Infrared drying of germinated paddy with high temperature ranges: drying kinetics and physical quality aspect

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Summary
Drying is a popular food preservation method by which the process can affect the physico-chemical properties of food. Therefore, this study investigated the effect of infrared radiation drying on drying kinetics and physico-chemical properties of the germinated brown rice variety. The germinated paddies were dried at temperatures of 90 °C, 110 °C or 130 °C under three levels of powers (1 000 W, 1 350 W and 1 500 W). The approximation of the diffusion model was the best for predicting the drying characteristics of the germinated paddy. The effective diffusion coefficient of the germinated brown rice, analysed using the Fick's law of diffusion, was in the range from 2.034×10^{-10} $m^2 \cdot s^{-1}$ to 4.023×10^{-10} $m^2 \cdot s^{-1}$. The percentage changes of the head rice yield of paddy after germination and drying were higher than the non-germinated paddy. The changes in physico-chemical properties (cooking time, solid loss, water uptake and texture) after drying were significantly influenced by the drying conditions. The drying temperature affected the morphology and thermal properties of the germinated rice. The conditions of drying did not affect the γ-aminobutyric acid content. The specific energy consumption of drying the germinated brown rice at high temperature was lower than that at low temperature.

Keywords
effective diffusion; germinated brown rice; infrared dryer; cooking time; solid loss; water uptake

Hawm Gra Dung Ngah rice variety, a local line of Narathiwat, a province in the south of Thailand, is rich in antioxidants, iron, zinc and calcium. In addition, it has remarkably mild aroma and the cooked rice is sleazy-crumbly. Therefore, this rice variety is worth processing to add its nutritional value, which can be achieved by germination. Currently, germinated rice is considered to be a health-promoting food for health-conscious individuals. The germination process may deliver the improvement of the texture quality of cooked brown rice and increase the levels of bioactive compounds. γ-Aminobutyric acid (GABA) in particular has attracted most attention due to its unique bioactivity of the germinated brown rice (GBR) [1]. GABA was reported to improve brain functioning, sleep-enhancing, lowering blood pressure and balancing blood sugar levels. As a result, this reduces the stress and the risks of high blood pressure [2, 3].

As the germination process leads to a high moisture content of grains, storage of germinated rice is inappropriate as it may cause spoilage from the invasion of microorganisms, resulting in a loss of value. This can be solved by thermal drying to achieve safe storage and preservation of quality [4]. Dying is an effective process for germinated rice before storing it. Drying of the crops does not only reduce moisture but also minimizes microbial spoilage levels. As a result, dried crops can be stored much longer. Various drying techniques are used for drying the germinated brown rice, namely, sun drying [3], hot-air drying [5] and microwave drying [4]. Sun drying and hot-air drying require a large space and long drying times. Such long drying time may affect the quality of the

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germinated brown rice [6]. Microwave drying is a technique with a high drying rate, but some its disadvantages were identified for, such as partial loss of aroma and texture damage [7]. Thus, an alternative method to preserve the quality of the crops and their nutritive value is required.

An effective method for preserving the quality of agricultural products is infrared drying. For this method, infrared radiation is transferred from the heating element to the surface of the product, not through any intermediary medium. The radiation impinges on the exposed material and penetrates it. Then, it is transformed to sensible heat. In addition, infrared radiative heating is assumed to inactivate microorganisms [8]. This technique directly generates heat inside the product, which decreases energy requirement and improves efficiency of heating leading to a better quality of the product [9]. However, the quality of the product also depends on its properties [10].

According to the advantage of the infrared drying technique mentioned above, many studies have been conducted to observe the effects of infrared drying on the quality of the product [11]. Chatchavanthatri et al. [12] studied the effects of parboiling and infrared radiation drying on the quality of germinated brown rice. Adak et al. [13] analysed the nutrient quality and bioactivity of dried strawberries using a convective-infrared drying system.

In this work, we investigated the influence of infrared radiation, drying temperature and drying kinetics as well as physical properties of a germinated brown rice variant.

MATERIALS AND METHODS

Sample

Hawm Gra Dung Ngah rice variety was obtained from the Rice Research Institute in Pattani Province (Pattani, Thailand). The paddy was cleaned and then soaked in water at room temperature (±30 °C) for 24 h. During the soaking process, the water was changed every 4 h. Then, the paddy sample was removed and put into a box that was covered with a moistened thin cloth and the lid of the box was closed for 48 h [14]. At every 6 h, the paddy sample was sprayed with water to add moisture. After the paddy sprouted for approximately 0.5–1 mm, it was steamed at 95 ± 5 °C for 30 min [15]. After that, it was placed in ambient air before drying. The moisture content of the sprouted paddy was analysed by AOAC method 977.11 [16].

Infrared drying

The samples were dried using an infrared dryer, the schematic diagram of which is shown in Fig. 1. It consisted of a drying chamber with inner dimensions of 52 cm × 60 cm × 36 cm. Three infrared heaters (Infrapara, Guangdong, China) were installed with a 15 cm distance between the lamps, together with a 48 W cooling fan (Sunon, Kaohsiung, Taiwan). The samples were placed 20 cm away from the infrared heat source.

Drying process

Samples (700 g) with initial moisture content of approximately 50–55 % were dried with the infra-

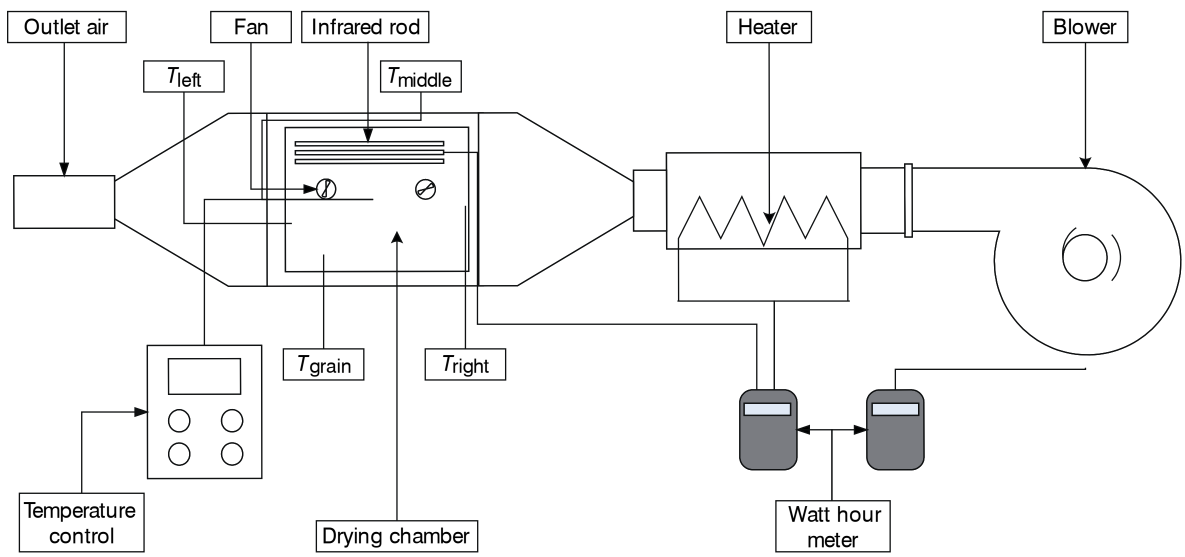

Fig. 1. A schematic diagram of the infrared dryer.

Tab. 1. The constant values of empirical models of drying the germinated paddy under various conditions.

Name of model	Model equation	Constant of model	R^2	χ^2
Newton	$MR = \exp(-kt)$	$k = 0.0216 - 0.003T - 0.00001P$	0.9940	0.0003
Logarithmic	$MR = a\exp(-kt) + b$	$k = 2.9127 + 0.0113T + 0.0005P$ $a = -0.0001$ $c = 0.9604$	0.9807	0.0009
Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(kat)$	$k = 57.2724 - 0.7671T - 0.0319P$ $a = 0.0004$	0.9939	0.0004
Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	$k = 17.3876 - 0.2329T - 0.0097P$ $a = 0.0004$ $b = 0.0012$	0.9941	0.0003
Logistic	$MR = \frac{a}{1+\exp(kt)}$	$k = -0.0317 + 0.0004T + 0.00002P$ $a = 1.9610$	0.9905	0.0006

MR – moisture ratio (in percent); *t* – time (in minutes); *a, b, c, k* – constants in thin-layer drying equation, *T* –temperature of drying (in degrees celsius), *P* – power (in watt), R^2 – coefficient of determination, χ^2 – reduced chi-square.

red dryer using electrical power of 1 000 W, 1 350 W and 1 500 W at a temperature of 90 °C, 110 °C or 130 °C until the final moisture content was approximately 20–25 %. After drying, the samples were tempered immediately in an insulated container for 30 min [17]. Subsequently, the samples were ventilated by ambient air until its moisture content was reduced to 13–15 %. Following that, the physical quality of dried samples was analysed. Similarly, control samples were prepared by dehydrating paddy using ambient air ventilation until the final moisture content was approximately 13–15 %.

Drying kinetic

Tab. 1 presents the common models for the drying process. The validity of those models for describing the drying of germinated paddy was verified by the experimental data. The moisture ratios (*MR*) of germinated paddy during drying were calculated by using Eq. 1. [18]

$$MR = \frac{M_t - M_{eq}}{M_{in} - M_{eq}} \quad (1)$$

where M_t is moisture content at time t, M_{in} is initial moisture content and M_{eq} is equilibrium moisture content.

For infrared drying, M_{eq} is relatively small compared with M_{in}. Therefore, M_{eq} can be ignored and Eq. 1 can be simplified as Eq. 2. [19].

$$MR = \frac{M_t}{M_{in}} \quad (2)$$

The drying rate (*DR*) was computed from the change in moisture content that occured in each consecutive time interval as shown in Eq. 3 [18].

$$DR = \frac{(M_i - M_f)W_d}{\Delta t} \quad (3)$$

where M_i and M_f are initial and final moisture content (in percent of dry basis), respectively, W_d is dry weight of sample (in grams) and Δt is drying time (in minutes).

SPSS software (SPSS, Chicago, Illinois, USA) was used to analyse the parameters of the non-linear regression equation. The models for the drying process were validated based on coefficient of determination (R^2) and reduced chi-square (χ^2). The model with the highest values of R^2 and the lowest values of χ^2 was considered the most suitable. R^2 and χ^2 were calculated by Eq. 4 and Eq. 5, respectively.

$$R^2 = 1 - \frac{\sum\left(MR_{pre,i} - MR_{exp.i}\right)^2}{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{ave}\right)^2} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre.i}\right)^2}{N - z} \quad (5)$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted results of moisture ratio for a number of observations, respectively, MR_{ave} is the average moisture ratio of the experimental data, N is number of observations, and z is number of constants.

Effective diffusion coefficient

Fick's law of diffusion can be used to describe the diffusivity of the moisture transfer within the seed having cylindrical (finite cylinder) and short shape under the conditions of very small shrinkage and constant drying conditions [20]. The moisture diffusivity is described by Eq. 6.

$$MR = \left(\frac{8}{\pi^2}\right)\sum_{n=0}^{\infty}\frac{4}{\lambda_n^2}\exp\left(-\frac{\lambda_n^2 D_{eff} t}{r_0^2}\right) \times \sum_{m=1}^{\infty}\frac{1}{(2m+1)^2}\exp\left(-\frac{\pi^2(2m+1)^2 D_{eff} t}{4L^2}\right) \quad (6)$$

where λ_n is the root of a Bessel function of the first kind and zero-order, r is the radius of the paddy kernel (in metres). D_{eff} is effective moisture diffusivity (in square meter per second), t is drying time (in minutes), L is the grain length (in metres). Only $n = (1, 2)$ and $m = (0, 1)$ are considered. The first three terms were considered due the lengthy drying time resulting in the latter term being relatively small compared with the first three terms. The radius (r) and length (L) of the Hawm Gra Dung Ngah paddy kernel are 0.99×10^{-3} m and 9.13×10^{-3} m, respectively.

The effective diffusivity can be expressed by the Arrhenius equation, as shown in Eq. 7 [20].

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{7}$$

where D_0 is the pre-exponential factor of the Arrhenius equation, E_a is the activation energy (in joules per moles), R is the universal gas constant (8.314 $J \cdot mol^{-1} K^{-1}$) and T is the absolute air temperature (in kelvins).

Head rice yield

Dried germinated paddy samples of 125 g were dehulled in a rubber roller dehuller (Model P-1, Ngek Seng Huat, Bangkok, Thailand). After that, the germinated brown rice was graded by a cylindrical separator (Model I-1, Ngek Seng Huat) by which a kernel with three-quarters of length was selected and weighed. The head rice yield (HRY) of the germinated brown rice was calculated by Eq. 8 and expressed in percent.

$$HRY = \frac{M_{GBR}}{M_{GP}} \times 100 \tag{8}$$

where M_{GBR} is the mass of a full grain of the germinated brown rice (in grams), M_{GP} is the mass of germinated paddy (in grams).

Cooking properties

Cooking time was determined by the method of Sarangapani et al. [21]. Germinated brown rice samples (2 g) were put in the test tube containing deionized water (20 ± 0.01 ml). After that, the test tube was put in a water bath and the temperature was set at 98 ± 1 °C. After 15 min of cooking, five grains of rice samples were removed at every 1 min interval to determine optimum cooking time. The suitable cooking time was predicted by pressing the cooked rice sample between two glass slides until no white core was left.

Solid loss and water uptake

The solid loss and water uptake were determined by using the modified method of Sarangapani et al. [21]. Germinated brown rice sample of 2 g was put in the test tube containing 20 ± 0.01 ml of deionized water. After that, the test tube was put in a water bath at a temperature of 98 ± 1 °C and incubated for a specified time. Then, the water in test tube was drained into an aluminium cup and dried in an oven at a temperature of 100 °C for 24 h. The solid loss (SL) was estimated by Eq. 9 and expressed in percent.

$$SL = \frac{W_a - W_d}{W_s} \times 100 \tag{9}$$

where W_a is weight of aluminium cup (in grams), W_d is weight of aluminium cup after drying (in grams), W_s is weight of the germinated brown rice sample (in grams).

Finally, the rice sample in the test tube was weighed and the water uptake (WU) was calculated by Eq. 10.

$$WU = \frac{W_c - W_{uc}}{W_{uc}} \tag{10}$$

where W_c is weight of cooked the germinated brown rice kernels (in grams) and W_{uc} is weight of uncooked germinated brown rice kernels (in grams).

Textural properties of germinated rice

The germinated brown rice samples were cooked in the aluminium cup using at a ratio of water to rice of 1.5 : 1. Textural properties were determined by the method of Chungcharoen et al. [22] using Texture Analyzer TA.XT2i (Stable Micro Systems, Godalming, United Kingdom). Ten kernels of cooked germinated brown rice samples were placed on a plate. A cylindrical probe with a diameter of 50 mm was used to compress during the test and post-test, with the probe speed of 1 $mm \cdot s^{-1}$ and 10 $mm \cdot s^{-1}$, respectively. The hardness of the cooked germinated brown rice was determined as a maximum compressive force at 85% strain of force deformation curve.

Scanning electron microscopy

A scanning electron microscope (model JSM-5800LV/JSM-5800 (JEOL, Tokyo, Japan) at an acceleration voltage of 15 kV, with a magnification of 1 000×, was utilized to investigate the microstructure (kernel surface and center of the endosperm) of the dried rice. The method followed that of Lang et al. [23].

γ-Aminobutyric acid content

GABA analysis was performed according to the procedure of Netkham et al. [24]. Germinated brown rice was mashed and sifted through a 11-μm sieve. Each of the rice flour samples (3 mg) was mixed with 30 ml of 80% (v/v) ethanol (RIC Labscan, Bangkok, Thailand), shaken for 24 h and then filtered through Whatman paper No. 1 (Whatman, Maidstone, United Kingdom). The collected supernatant was dried in an evaporator at 40 °C under vacuum. The dried sample was dissolved in 3 ml of deionized water. The sample solution (0.2 ml) was added to the test tube together with 0.2 ml of 0.2 mol·l^{-1} borate buffer of pH 9 (Sigma Aldrich, St. Louis, Missouri, USA) and 1.0 ml of 6% phenol (Sigma Aldrich). The solutions were shaken and cooled in a cooling bath for 5 min. Subsequently, 0.4 ml of 75 g·l^{-1} sodium hypochlorite (RIC Labscan) was added to the test tube. Finally, the solution was boiled in a water bath for 10 min and cooled in an ice bath for 5 min The absorbance was measured at 630 nm using UV-Vis spectrophotometer.

Specific energy consumption

The specific energy consumption (*SEC*) is defined as the energy required to remove a unit mass of water from the sample with an initial moisture content of 55.0 ± 5.0 % to reach 20.0 ± 5.0 %. The total energy was measured as the sum of energy consumption by the infrared radiation source (*P*), which had no heat recovery of the heat loss in the exhaust air. *SEC* was expressed in megajoule per mole and determined by Eq. 11.

$$SEC = \frac{3.6P}{(M_{in} - M_f)W_d} \quad (11)$$

where P is total amount of energy consumed during infrared drying (in kilowatt hour), M_{in} is initial moisture content, M_f is final moisture content, W_d is the dry weight (in kilograms), and 3.6 is a conversion factor of energy units from kilowatt hour to megajoule.

Statistical analysis

Data analysis was performed using SPSS software (SPSS). Differences between mean values were estimated using one-way analysis of variance with Duncan's multiple range tests at a confidence level of 95% ($p < 0.05$).

RESULTS AND DISCUSSION

Drying kinetics

Fig. 2 shows the drying curve (moisture ratio against drying time) of germinated paddy for various infrared radiation powers and drying temperatures. From the plot it can be seen that the moisture ratio for all experiments decreased with an increase in drying time. At different drying temperatures (Fig. 2A), the results indicated that the increase in the drying temperature resulted in an increase in the drying rate and a decrease in drying time. This outcome was obtained because the increase in drying temperature generated an increase in the temperature gradient between the energy source and material, whereas the higher the moisture transfer rate, the higher the drying rates [25].

Fig. 2B demonstrates the effect of power level on the moisture ratio of germinated paddy at various times. It was observed that increasing the infrared radiation power had a significant effect on the drying time. That was because the thermal gradient in the product was greater in higher powers and this accelerated the process of drying. The duration of drying at 1 000 W, 1 350 W

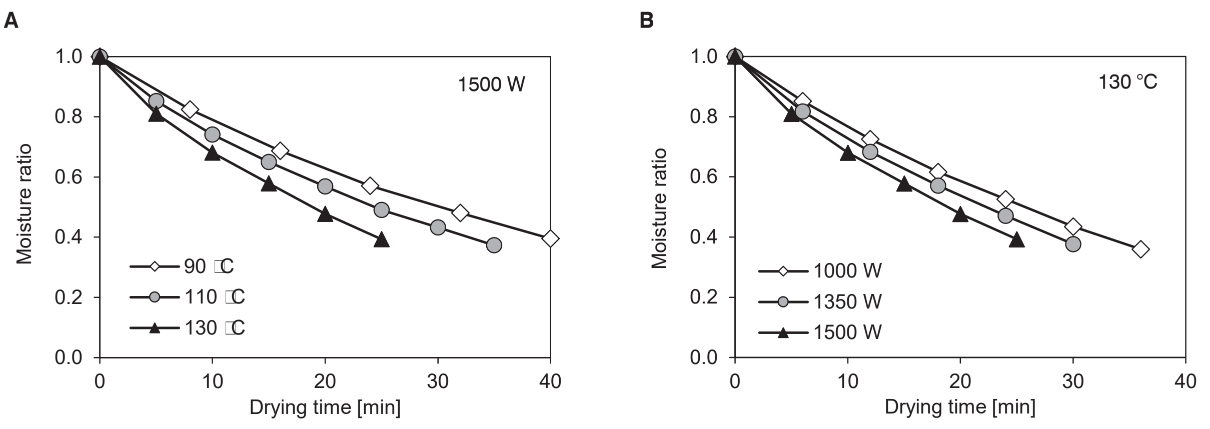

Fig. 2. Drying curves of germinated paddy.

A – various drying temperatures at infrared power 1 500 W, B – various infrared radiation powers at drying temperature 130 °C.

and 1 500 W was found to be 50 min, 45 min and 40 min, respectively. Similar results have been reported for drying garlic slices [26] white mulberry [27] and strawberry [13].

Five of nine models were used to predict the changes in moisture content with the drying time in the germinated paddy. The obtained statistical parameters for data fitting are presented in Tab. 1. The five models revealed high values of R^2 that varied between 0.9807 and 0.9941. Accordingly, the five tested models from nine could adequately describe the behaviour of germinated paddy during drying using an infrared radiation system. Nevertheless, the approximation of diffusion model displayed the highest average value R^2 and the lowest values χ^2. Consequently, this model can be taken as the most suitable model to describe the thin-layer drying behaviour of germinated paddy under the studied conditions. The constants of the best model for describing the thin-layer germinated paddy drying curves are shown in Tab. 1.

Drying rate

Drying rates of germinated paddy at high temperature were computed using Eq. 3. Fig. 3 shows that the drying rate was a function of drying time at various temperatures. The drying rate increased with drying temperature, which meant that at the elevated temperature, heat and mass transfer were higher and the water loss was more excessive. It could be seen that temperature had a crucial effect on the drying rate. During the drying process, the drying rates are higher at the beginning of the process and then decline when the moisture content in the samples decreases [26, 28].

Effective moisture diffusivity

The effective moisture diffusivity (D_{eff}) values determined using Eq. 7 are shown in Tab. 2. The minimum moisture diffusivity was 2.03×10^{-10} $m^2 \cdot s^{-1}$ at the power of infrared radiation of 1 000 W and at the drying temperature of 90 °C. The maximum moisture diffusivity was 4.02×10^{-10} $m^2 \cdot s^{-1}$ at the power of infrared radiation of 1 500 W and drying temperature of 130 °C. Generally, for rice, D_{eff} value is in the range of 10^{-12} $m^2 \cdot s^{-1}$ to 10^{-10} $m^2 \cdot s^{-1}$ [29, 30]. Tab. 2 shows the values of D_{eff} plotted versus power of infrared radiation at various levels and various drying temperatures. It is evident from this table that D_{eff} increased with the increase in the drying temperature and infrared radiation intensity. At constant temperature, the higher power level resulted in faster heating and higher effective moisture diffusivity because of higher mass transfer.

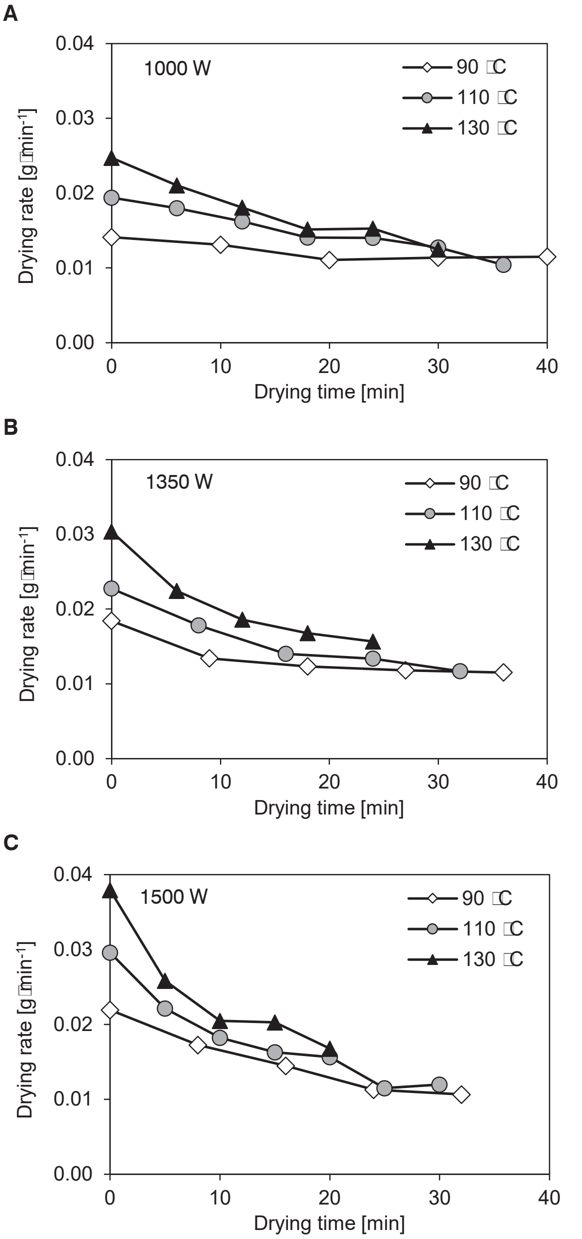

Fig. 3. Drying rates of germinated paddy during drying with various infrared radiation.

A – infrared power 1 000 W, B – infrared power 1 350 W, C – infrared power 1 500 W.

Head rice yield

Data on head rice yield (*HRY*) of germinated paddy dried at various drying temperatures and power levels are presented in Tab. 3. *HRY* was found to be 67.5 %, 76.4 % and 74.8–75.4 % in reference rice, control rice and dried germinated rice at different conditions, respectively. Control rice and germinated rice were found to have higher *HRY* compared to reference rice. This was because partial gelatinization in the steaming

Tab. 2. Effective moisture diffusivity and specific energy consumption of germinated paddy.

Drying temperature [°C]	Drying time [min]	Initial moisture content [%]	Final moisture content [%]	Drying rate [g·min^{-1}]	E_a [kJ·mol^{-1}]	D_0 [m^2·s^{-1}]	D_{eff} [m^2·s^{-1}]	*SEC* [MJ·kg^{-1}]
Infrared power of 1 000 W								
90	50	54.0	21.0	18.2			2.03×10^{-10}	5.94
110	42	54.2	20.1	22.3	12.61	1.34×10^{-8}	2.59×10^{-10}	4.61
130	36	55.7	20.0	26.6			3.09×10^{-10}	3.39
Infrared power of 1 350 W								
90	45	55.2	21.7	20.3			2.23×10^{-10}	4.72
110	38	55.5	21.5	24.4	14.03	2.29×10^{-8}	2.75×10^{-10}	3.49
130	30	55.9	21.1	31.6			3.51×10^{-10}	3.42
Infrared power of 1500 W								
90	40	54.1	21.4	22.5			2.27×10^{-10}	3.60
110	35	55.7	20.8	27.2	17.53	7.50×10^{-8}	3.03×10^{-10}	3.41
130	25	54.9	21.6	36.5			4.02×10^{-10}	2.37

E_a – activation energy, D_0 – pre-exponential factor of the Arrhenius equation, D_{eff} – effective moisture diffusivity, *SEC* – specific energy consumption (expressed in megajoule per kilogram of evaporated water).

Tab. 3. Cooking properties of germinated brown rice processed under various conditions.

T. [°C]	*HRY* [%]	Cooking time [min]	Water uptake [%]	Solid loss [%]	Hardness [N]	GABA content [g·kg^{-1}]
Reference rice	67.5 ± 0.09^{c}	27.00 ± 1.15^{c}	298.7 ± 2.8^{a}	4.0 ± 0.5^{a}	50.58 ± 1.03^{a}	4.35 ± 0.75^{d}
Control rice*	76.4 ± 0.10^{a}	30.33 ± 0.33^{bc}	255.0 ± 2.2^{b}	3.3 ± 0.8^{b}	42.44 ± 2.12^{b}	41.60 ± 1.15^{a}
Infrared power of 1 000 W						
90	75.4 ± 0.02^{b}	33.67 ± 0.88^{ab}	223.4 ± 2.9^{c}	2.2 ± 0.3^{c}	42.35 ± 0.95^{ab}	34.35 ± 0.75^{bc}
110	75.0 ± 0.14^{b}	34.67 ± 0.67^{c}	219.5 ± 2.6^{cde}	1.7 ± 0.3^{c}	44.92 ± 1.00^{ab}	32.85 ± 0.75^{c}
130	75.0 ± 0.27^{b}	35.33 ± 0.33^{c}	212.1 ± 1.6^{def}	1.5 ± 0.5^{c}	46.78 ± 0.70^{ab}	32.35 ± 1.56^{c}
Infrared power of 1 350 W						
90	75.5 ± 0.20^{ab}	34.33 ± 0.33^{ab}	222.5 ± 2.6^{cd}	1.8 ± 0.3^{c}	41.65 ± 1.73^{ab}	34.85 ± 1.56^{bc}
110	75.2 ± 0.06^{b}	35.00 ± 0.58^{c}	213.5 ± 2.1^{cdef}	1.7 ± 0.3^{c}	44.40 ± 0.99^{ab}	33.85 ± 1.56^{bc}
130	74.9 ± 0.07^{b}	35.33 ± 0.33^{c}	205.1 ± 2.2^{f}	1.5 ± 0.1^{c}	46.40 ± 0.99^{ab}	32.85 ± 1.50^{c}
Infrared power of 1 500 W						
90	75.3 ± 0.21^{b}	33.67 ± 0.33^{ab}	220.4 ± 0.8^{cde}	1.8 ± 0.3^{c}	40.94 ± 0.60^{ab}	35.85 ± 0.75^{b}
110	75.0 ± 0.15^{b}	34.67 ± 0.33^{c}	217.4 ± 1.8^{cde}	1.7 ± 0.3^{c}	43.89 ± 0.51^{ab}	34.35 ± 1.50^{bc}
130	74.8 ± 0.10^{b}	35.33 ± 0.88^{c}	210.8 ± 1.6^{ef}	1.5 ± 0.1^{c}	46.02 ± 1.01^{ab}	33.60 ± 1.98^{bc}

Values represent mean ± standard deviation. Different superscripts in the same column indicate significant difference ($P < 0.05$). * – control rice is germinated paddy that was steamed and dried in shade, *HRY* – head rice yield, *T* – drying temperature, GABA – γ-aminobutyric acid.

and drying processes caused starch molecules to merge, leading to improved structural strength of grain and the ability to withstand milling. Gelatinization of germinated paddy in the steaming and drying processes causes an increase in head rice yield [31].

Cooking quality

Data on the cooking qualities in terms of cooking time, water uptake and solid loss are shown in Tab. 3. The cooking times of control rice and germinated rice were longer than that of reference rice. The duration of cooking of control rice and germinated rice was longer than that of reference rice. Because the dried control rice and germinated rice underwent steaming and drying, partial or complete gelatinization occurred due to the transfer of heat and moisture from saturated steam to the rice grains. The gelatinization assisted in merging the cracks inside the kernels, resulting in a slow diffusion of water from the surface to the interior of the grains during the cooking process, which caused an increase in the cooking time. The cooking time of germinated brown rice was longer than that of control rice because germinated brown rice was dried and this process created increased gelatinization. Similar result were reported by TAECHAPAIROJ and KAEWYOT [32].

Data on the percentage of solid loss and water uptake in brown rice and germinated brown rice are shown in Tab. 3. They indicated that the control rice and germinated rice had a solid loss and water uptake lower than the reference rice. This was because control rice and dried germinated rice were processed by steaming and drying, which resulted in gelatinization of the starch kernel. This provided a barrier that reduced starch swelling during cooking and retarded water penetration [33]. In addition, the percentage of solid loss of germinated brown rice was lower than of control rice. This was because the higher drying temperature generated higher gelatinization. As a result, strength and tightness of rice increased. These results correspond with the study of PARNSAKHORN and LANGKAPIN [33].

Textural properties of germinated rice

Data on textural properties of cooked germinated rice in terms of hardness are shown in Tab. 3. It was observed that the hardness of germinated brown rice decreased compared to reference rice. This is explained by the fact that the germination process activates amylase, which may cause the germinated brown rice hardness to decrease. Moreover, it was found that the drying temperature did not affect the hardness of cooked dried germinated brown rice at various drying temperatures. Although gelatinization occurred at high drying temperature, the hardness of cooked germinated brown rice increased insignificantly. This may be because gelatinization may have a negligible effect on the hardness of germinated brown rice [34].

γ-Aminobutyric acid content

Data on GABA contents of brown rice and germinated rice at various conditions are shown in Tab. 3. The GABA contents of brown rice was 4.35 ± 0.75 g·kg^{-1}. After germination, the GABA content of the control rice and germinated brown rice samples increased significantly compared to the brown rice. This can be explained by a theory that the germination process resulted in intracellular synthesis and degradation of nutrients within the cell, the proteins being digested to glutamate by protease. Glutamate is a substrate for decarboxylation and glutamate decarboxylase produces γ-aminobutyric acid [13, 29]. The results of this work revealed that the GABA content of the control rice was higher than that of germinated brown rice. Because germinated brown rice was subjected to heating and drying processes, GABA content decreased. In a case study of GABA content in germinated brown rice at different drying temperatures, it was found that the GABA content decreased. It can be seen that high drying temperature had an effect on the GABA content of grains. As grain temperature increased, the GABA content decreased. A similar effect of heating on reduction of the GABA content was reported by CHEEVITSOPON and NOOMHORM [35].

Specific energy consumption

Data on specific energy consumption (*SEC*) determined by Eq. 11 are presented in Tab. 2. As observed, SEC decreased with the drying temperature. These results were in accordance with previous works related to drying of biomaterials and grain kernels. Drying the germinated paddy by infrared radiation at 130 °C using power of 1 500 W required the lowest energy.

Scanning electron microscopy

The morphology images of the cross-section of the rice grains at various drying conditions are shown in Fig. 4.

The reference rice (Fig. 4A) contained starch granules as the main component and no gelatinization was present. The structure of starch granules that resembled crystal structure could be clearly seen and had air spaces, which could enhance the diffusion of water, leading to shorter cooking times [31]. Fig. 4B shows the starch granules of control rice. It was observed that the starch granules shrank after the control rice was steamed resulting in gelatinization. Figs. 4C–4K demonstrate the starch granules of germinated rice, dried by various infrared radiation power at various drying temperatures. It was seen that the starch granules swelled and changed from crystalline to amorphous state with increasing drying temperature. The rice kernels were thus observed to have a smoother appearance. This was because the drying process generated gelatinization. This structure transition causes head rice yield of dried germinated paddy to increase [31].

CONCLUSIONS

In this work, the germinated rice drying process using infrared radiation was examined. Results showed that drying the germinated paddy could change physical properties (head rice yield, cooking time, solid loss, water uptake and texture) as well as physico-chemical properties (structure)

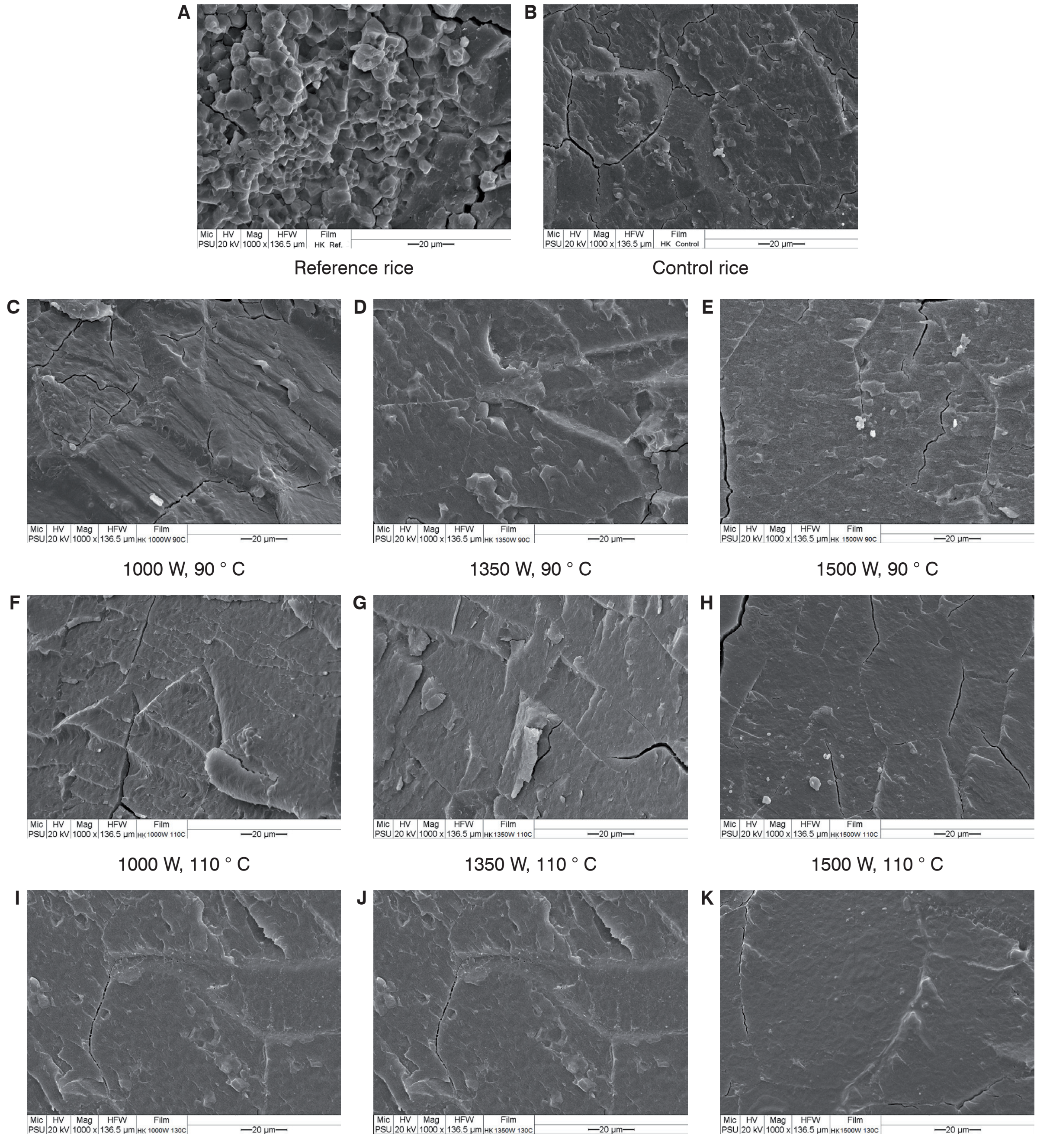

Fig. 4. Scanning electron microscopy pictures of the cross-section of rice dried at various conditions. Magnification 1 000×.

of germinated rice. Steaming and drying processes resulted in gelatinization, which caused the microstructure of germinated rice to change. The modification of microstructure increased head rice yield, cooking time and hardness but reduced solid loss and water uptake. Drying temperature and infrared radiation power used in this study did not affect the GABA content. The specific energy consumption declined when drying temperature increased.

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