*, a*, b*) color scale using a chromameter (CR-400, Konica Minolta Sensing, Osaka, Japan). The whiteness index (WI) derived from Horrungsiwat et al. [6] was used to calculate and compare rice whiteness as shown in Equation (5).

$$\text{Whiteness index (WI)} = 100 - \sqrt{\left[(100 - L^*)^2 + a^{*2} + b^{*2}\right]} \tag{5}$$

where L* represents lightness–darkness ($0 \leq L \leq 100$), a* represents redness in positive value, a* represents greenness in negative value, b* represents yellowness in positive value, and b*represents blueness in negative value. The total color difference (ΔE*) which was used in the repeatability test and intended to be a single number metric for pass/fail decisions were defined in Equation (6).

$$\text{Total color difference } (\Delta E^*) = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{6}$$

where ΔL* is L* specimen minus L* reference, Δa* is a* specimen minus a* reference, and Δb* is b* specimen minus b* reference. In each replication, the measurement was repeated three times and reported as mean and standard deviation.

2.6. Sensory Evaluation

Sensory evaluation was assessed using hedonic scales for capturing liking data based on the method described by Horrungsiwat et al. [6]. The milled rice from three replicates within each treatment was thoroughly mixed, prepared and cooked with a rice to water ratio of 1:1.7 in an electric rice cooker. The cooked rice (1.5 g) was served in a white plastic bowl at 60 °C for sensory evaluation. The bowls were coded with three-digit numbers randomly selected for each treatment, so there were five codes. All five samples were served to each assessor simultaneously. The liking scores of color, odor, adhesiveness, texture, flavor, and overall were rated on a 9-point hedonic scale (1 means dislike very much, whereas 9 means like very much) by 100 untrained panelists who normally consume rice on a regular basis. The scores were recorded on a data sheet provided to each assessor.

2.7. Energy Consumption

A specific energy consumption (SEC) of the drying was determined using Equation (7) [20]:

$$\text{Specific energy consumption (SEC)} = \frac{E_{total}}{m_{eva}} \tag{7}$$

where SEC is the specific energy consumption (MJ/kg-H_2O), E_{total} is the total electrical energy supplied to the dryer and RF heating systems during the drying process (kWh), and m_{eva} is the amount of evaporated water resulting from the difference in weight of paddy before and after drying (kg-H_2O). Since the cost of electricity in Thailand is 3.2484 Thai baht per kWh, the exchange rate of Thai baht and US dollar was 33.47:1 on 9 December 2021, so the energy cost per kg of water evaporated (USD/kg-H_2O) was calculated using Equation (8):

$$\text{Energy cos t} = \frac{\left(P_{dryer} + P_{rf}\right)}{m_{eva}} \times \frac{3.2484}{33.47} \tag{8}$$

where P_{dryer} is the power supplied to dryer system and P_{rf} is the power supplied to RF heating system.

2.8. Statistical Analysis

All experimental data were reported as mean ± standard deviation (SD). The analysis was carried out by analysis of variance (ANOVA) and Duncan's new multiple range test (DMRT) for means comparison at a 5% probability level ($p < 0.05$) using SPSS software version 25 (IBM, New York, NY, USA).

3. Results and Discussions

3.1. Drying Characteristics

The drying rate versus the drying time of paddy drying by hot air and hot air combined with different RF heating temperature is shown in Figure 3. In the first 30 min of drying, the drying rate of paddy by hot air (HA), hot air with RF of 45 °C (HA/RF45), hot air with RF of 50 °C (HA/RF50), hot air with RF of 55 °C (HA/RF55), and hot air with RF of 60 °C (HA/RF60) were 0.0444, 0.0925, 0.1240, 0.1579, and 0.1769 kg water/kg dry matter per minute, respectively. Two distinct drying periods were observed; namely, an initial heating up period where the drying rate increased to the peak in the first 30 min followed by a falling rate period while the hot-air drying rate reached its peak in the first 120 min. The difference in peak shows that the RF heating was responsible for heating the paddy thoroughly in a shorter time compared to convective heating.

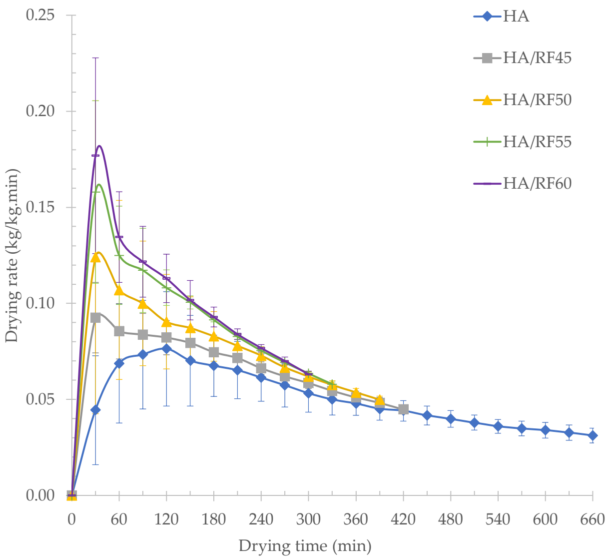


Figure 3. The drying rate versus drying time of paddy drying by hot air and hot air combined with different RF heating temperatures.

The drying resulted in a decrease in the moisture content of the paddy from an initial moisture content of 25–26% (w.b.) to a final moisture content of 14%. With regard to the final drying time, at which the final moisture content was 14%, drying paddy by HA, HA/RF45, HA/RF50, HA/RF55, and HA/RF60 took approximately 660, 420, 390, 330, and 300 min, respectively. Thus, the drying time saving was 36.36%, 40.91%, 50.00%, and 54.44%, respectively, when compared with the HA drying time as a baseline. Therefore, drying time required was less for combined drying using RF and hot air (HA/RF) as compared with hot air drying (HA). A drastic moisture loss was observed in the initial stage of the process, which was the first 120 min of drying time.

For all treatments, the drying time was found to reduce when increasing RF heating temperature as in the early drying stage, the moisture content of fresh paddy was as high as 25–26% (w.b.), the high water content in the paddy absorbed more energy due to the dielectric properties of paddy seed in different moisture contents, as reported by Pakawattana [21], and free water with high water activity was the majority of the water portion in the paddy in this early stage. The transfer and accumulation of heat accelerated the evaporation of the free water in the paddy. For the radiation heating method, the drying rate was found to be directly dependent on RF heating temperature level in this study, similar to that reported by Das et al. [22], who stated that the drying rate was found to be dependent on the radiation intensity level and that drying time was reduced when increasing radiation intensity.

3.2. Drying Kinetics

Due to the fact that the initial moisture content of paddy was not exactly the same for all the treatments, the moisture content data were transformed to the dimensionless moisture ratio by following Equation (9). Over a long period of time, the value of the equilibrium moisture content (M_e) becomes insignificant and relatively small compared to the moisture content of paddy at any time (M_t) and the initial moisture content of paddy (M_0) [23,24], since the prolonged exposure of grain to infrared radiation eventually caused the burning of the material [25]. The moisture ratio (MR) can be simplified as:

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} = \frac{\mathrm{M_t}}{\mathrm{M_0}} \tag{9}$$

The moisture ratio versus drying time of paddy drying by hot air and hot air combined with different RF heating temperatures is shown in Figure 4. After the first 30 min of drying, the moisture ratio of paddy dried by HA, HA/RF45, HA/RF50, HA/RF55, and HA/RF60 were 0.9636, 0.9186, 0.8912, 0.8624, and 0.8460, respectively. Afterwards, the curves indicated exponential decay. For all drying treatments, the drying time was reduced as the RF heating was combined. The higher the combined RF heating temperature, the shorter the drying time that was observed.

The thin-layer drying model was fitted to describe the drying curves. The Henderson and Pabis (single-term) model, derived from Fick's second law of diffusion, was used to describe the drying kinetics of this study. The model is shown in Equation (10).

$$\mathrm{MR} = \mathrm{a}\,\mathrm{e}^{-\mathrm{kt}} \tag{10}$$

where MR is the moisture ratio, a is the model constant, k is the rate constant, and t is the drying time in minutes. The rate constant (k) indicates the drying performance, where a high drying rate is represented with a high value [26]. The effective moisture diffusivity was calculated to describe the moisture migration in paddy during the drying process by using Equations (11)–(13) [27].

$$\mathrm{MR} = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 \mathrm{D_{eff}} \mathrm{t}}{\mathrm{R_s^2}}\right) \tag{11}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), t is the drying time in minutes, and R_s^2 is equivalent radius of sphere (m). Equation (11) evaluated numerically for Fourier number (Fo) given by ($D_{eff}t/R_s^2$) for diffusion and can be rewritten as:

$$\mathrm{MR} = \frac{6}{\pi^2}\exp\left(-\pi^2\mathrm{Fo}\right) \tag{12}$$

$$\mathrm{Fo} = -0.1013\ln(\mathrm{MR}) - 0.0504 \tag{13}$$

$$D_{eff} = \left(\frac{\mathrm{Fo}}{t/R_s^2}\right) \tag{14}$$

where D_{eff} was estimated by substituting the positive values of Fo and the drying time (t) along with equivalent radius of paddy grain in Equation (14). The paddy grain is approximated as isotropic spheres of 3 mm diameter [27]. The values of drying rate constant (k) as a function of RF heating temperature and the average effective moisture diffusivity (D_{eff}) of combined RF heating with hot air drying are presented in Table 1. The values of k and D_{eff} were found to increase with RF heating temperature. This could imply that the RF energy affected the rapid rise in temperature of the paddy from inside to outside paddy kernels, which in turn increased the vapor pressure and consequently led to faster drying diffusion of moisture towards the surface [28].

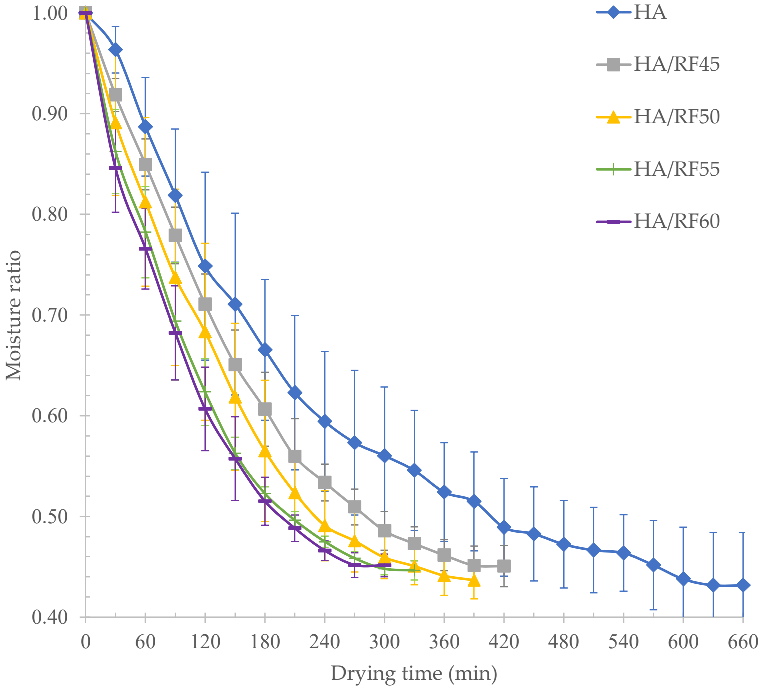


Figure 4. Drying kinetics for paddy drying with hot air and hot air combined with different RF heating temperatures.

Table 1. Thin layer drying model and average effective moisture diffusivity (D_{eff}) of combined RF heating with hot air drying.

Treatment	a	k	R^2	Average ($D_{eff} \times 10^{-9}$ m^2/s)
HA	0.8777	-1.2471×10^{-3}	0.9243	5.89 ± 1.84
HA/RF45	0.9203	-1.9822×10^{-3}	0.9489	8.15 ± 3.25
HA/RF50	0.9022	-2.1761×10^{-3}	0.9405	11.11 ± 2.28
HA/RF55	0.8895	-2.4665×10^{-3}	0.9293	12.41 ± 2.36
HA/RF60	0.8942	-2.6695×10^{-3}	0.9386	11.26 ± 5.04

Data are expressed as mean ± SD of triplicate determinations.

3.3. Fissure Percentage

The effects of different RF heating temperature conditions on the fissure percentage of brown rice kernels with different fissure degrees are shown in Table 2. The fissure percentage was divided into four groups, namely None (0 fissure), Few (1–2 fissures), Moderate (3–4 fissures), and Severe (>5 fissures), as reported by Shen et al. [4]. The morphology of fissures in white rice with different fissure degree is shown in Figure 5. When combining RF heating with a drying process at 45–60 °C, the fissure percentage of brown rice kernels with "None" fissure degree was significantly decreased from 94.22 ± 2.99% to 30.89 ± 8.79%. On the contrary, the fissure percentage of brown rice kernels with "Few", and "Severe" fissure degree were significantly increased from 5.11 ± 2.41% to 23.33 ± 3.85%, and 0.00% to 44.67 ± 8.09%, respectively. However, the fissure percentage of brown rice kernels with "Moderate" fissure degree showed no significant difference. The "None" fissure degree of brown rice kernels in HA, and HA/RF45 were not significantly different, but it dramatically decreased as RF heating temperature increased. Consequently, the "Few" fissure degree of brown rice kernels began to rise at HA/RF45 and reached its maximum value at HA/RF50, before gradually decreasing at HA/RF55 and HA/RF60, respectively. Moreover, the "Severe" fissure degree of brown rice kernels started appearing in HA/RF45 and dramatically increased at HA/RF55 and the maximum value was observed at HA/RF60. This result showed that RF heating affected the fissure percentage significantly due to the high absorption of RF energy inside the rice kernels, which was also reported by Shen et al. [4]. The overall temperature of germinated brown rice kernels was improved to form a greater moisture content gradient because of the high absorption of microwave energy inside the kernels. Therefore, the optimum condition was determined to be HA/RF45 in terms of fissure percentage, while no rice fissure degree was significantly different when compared to the HA treatment.

Table 2. Effects of different RF heating temperature conditions on the fissure percentage of brown rice kernels with different fissure degrees.

Treatment	None (0 Fissure)	Few (1–2 Fissures)	Moderate (3–4 Fissures)	Severe (>5 Fissures)
HA	94.22 ± 2.99^{d}	5.11 ± 2.41^{a}	0.67 ± 0.67^{ab}	0.00^{a}
HA/RF45	84.89 ± 4.74^{d}	13.00 ± 6.93^{ab}	0.33 ± 0.58^{a}	1.78 ± 2.51^{a}
HA/RF50	69.33 ± 3.00^{c}	23.33 ± 3.85^{b}	1.44 ± 1.26^{ab}	5.89 ± 4.35^{a}
HA/RF55	50.78 ± 9.10^{b}	22.67 ± 6.66^{b}	2.33 ± 2.60^{ab}	24.22 ± 15.11^{b}
HA/RF60	30.89 ± 8.79^{a}	21.44 ± 7.41^{b}	3.00 ± 0.58^{b}	44.67 ± 8.09^{c}

Data are expressed as mean ± SD of triplicate determinations. The same letter indicates that there was no significant difference ($p > 0.05$) between the same fissure percentage in a column.

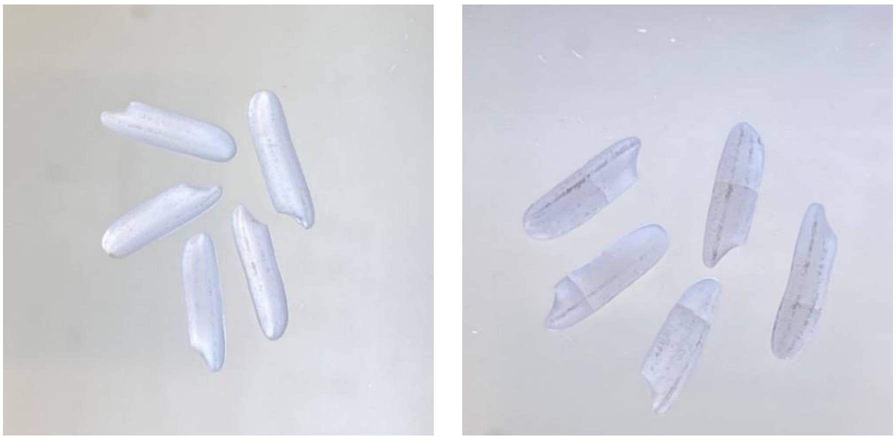
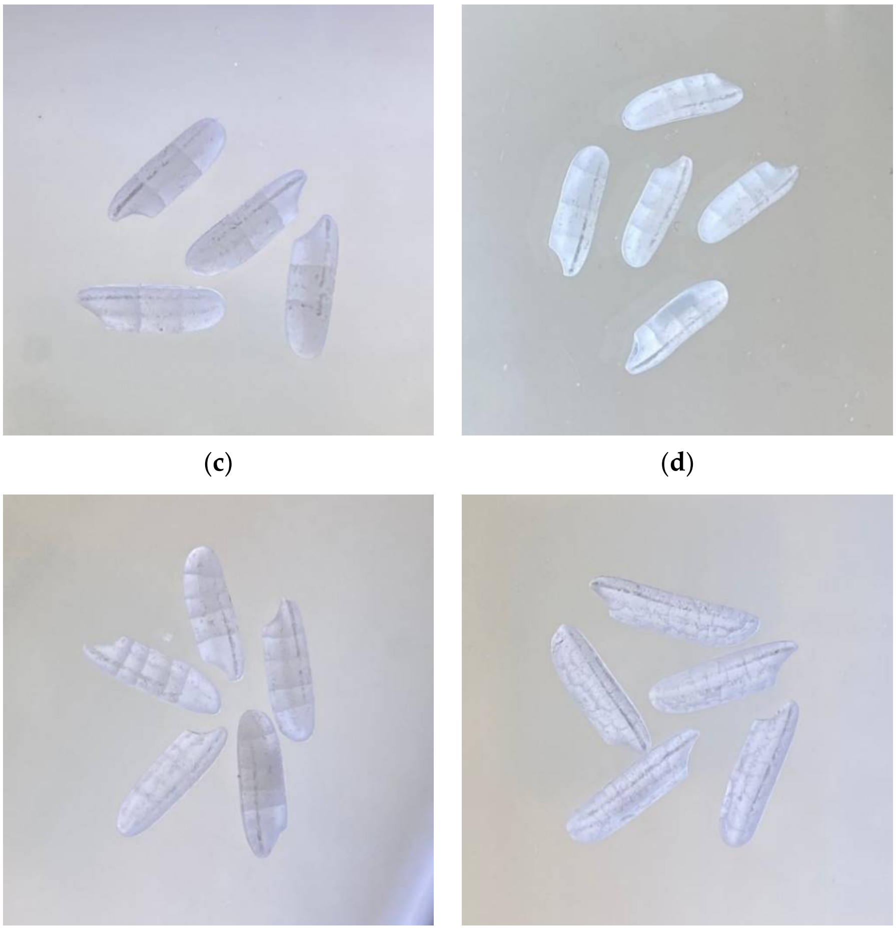

(**a**) (**b**)

Figure 5. *Cont.*



(**c**) (**d**)

(**e**) (**f**)

Figure 5. Morphology of fissures in white rice with different fissure degrees: (**a**) white rice with 0 fissure; (**b**) white rice with 1 fissure; (**c**) white rice with 2 fissures; (**d**) white rice with 3 fissures; (**e**) white rice with 4 fissures; (**f**) white rice with >5 fissures.

3.4. Color Evaluation

Table 3 shows the color evaluation of white rice after being dried at different RF heating temperature conditions. It was found that the white rice, after being treated, had a slightly greenish-yellowish color where the L* and a* values ranged from 66.99 ± 0.41 to 69.50 ± 0.57, and −0.44 ± 0.18 to −0.07 ± 0.14, respectively. There was a significant difference in lightness value (L*) and red–green value (a*), while yellow–blue value (b*) and whiteness index (WI) showed no significant differences. The L* value of the white rice tended to decrease but the a* value tended to increase with RF heating temperatures. Moreover, no significant difference in total color difference (ΔE*) was observed between white rice dried at different RF heating temperatures. Considering HA treatment as a conventional convective method in industrial paddy dryers presently, all color values were visualized as acceptable values. Consequently, the RF heating was combined with the drying process. The L* value started to decrease significantly as a result of rice granules changing from a rough to smooth surface, particularly at high microwave power intensity (4–6 W/g), as reported by Horrungsiwat [6]. Nevertheless, it increased in HA/RF55. Additionally, the a* value was significantly increased, yet it dropped in HA/RF60.

These color values altered depending on the convective drying conditions, with an instant increase in paddy temperature being caused by RF energy, which accelerated the Maillard reaction and the transition of color substances from rice husk and rice bran to endosperm, causing discoloration [6,7,29,30]. Accordingly, combining RF heating and convective drying at all given conditions could be statistically applied in terms of the b* and WI values, even though there were significant differences in L* and a* values.

Table 3. Color evaluation of white rice after being dried at different RF heating temperature conditions.

Treatment	L*	a*	b*	WI	ΔE*
HA	69.50 ± 0.57^{b}	-0.44 ± 0.18^{a}	10.31 ± 1.72	67.77 ± 0.17^{b}	0.00
HA/RF45	66.99 ± 0.41^{a}	-0.27 ± 0.14^{ab}	8.95 ± 0.62	65.79 ± 0.42^{ab}	2.99 ± 0.74^{a}
HA/RF50	67.00 ± 1.19^{a}	-0.19 ± 0.06^{b}	10.09 ± 1.59	65.47 ± 1.39^{a}	2.67 ± 1.29^{a}
HA/RF55	67.72 ± 1.71^{a}	-0.07 ± 0.14^{b}	9.54 ± 1.05	66.33 ± 1.67^{ab}	2.69 ± 0.96^{a}
HA/RF60	67.46 ± 0.21^{a}	-0.16 ± 0.11^{b}	9.83 ± 1.31	65.99 ± 0.56^{ab}	2.77 ± 0.40^{a}

Data are expressed as mean ± SD of triplicate determinations. The same letter indicates that there was no significant difference ($p > 0.05$) between the same color value in a column.

3.5. Milling Quality Determination

The data of milling quality for every treatment was collected by milling three replicates and there were three measurements (125 g of paddy per measurement) within each replicate. The milling quality determination of paddy after being dried at different RF heating temperatures is shown in Table 4. It was found that head rice (HRY) and bran yield (BY) after treatment were significantly different, ranging from 27.56 ± 1.20 to 33.42 ± 1.31 and 9.96 ± 0.77 to 12.09 ± 0.77, respectively, whereas there was no significant difference in husk, brown rice, white rice, and brokens yield. Considering a yield of HA treatment as a baseline, the head rice yield was maximized in HA/RF45 treatment, but gradually decreased to the minimum yield with HA/RF60 treatment. While the bran yield was gradually increased and reached a maximum value with HA/RF60 treatment. The various combined RF heating levels led to paddy temperature differences during drying. This result indicates that paddy temperature played an important role in causing a moisture gradient inside rice kernels, which generated differential stress and fissure, as is supported by Cnossen et al. [31]. The fissure formation was based on the response of rice kernels to tensile and compressive stresses due to moisture content gradients within kernels. Le et al. [32] reported that the fluctuation in HRY was due to the fluctuated heat generation by microwave heating because the microwave heating was the selected heating technique, and the suitable moisture content might cause a change in rice starch properties in terms of more agglomeration. With regard to milling quality, the HRY is the most important characteristic concerned in industrial rice millers as it proportionally affects the income of the business. Normally, the higher the HRY is, the more preferable the drying condition. This study might show different milling quality compared to other studies as it was also dependent on rice varieties, cultivation practices, drying conditions [33] and inherent fissures that occur in the field prior to harvest or during harvesting and processing [31]. Additionally, the bran yield (BY) was increased because the bran layer was easily peeled off from the brown rice kernel. Therefore, the degree of milling was increased despite milling time being constant at 20 s for every measurement. The degree of milling was observed by determining the extent of removal of germ or layers of bran from rice kernels during various milling operations [34]. The BY was subjected to different combined RF heating in the drying process starting from HA/RF50. The rice starch granule was changed from rough to smooth surface and regarded as the disappearance of starch granules attributed to the microwave heating drying process [5,6]. This might imply that when the temperature inside the rice kernel was higher than 50 °C, the heat gradient inside the rice kernel was too high, and this resulted in surface baking and case-hardening. This phenomenon was observed in rice drying using microwaves as reported by Olatunde and Atungulu [5]. The result showed that the RF heating had beneficial effects on the HRY and BY and the preferable treatment was determined to be the HA/RF50 condition.

Table 4. Milling quality determination of rice after being dried at different RF heating temperature conditions.

Treatment	Husk	Brown Rice	White Rice	Head Rice	Brokens	Bran
HA	30.22 ± 0.94	69.78 ± 0.94	59.82 ± 1.63	32.80 ± 1.92 ^{c}	27.02 ± 0.31	9.96 ± 0.77 ^{a}
HA/RF45	28.44 ± 0.67	71.56 ± 0.67	60.80 ± 0.53	33.42 ± 1.31 ^{c}	27.73 ± 2.28	10.76 ± 0.15 ^{ab}
HA/RF50	27.64 ± 1.51	72.36 ± 1.51	61.07 ± 0.80	31.91 ± 0.67 ^{bc}	29.33 ± 0.26	11.29 ± 0.77 ^{bc}
HA/RF55	28.18 ± 1.34	71.82 ± 1.34	59.82 ± 2.54	29.16 ± 1.61 ^{ab}	30.76 ± 2.26	12.00 ± 1.22 ^{c}
HA/RF60	29.60 ± 1.33	70.40 ± 1.33	58.31 ± 2.04	27.56 ± 1.20 ^{a}	30.40 ± 2.78	12.09 ± 0.77 ^{c}

Data are expressed as mean ± SD of triplicate determinations. The same letter indicates that there was no significant difference ($p > 0.05$) between the same yield value in a column.

3.6. Sensory Evaluation

The liking score of cooked rice after each treatment was recorded by 100 untrained panelists and is shown in Table 5. The data show that all seven sensory attributes were significantly different. It was observed that the cooked rice with HA treatment scored the highest among all attributes and that the scores gradually decreased in HA/RF45 and HA/RF50, while the score of all attributes in HA/RF55 were slightly increased before once again dropping for HA/RF60. This could mean that combining RF heating into the convective drying process adversely affected the cooked rice quality starting from the lowest RF heating level at HA/RF45 as demonstrated by untrained panelists. Similarly, Jiao et al. [35] also reported that the RF treatment had an adverse impact on the stickiness and cold rice texture, while Liu and Wang [36] argued that RF disinfestation treatment had no significant influence on the flavor, appearance, or taste of the milled rice and Horrungsiwat et al. [6] also came to the same conclusion. Although the properties of the rice and the quality of the cooked rice from the combined microwave and hot air drying conditions varied, liking scores based on the color, adhesiveness, odor, flavor, taste, and overall scores were no different. Thus, we expected that further quantitative standard measurement in each attribute would be able to describe the physico-chemical property changes in the rice kernels.

Table 5. Liking scores of cooked rice after being dried under different RF heating temperature conditions.

Treatment	Color	Odor	Adhesiveness	Texture	Flavor	Overall
HA	6.97 ± 1.67 ^{c}	6.39 ± 1.79 ^{c}	7.27 ± 1.51 ^{d}	7.02 ± 1.71 ^{c}	7.16 ± 1.61 ^{c}	7.47 ± 1.39 ^{d}
HA/RF45	7.05 ± 1.60 ^{c}	6.10 ± 1.87 ^{c}	5.85 ± 2.02 ^{c}	5.94 ± 1.97 ^{b}	6.35 ± 1.78 ^{b}	6.69 ± 1.69 ^{c}
HA/RF50	5.25 ± 1.90 ^{a}	4.87 ± 1.94 ^{a}	4.63 ± 2.00 ^{ab}	4.73 ± 2.07 ^{a}	5.10 ± 2.11 ^{a}	5.47 ± 1.74 ^{ab}
HA/RF55	6.11 ± 1.84 ^{b}	5.42 ± 1.53 ^{b}	5.01 ± 1.91 ^{b}	5.09 ± 1.83 ^{a}	5.42 ± 1.85 ^{a}	5.76 ± 1.74 ^{b}
HA/RF60	5.00 ± 1.98 ^{a}	5.02 ± 1.82 ^{ab}	4.25 ± 2.02 ^{a}	4.56 ± 1.89 ^{a}	4.89 ± 1.96 ^{a}	5.10 ± 1.95 ^{a}

Data are expressed as mean ± SD of triplicate determinations. The same letter indicates that there was no significant difference ($p > 0.05$) between the same sensory value in a column.

3.7. Energy Consumption

Table 6 shows the electricity power consumption of the drying system, including the hot air dryer and the RF heating machine, the specific energy consumption (SEC) indicating the amount of energy consumed (MJ) to evaporate the water in the paddy (kg-H_2O), and the specific energy cost indicating the electricity cost (USD) to evaporate the water per kilogram (kg-H_2O). The amount of SEC and specific energy cost decreased at all RF heating temperatures, with HA/RF45 having the lowest values for water evaporation of 3.25 ± 0.68 MJ/kg-H_2O and 0.0875 USD/kg-H_2O, respectively. These phenomena could be interpreted as follows. The moisture migration rate from inside the paddy kernels was increased at HA/RF45 in accordance with the moisture removal rate and thus was the most suitable condition in terms of SEC and the specific energy cost. Moreover, Shinde et al. [3] stated that the hybrid drying with hot air and RF was the least energy intensive, needing only 40% of the energy demanded by the hot air dryer with recirculation in tea drying.

Table 6. Electricity power consumption, specific energy consumption and specific energy cost after being dried under different RF heating temperature conditions.

Treatment	Power Consumption (kWh)		SEC	Energy Cost
	Hot Air Dryer	RF Machine	(MJ/kg-H_2O)	(USD/kg-H_2O)
HA	68.67 ± 8.50 ^{b}	0.00	4.22 ± 0.92	0.1139 ± 0.0247
HA/RF45	33.00 ± 4.36 ^{a}	18.20 ± 6.89 ^{a}	3.25 ± 0.68	0.0875 ± 0.0184
HA/RF50	31.67 ± 2.08 ^{a}	26.13 ± 9.87 ^{ab}	3.95 ± 0.10	0.1064 ± 0.0027
HA/RF55	26.67 ± 1.53 ^{a}	26.87 ± 1.53 ^{ab}	3.99 ± 0.45	0.1076 ± 0.0120
HA/RF60	25.33 ± 1.53 ^{a}	29.00 ± 2.00 ^{b}	4.18 ± 0.39	0.1127 ± 0.0105

Data are expressed as mean ± SD of triplicate determinations. The same letter indicates that there was no significant difference ($p > 0.05$) between the same sensory value in a column.

4. Conclusions

The effects of the four different RF heating temperature levels combined with the hot air drying process were compared to convective hot air drying. The drying characteristics and the moisture diffusivity showed that the higher the combined RF heating temperature, the shorter the observed drying time. Although the HA/RF60 had the shortest drying time, the fissure percentage and milling quality data showed that the optimum conditions were HA/RF45 and HA/RF50, respectively. None of the five treatments significantly affected the discoloration of white rice. The liking scores of cooked rice after being dried by the HA method were the highest, whereas they gradually decreased significantly as the RF heating temperature increased. Lastly, the amount of SEC and specific energy cost decreased at all RF heating temperatures compared to the hot air (control) treatment. This study concluded that HA/RF45 was the optimum condition for using a hot air dryer combined with radio frequency heating in an industrial scale process. Further studies should be conducted focusing on low RF heating temperatures and observed physico-chemical property changes in the rice kernels after treatment.

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