

Drying Characteristics of Cooked Jasmine Brown Rice and True Densities of Dried Products

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ABSTRACT

Drying is a vital process for manufacturing instant brown rice. In this study, cooked jasmine brown rice was dried using various drying methods comprising single-stage drying by a hot-air dryer (HAD) and a microwave dryer (MWD) and two-stage drying using a MWD in the first stage and then a HAD, a fluidized bed dryer (FBD) and a MWD for the second stage. The main objective was to investigate the drying kinetics, effective moisture diffusivities and true densities of cooked brown rice dried in a FBD, a HAD and a MWD. The results proved that a MWD provided the highest drying rate when compared to its counterparts. The drying experimental data were well-fitted to the empirical equations. The moisture diffusivities of cooked brown rice during drying depended on the moisture transport mechanism occurring inside the rice kernel. The moisture diffusivities were much higher for microwave drying than hot-air drying. The true densities of samples that were dried in the HAD were higher than those dried in the MWD indicating a more porous structure in the microwave-dried samples.

Keywords: brown rice, fluidized bed drying, instant rice, microwave drying, physical property

INTRODUCTION

During the last decade, the consumption of brown rice has been noticeably increasing due to the health concerns of people (Heinemann *et al.*, 2005). It is well-known that brown rice is a health food that is rich in dietary fiber, mineral oils, and various vitamins which may be able to prevent various forms of cancer (Jaisut *et al.*, 2009). Although brown rice provides some health benefits, it needs a much longer cooking time than white milled rice leading to inconvenience for consumers especially for the new generation that normally requires quick-cooking food owing to

their rushed lifestyles. The development of instant brown rice products is considered as a solution to this problem. In addition, this kind of product is of interest to both the national government and the food industry because it can help raising the marketing and economic values of rice in Thailand.

So far, there has been a lack of research in the area of instant brown rice production whereas a limited number of published works about instant white rice can be found such as Ozai-Durrani (1965), Ramesh and Srinivasa Rao (1996), Luangmalawat *et al.* (2008), Prasert and Suwannaporn (2009) and Rewthong *et al.* (2011).

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According to the literature, in order to manufacture instant rice, the rice must be cooked and rapidly dried so that the rice structure is more porous or sponge-like; as a result, it can be rehydrated and ready to consume within a short period of time (Prasert and Suwannaporn, 2009). Ozai-Durrani (1965) suggested that instant rice would be more porous and faster to rehydrate if after cooking, the cooked rice is frozen and slowly thawed prior to the drying process. It was considered to be the volume expansion of ice crystals during freezing that caused the greater porosity of the rice after the thawing and drying processes. Rewthong *et al.* (2011) pointed out that the microstructure, texture and starch digestibility of instant rice are directly related to the cooking, drying and pretreatment methods. Prasert and Suwannaporn (2009) stated that the initial moisture content, degree of gelatinization and drying conditions are the most important key factors that contribute to the rehydration capability and eating quality of instant rice products.

Drying is one of the most important processes for instant rice production. Different drying methods and conditions result in differences in the structure of instant rice. Changes in the food structure during drying are usually caused by collapse due to water loss or are the result of expansion due to vapor generation (Wang and Brennan, 1992). From the published works, there have been some drying techniques applied for manufacturing instant rice; Ramesh and Srinivasa Rao (1996) applied a single-stage drying method using a vibrofluidized bed dryer at a minimum fluidization velocity of 4–5 m.s⁻¹ and drying air temperatures from 160 to 240 °C. The vibrofluidized bed drying technique can expedite the moisture transfer rate; subsequently, a porous structure and short rehydration time of the instant rice product can be expected. Luangmalawat *et al.* (2008) dried cooked white rice with one drying stage using a hot-air dryer at five drying temperatures of 50, 60, 80, 100 and 120 °C. This

drying method required long drying times due to the low air velocity of 0.4 m.s⁻¹ even in the case of 120 °C; therefore, it is not surprising that the different drying temperatures had an insignificant effect on the shrinkage and rehydration capability of the dried rice samples. Moreover, Prasert and Suwannaporn (2009) dried their cooked and pressurized jasmine rice in a single drying step using a tray dryer at temperatures from 166.4 to 233.6 °C. Although it appeared that the higher drying temperatures of the tray dryer resulted in increased hardness and chewiness of the rice, the effects of soaking and high pressure cooking were more obvious. In addition, Rewthong *et al.* (2011) utilized two methods for single-stage drying of their cooked jasmine white rice comprising 1) hot-air drying at an air velocity of 0.6 m.s⁻¹ and a temperature of 80 °C and 2) freeze drying with a temperature range of -45 to -50 °C and a pressure of 0.013 Pa. Larger pores were found in the freeze-dried cooked rice as a result of the growth of ice crystals during freezing. Apart from the application of single-stage drying by different dryers, some researchers dried their cooked rice using two-stage drying schemes. For example, Ramesh (2003) dry-cooked basmati rice in two stages using a through-flow dryer at 60 °C for 60 min for an initial stage to dry cooked rice from approximately 300% (dry basis, db) down to 122% (db) and then a vibrofluidized bed dryer at 180 °C for 1–2 min to reduce the moisture content of product to about 6.4% (db).

Although a range of drying methods has been applied in the production of instant rice, at present there is no consensus about the most appropriate drying method for instant rice production. Also, the drying processes of cooked white milled rice and that of cooked brown rice must be dissimilar because of the differences in the composition and the outer layer of the rice types. Therefore, in the current study, cooked brown rice was dried by both single stage and two stage drying using three kinds of proficient dryers—namely, a

fluidized bed dryer (FBD), a hot-air dryer (HAD) and a microwave dryer (MWD)—in order to determine the drying characteristics and some physical properties of cooked brown rice. The objectives of this research were 1) to investigate the drying characteristics of cooked brown rice in a FBD, a HAD and a MWD, 2) to develop thin-layer drying models for cooked brown rice and 3) to determine the effective moisture diffusivity and density of cooked brown rice.

MATERIALS AND METHODS

Sample preparation

Rice seeds (*Oryza sativa* L.) of the KDML105 variety (jasmine rice) were chosen for the present study because of their better market price and popularity. The seeds were obtained from the Chonburi Rice Seed Center located in Chonburi province, Thailand. The seeds were dehusked to make brown rice using a laboratory deharker (Ngek Seng Huat Part., Ltd., Bangkok, Thailand) with a speed differences between the rollers of 740 and 870 rpm and a roller clearance of 0.8–1.5 mm.

After separating out the husk and broken rice, 500 g of jasmine brown rice was washed by tap water and then cooked in a digital pressure cooker (Zebra, model ZB-DEP2200, Satien Stainless Steel Public Co.,Ltd., Bangkok, Thailand) for 18 min under an operating pressure of 40–70 kPa with a ratio of potable water to rice of 1.5:1. After the cooking period, the sample was warmed in the cooker at a temperature range of 60–80 °C for 15 min to increase the degree of gelatinization. The cooked brown rice was then exposed to some pretreatments before drying in order to increase the porosity of the rice microstructure and the subsequent instant brown rice product. The pretreatments consisted of 1) freezing the cooked brown rice in a chest freezer (Apache Daily Cool Co., Ltd., Nonthaburi, Thailand) at a temperature of -18 °C for 90 min

by spreading the rice in a thin layer on aluminum trays and 2) thawing the frozen cooked brown rice in two stages. The first stage of thawing was conducted in a refrigerator (HITACHI, model RZ440VX, Tokyo, Japan) at a temperature about 6 °C for 40 min and was followed by the second stage at room temperature for 20 min. Prior to drying, the sample was sprayed with cold water at a temperature of 8 °C in order to easily separate any cooked rice that had agglomerated. The moisture content of the brown rice sample before drying was approximately 68–70% on wet basis (wb).

Drying experiments

The cooked brown rice prepared by the method described above was dried by five different drying schemes that were considered to have the potential to produce instant brown rice. A diagram showing the sequence of steps in each experimental drying scheme is presented in Figure 1.

All of the dryers used in this study were operated in batch mode. The FBD (Sherwood Scientific, Cambridge, England), had an electrical power supply of 230 V/50 Hz/3 kW. The HAD was a model T.308L (Memmert GmbH & Co. KG, Frankfurt, Germany). The MWD (SHARP, model R-892P, Osaka, Japan) had a maximum output power of 850 W and an operating frequency of 2,450 MHz.

The static bed depth of the samples in the FBD was approximately 10 cm while the samples were dried as a single layer on a perforated tray and on a turntable dish (320 mm diameter) in the HAD and MWD, respectively. The FBD applied a superficial air velocity of 9 m.s⁻¹ which was calculated by averaging the air velocities that were measured at different positions in the plenum (Sootjarit *et al.*, 2011). The drying air velocity above the samples in the HAD was about 0.4 m.s⁻¹. All the air velocities were measured using a multi-parameter instrument differential pressure and velocity meters (Testo, model 400, Brandt

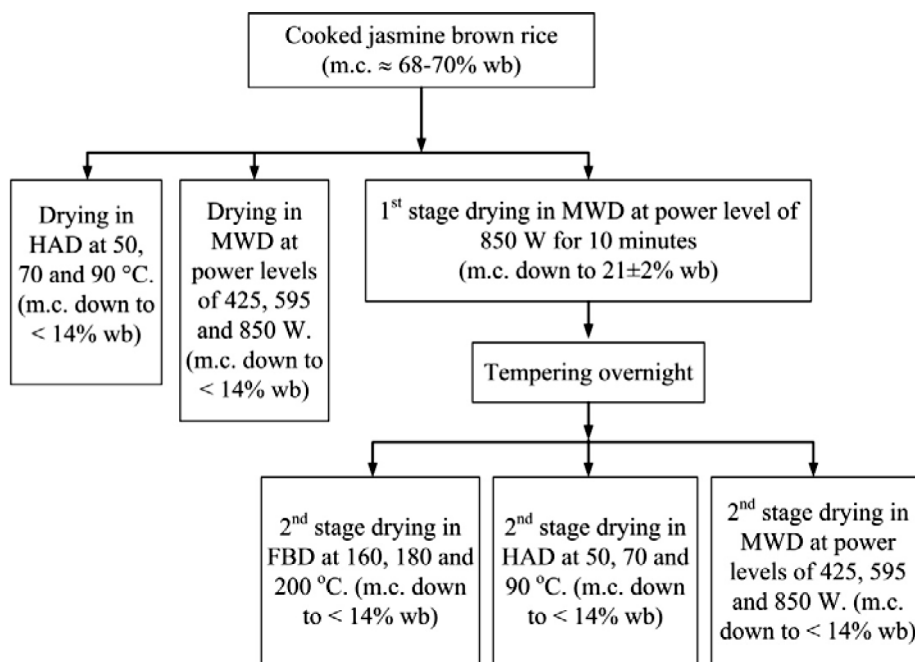


Figure 1 Experimental drying plans. (m.c. = moisture content of sample; wb = wet basis; FBD = Fluidized bed dryer; HAD = Hot-air dryer; MWD = Microwave dryer).

Instruments Inc., Los Angeles, USA).

For the two-stage drying scheme, a tempering step was applied between the drying stages by keeping the samples in a sealed container overnight so that the moisture and temperature stresses within the grain would be released.

Samples were collected during drying at each time interval for moisture content determination and true density measurement.

Moisture content determination

The moisture content of samples was determined in duplicate using approximately 10 g for each sample and applying an oven method at 105 °C for 24 hr (Swamy *et al.*, 1971).

Thin-layer drying model development

The experimental data from each drying run were fitted into two thin-layer drying models—namely, a modified Page model and a modified two-compartment model. The patterns of

these models are illustrated in Table 1. Modified models have been efficiently used to estimate the drying kinetics of some food grains such as pumpkin seeds (Jittanit, 2011) and pre-germinated brown rice and rough rice (Sootjarit *et al.*, 2011). The advantage of these modified models is their wider applicable temperature range compared with common thin-layer drying models (Jittanit, 2011; Sootjarit *et al.*, 2011).

For the model development of microwave drying, the temperature parameter in the model was replaced by the microwave power level in watts.

The equilibrium moisture content (M_e) for each of the drying temperatures of 50, 70 and 90 °C were estimated by prolonging the drying process at the corresponding temperature until reaching a constant weight. In contrast, M_e was zero if the drying temperature was higher than 100 °C (Taechapairoj *et al.*, 2003). Furthermore, M_e was assumed to be zero for drying using the

Table 1 Patterns of the two modified drying models.

Model	Equation	Reference
Modified page model	$MR = \exp\left(-kt^N \exp\left(-\frac{A}{T_K}\right)\right)$	Jittanit (2011) and Sootjarit <i>et al.</i> (2011)
Modified two-compartment model	$MR = A_1 \exp\left(-k_1 t \exp\left(-\frac{B}{T_K}\right)\right) + A_2 \exp\left(-k_2 t \exp\left(-\frac{B}{T_K}\right)\right)$	Jittanit (2011) and Sootjarit <i>et al.</i> (2011)

$$MR = \text{the dimensionless moisture ratio} = \frac{M_t - M_e}{M_i - M_e},$$

M_t = the moisture content (% db) at any time t during drying,

M_i = the initial moisture content (% db),

M_e = the equilibrium moisture content (% db),

T_K = the drying temperature (°K),

k , k_1 and k_2 are the drying rate constants and N , A , A_1 , A_2 and B are constants

MWD because the sample temperature would be over 100 °C in the drying procedure.

The model fitting was performed by applying the least square method for non-linear regression analysis using the statistical software package Statistica 5.5 (StatSoft, Inc. Tulsa, OK, USA). The goodness of fit of each model was evaluated basing on the coefficient of determination (R^2), the root mean square error (RMSE) and the relative error percentage (PE) that were calculated by Equations 1 to 3, respectively:

$$R^2 = 1 - \frac{\sum_{i=1}^n (\text{Measured } MR \text{ value} - \text{Predicted } MR \text{ value})^2}{\sum_{i=1}^n (\text{Measured } MR \text{ value} - \text{Average } MR \text{ value})^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\text{Measured } M_t \text{ value} - \text{Predicted } M_t \text{ value})^2}{n}}$$

$$PE(\%) = \frac{100}{n} \sum_{i=1}^n \frac{|\text{Measured } M_t \text{ value} - \text{Predicted } M_t \text{ value}|}{\text{Measured } M_t \text{ value}}$$

where MR = the dimensionless moisture ratio; M_t = the moisture content (% db) at any time t during drying; n = number of data

Effective moisture diffusivity determination

The effective moisture diffusivity is an overall mass transport property of the water in the drying material involving liquid diffusion, vapor diffusion, hydrodynamic flow and other possible mass transfer mechanisms (Karathanos *et al.*, 1990). The drying of most food materials usually occurs in the falling rate period indicating that the moisture transfer during drying is limited and controlled by internal diffusion (Wang and Brennan, 1992). The moisture diffusion from the inner part to the sample surface is described by Fick's second law of diffusion as shown in Equation 4 (Crank, 1975):

$$\frac{\partial M}{\partial t} = \nabla \cdot (D_{eff} \nabla M) \quad (4)$$

where M = moisture content (kg water/kg dry matter), t = time (s) and D_{eff} = effective moisture diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$).

For the determination of moisture diffusivity, the cooked brown rice was considered as a finite cylindrical shape. The analytical solution of Fick's second law of diffusion for finite, cylindrical-shaped material, with the assumptions of moisture

transfer by diffusion, negligible shrinkage, and constant diffusion coefficients and temperature is provided by Equation 5 (Nathakaranakule and Prachayawarakorn, 1998; Sootjarit *et al.*, 2011):

$$MR = \left(\frac{8}{\pi^2} \right) \sum_{m=1}^{\infty} \frac{4}{\lambda_m^2} \exp \left(-\frac{\lambda_m^2 D_{eff} t}{r_0^2} \right) \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left(-\frac{\pi^2 (2n+1)^2 D_{eff} t}{4l^2} \right) \quad (5)$$

where λ_m = the root of the Bessel function of the first kind and zero order, r_0 = radius of cooked brown rice (1.65×10^{-3} m), l = half length of cooked brown rice (4.07×10^{-3} m) and m, n = integral numbers. From Equation (5), if considering only $m = 1, 2$ and $n = 0, 1$, the expansion of Equation (5) becomes Equation 6:

$$MR = 0.561 e^{-5.78 N_{Fi} - 2.46 N_{Fo}} + 0.062 e^{-5.78 N_{Fi} - 22.18 N_{Fo}} + 0.107 e^{-30.47 N_{Fi} - 2.46 N_{Fo}} + 0.012 e^{-30.47 N_{Fi} - 22.18 N_{Fo}} \quad (6)$$

where N_{Fi} = Fick's number $\left((D_{eff} t) / r_0^2 \right)$ and N_{Fo} = Fourier's number $\left((D_{eff} t) / l^2 \right)$. As reported by Sootjarit *et al.* (2011), it is clear that the first term of the series solution in Equation (6) will dominate the rest. Thus, Equation (6) can be rewritten as Equation 7:

$$MR \approx 0.561 e^{-5.78 N_{Fi} - 2.46 N_{Fo}} \quad (7)$$

There are two methods for determining the effective moisture diffusivity from the drying experimental data—namely, the regular regime method (Jittanit, 2011; Sootjarit *et al.*, 2011) and the slope method (Ramesh, 2003; Luangmalawat *et al.*, 2008). In the current study, the slope method was applied and, accordingly, the moisture diffusivities were calculated by applying the slope of the experimental drying curve, $(dMR/dt)_{exp}$, and that of the theoretical curve, $(dMR/dFo)_{theo}$, in the following steps. Kim and Bhowmik (1995) and Sharma *et al.* (2009) also applied the slope method

to determine the effective moisture diffusivity of food samples during microwave-vacuum drying and microwave-convective drying.

From the formula of N_{Fi} and N_{Fo} , N_{Fi} can be presented as a function of N_{Fo} using Equation 8 below:

$$N_{Fi} = N_{Fo} \frac{l^2}{r_0^2} \quad (8)$$

Replacing N_{Fi} in Equation (7) and then differentiating with respect to N_{Fo} , produces Equation 9:

$$\frac{\partial MR}{\partial N_{Fo}} = 0.561 e^{\left(-\frac{5.78 l^2}{r_0^2} - 2.46 \right) N_{Fo}} \left(-\frac{5.78 l^2}{r_0^2} - 2.46 \right) \quad (9)$$

Similarly, after substituting N_{Fi} and N_{Fo} by $(D_{eff} t) / r_0^2$ and $(D_{eff} t) / l^2$, respectively, in Equation (7) and then differentiating with respect to time (t), the solution can be represented by Equation 10:

$$\frac{\partial MR}{\partial t} = 0.561 e^{\left(-\frac{5.78 l^2}{r_0^2} - 2.46 \right) \left(\frac{D_{eff} t}{l^2} \right)} \left(-\frac{5.78 l^2}{r_0^2} - 2.46 \right) \left(\frac{D_{eff}}{l^2} \right) \quad (10)$$

As a result of manipulating Equations 9 and 10, the effective moisture diffusivity of cooked brown rice can be calculated by Equation (11):

$$D_{eff} = \frac{(\partial MR / \partial t)}{(\partial MR / \partial N_{Fo})} l^2 \quad (11)$$

It is noted here that for the determination of D_{eff} in this work, the value of $(\partial MR / \partial t)$ at each moisture content level of the sample was calculated using the drying experimental results, whereas, that of $(\partial MR / \partial N_{Fo})$ was calculated using Equation 9 that is based on diffusion theory (Luangmalawat *et al.*, 2008). The value of N_{Fo} that is a variable in Equation 9 was determined by taking the natural logarithm (ln) of Equation 7 and then replacing the measured values of MR , l and r_0 into the equation.

True density determination

Information about the true density of the cooked brown rice after drying for each time step is useful for analyzing the extent of the porous or sponge-like structure of the dried rice samples. These kinds of structures are directly related to the rehydration rate of dried products that is commonly required in instant or quick-cooking rice. In the current work, the true densities of the cooked jasmine brown rice samples that were dried by a single-stage drying scheme in the HAD and MWD were determined by applying the liquid displacement method. The true density is defined as the ratio of the sample weight to the true volume of sample (excluding any air space between the grains). An amount of rice sample was put into a 500 mL volumetric flask prior to filling with tap water at room temperature until reaching the specified volume of 500 mL. The weight and volume of the filled water were known; thus, the true volume and subsequent true density could be calculated. To avoid the effects of moisture diffusion into the rice kernel and sample swelling on the true density measurement, the measurement was conducted and recorded immediately after filling the flask with water.

Stereomicroscopy

Images of the dried cooked brown rice (moisture content < 14% wb) were captured by a stereo microscope (Leica, model S8APO, Leica Microsystems Imaging Solutions Ltd., Cambridge, UK) at 16× magnification operating with a transmitted-light stand (Leica, model TL BFDF, Leica Microsystems Imaging Solutions Ltd., Cambridge, UK), a digital camera (Leica, model DFC280, Leica Microsystems Imaging Solutions Ltd., Cambridge, UK) attached to the microscope and the Leica Application Suite software (Leica Microsystems Imaging Solutions Ltd., Cambridge, UK) so that the effect of the drying conditions on the structure of the rice could be observed. In addition to the dried rice, stereomicroscopic images of the freshly cooked brown rice and the

brown rice after cooking, freezing and thawing were captured in order to observe the consequences of the freezing and thawing pretreatments on the structure of the rice.

RESULTS AND DISCUSSION

Drying characteristics

The drying characteristics of cooked jasmine brown rice during single-stage drying in the HAD and MWD are illustrated in Figure 2; those of the second-stage drying in the FBD, HAD

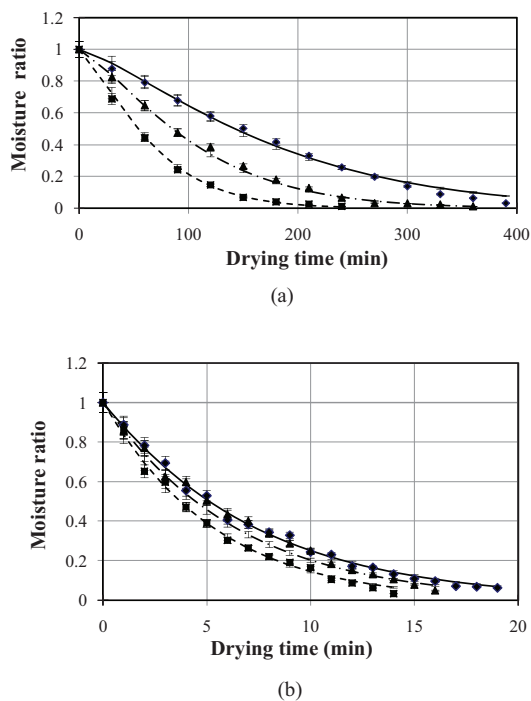


Figure 2 Drying curves of cooked brown rice during single-stage drying (a) HAD (♦ = experimental 50 °C; ▲ = experimental 70 °C; ■ = experimental 90 °C; — = predicted 50 °C; - - - = predicted 70 °C; - - - = predicted 90 °C) and (b) MWD (♦ = experimental 425 W; ▲ = experimental 595 W; ■ = experimental 850 W; — = predicted 425 W; - - - = predicted 595 W; - - - = predicted 850 W. Vertical bars indicate the SE of the mean values).

and MWD are presented in Figure 3. It appeared that for the single-stage drying, the drying rate was constant during the early stage of the experiments;

however, after a short period, the rate fell for the remainder of the time. In contrast, there was no noticeable constant drying rate for the second-

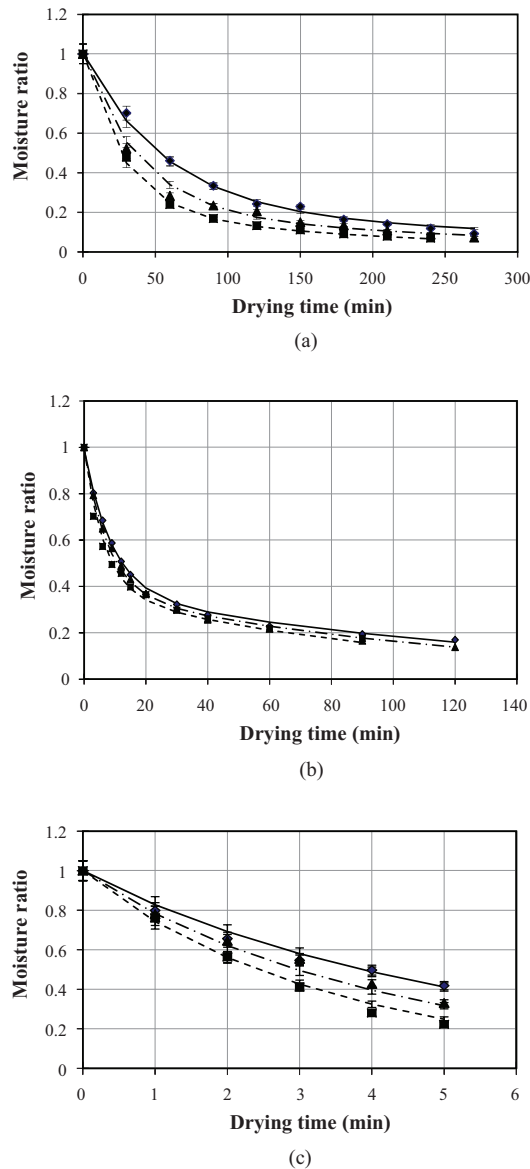


Figure 3 Drying curves of cooked brown rice during second-stage drying (a) HAD (♦ = experimental 50 °C; ▲ = experimental 70 °C; ■ = experimental 90 °C; — = predicted 50 °C; - - - = predicted 70 °C; . . . = predicted 90 °C) and (b) FBD (♦ = experimental 160 °C; ▲ = experimental 180 °C; ■ = experimental 200 °C; — = predicted 160 °C; - - - = predicted 180 °C; . . . = predicted 200 °C) and (c) MWD (♦ = experimental 425 W; ▲ = experimental 595 W; ■ = experimental 850 W; — = predicted 425 W; - - - = predicted 595 W; . . . = predicted 850 W. Vertical bars indicate the SE of the mean values).

stage drying because the initial moisture contents of the samples were high (approximately 68–70% wb) for the single-stage drying; as a consequence, most of the evaporated moisture was moisture on the damp surface of the cooked brown rice. Thus, the drying rate would be fairly constant as long as the sample surface was still saturated with water. On the other hand, the initial moisture contents of samples for the second stage of drying were lower (approximately 21% wb); subsequently, the moisture evaporation rate was controlled by the capability of moisture diffusion from inside to the sample surface.

Figures 2 and 3 also indicate that either the higher drying temperature or more intense microwave power resulted in a faster drying rate due to the elevated driving force for moisture transfer (Nathakaranakule and Prachayawarakorn, 1998; Jittanit, 2011). The driving forces after increasing the drying temperature in the HAD were comprised of the moisture and temperature gradients between the center and the surface of the samples whereas only the temperature gradient was increased when raising the drying temperature in the FBD. The equilibrium moisture contents of samples were zero at temperatures over 100 °C (Taechapairoj, 2003); subsequently, the driving forces resulting from the moisture gradients were rather identical between the drying air temperatures of 160, 180 and 200 °C in the FBD. This explained the slight difference in the drying curves among these three drying temperatures applied in the FBD. For the MWD, an increase in the power level could boost the vapor pressure gradient between the center and the surface of the samples resulting in a stronger driving force for moisture transfer from inside to outside the sample and a higher drying rate. The mechanism of moisture transfer due to the vapor pressure gradient within the sample was the key reason for the extremely high drying rate of the MWD compared to its counterparts. The MWD is deemed as an interesting dryer for producing

quick-cooking brown rice or instant rice products because of its drying rate and the possibility of creating a highly porous structure from its moisture transfer mechanism. The MWD can be used as the first-stage or second-stage dryer in a two-stage drying process or as a single-stage dryer. If it is utilized as a single-stage dryer, the drying process will be short but the amount of broken rice kernels might be high due to mechanical stress. In contrast, the total production time would be much longer if the MWD were only used as the first-stage dryer in a two-stage drying process but the amount of broken rice might be reduced as a result of the tempering step between the drying stages. Two studies (Prachayawarakorn *et al.*, 2005; Seubrach *et al.*, 2006) pointed out that after the first-stage drying of food grains at high drying rates, a tempering step should be applied in order to relax the mechanical stress within the kernel prior to the second-stage drying so that the amount of broken grains can be significantly lessened. An interesting drying scheme for cooked brown rice is the utilization of the MWD in both the first and second drying stages with a tempering process in between because the drying process would be short, whereas the fissuring of rice was expected to be controllable.

Thin-layer drying models

The results of fitting the experimental data to the two modified drying models are shown in Table 2. After considering the values of R^2 , RMSE and PE, it was apparent that the modified Page model was the superior equation for single-stage drying whereas the modified two-compartment model provided the best fit for the second-stage drying in the HAD and FBD. However, the goodness of fit of both models was comparable for the second-stage drying in the MWD. The predictions of the modified Page model for single-stage drying and those of the modified two-compartment model for the second-stage drying are presented in Figures 2 and 3. It appeared

Table 2 Constant parameters of two modified drying models obtained from regression methods.

Model	Drying scheme	Condition	Constant parameters					R ²	RMSE (% db)	PE (%)
			k ₁ (min ⁻¹)	k ₂ (min ⁻¹)	A ₁	A ₂	B			
Modified two compartment	Single-stage drying	HAD at 50–90 °C	14.843	16.255	-6.5731	7.6007	2758.5	0.9927	5.79	18.80
		MWD at 425–850 W	0.100	0.257	0.5037	0.5049	-276.8	0.9937	5.40	11.23
	Second-stage drying	HAD at 50–90 °C	1.593	11.937	0.2111	0.7923	2104.7	0.9957	0.44	3.31
		FBD at 160–200 °C	3.883	0.250	0.6157	0.3767	1538.9	0.9956	0.46	3.30
		MWD at 425–850 W	0.447	0.447	0.4957	0.4957	392.3	0.9882	0.75	4.47
Model	Drying scheme	Condition	Constant parameters			R ²	RMSE (% db)	PE (%)		
			k (min ⁻¹)	N					A	
Modified Page	Single-stage drying	HAD at 50–90 °C	99.745	1.2982		3686.12	0.9962	3.77	9.96	
		MWD at 425–850 W	0.092	1.0311		-285.11	0.9939	5.19	10.11	
	Second-stage drying	HAD at 50–90 °C	3.171	0.6963		1367.00	0.9893	0.711	7.53	
		FBD at 160–200 °C	1.065	0.5133		770.15	0.9809	0.95	8.37	
		MWD at 425–850 W	0.467	0.9594		383.48	0.9884	0.75	4.36	

db = Dry basis.

that the drying models developed in this study can precisely predict the moisture content change of cooked brown rice during the drying process. These models are useful for the food industry and researchers who need to estimate a suitable drying time for manufacturing quick-cooking or instant brown rice.

Effective moisture diffusivity

The drying experimental data presented in Figures 2 and 3 were used to determine the effective moisture diffusivities of cooked brown rice using the method formerly mentioned. The plots of the moisture diffusivities versus the moisture contents of the samples are depicted in Figure 4. It appeared that the tendency of moisture diffusivities with the moisture content of single-stage drying was opposite to that of second-stage drying. The moisture diffusivities of the samples

in the case of single-stage drying increased along a declining moisture content during the drying process. The explanation for these phenomena is that for the single-stage drying, after a short period of drying at a constant rate, moisture transfer chiefly relied on diffusion; however, as the drying continued, a porous structure was formed and at the same time the moisture inside the sample was in a vapor form leading to an increase in the effective moisture diffusivities. Conversely, for the second-stage drying, the sample was kept overnight before drying so the moisture was redistributed throughout the kernel. Subsequently, at the start of drying, the surface of the cooked brown rice was rather moist and after that as the drying progressed, the sample surface became dry. At this stage, for the HAD and FBD, the moisture diffusivities dropped along a decreasing moisture content due to the difficulty of

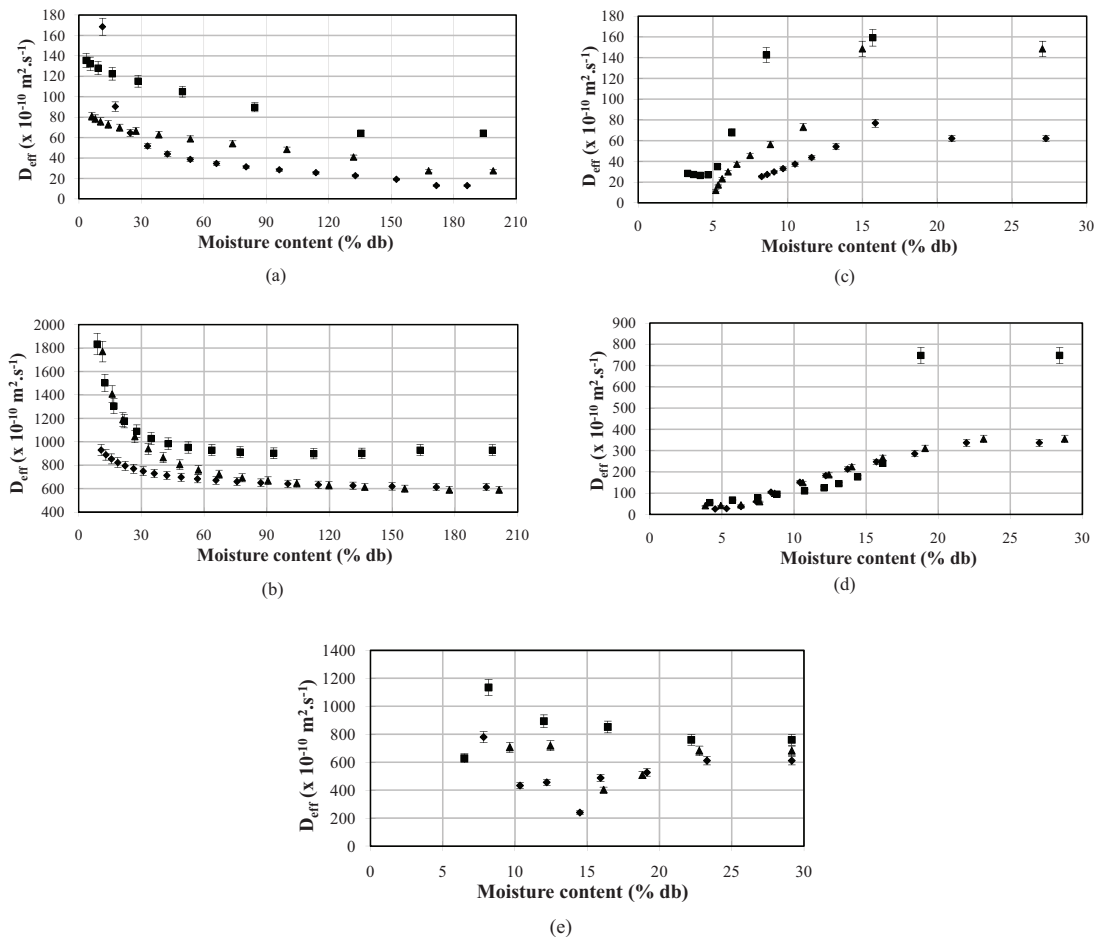


Figure 4 Effective moisture diffusivities determined by slope method: (a) Single-stage drying in HAD ($\diamond = 50$ °C; $\blacktriangle = 70$ °C; $\blacksquare = 90$ °C); (b) Single-stage drying in MWD ($\diamond = 425$ W; $\blacktriangle = 595$ W; $\blacksquare = 850$ W); (c) Second-stage drying in HAD ($\diamond = 50$ °C; $\blacktriangle = 70$ °C; $\blacksquare = 90$ °C); (d) Second-stage drying in FBD ($\diamond = 160$ °C; $\blacktriangle = 180$ °C; $\blacksquare = 200$ °C); (e) Second-stage drying in MWD ($\diamond = 425$ W; $\blacktriangle = 595$ W; $\blacksquare = 850$ W). (db = Dry basis. Vertical bars indicate the SE of the mean values.)

removing the remaining bound moisture (Ramesh, 2003). In this case, there was not as much vapor inside the sample due to the low moisture content and the low temperature within the sample as a consequence of the tempering process. A similar trend of moisture diffusivity change with moisture content was also found in other food products such as amioca starch gel (Karathanos *et al.*, 1990) and cooked rice (Luangmalawat *et al.*, 2008). However, for the second-stage drying in the MWD, the

moisture diffusivities did not obviously decrease along the declining moisture content because the moisture evaporation rate was fairly consistent during drying in the MWD as shown in Figure 3(c) due to the heating mechanism of the MWD that can expedite moisture removal from inside to the surface of the sample.

For the single-stage drying, the moisture diffusivities fell in a range between 13×10^{-10} and $168 \times 10^{-10} m^2.s^{-1}$ for the HAD and 589×10^{-10}

and $1,834 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$ for MWD, whereas for the second stage drying, they ranged between 12×10^{-10} and $159 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$ for the HAD, 26×10^{-10} and $748 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$ for the FBD, and 239×10^{-10} and $1,135 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$ for the MWD. They are much higher than those of rough rice (between 0.256×10^{-10} and $0.792 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$) and brown rice (between 0.389×10^{-10} and $1.46 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$) calculated by Thakur and Gupta (2006) and those of cooked jasmine white rice (between 0.06×10^{-10} and $4.87 \times 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$) determined by Luangmalawat *et al.* (2008). The causes of the higher diffusivities of cooked brown rice in the current study were their husk removal, the volume expansion and soft texture after pressure cooking, the pretreatment before drying and the drying methods applied. The values of diffusivities in the case of the MWD were higher than those of the HAD because of the much higher vapor pressure occurring inside the rice kernel. Chua and Chou (2005) stated that the mechanism of microwave heating does not rely on heat conduction, convection and radiation but it produces heat by releasing electromagnetic waves into the sample and then the electromagnetic energy is transformed into heat energy by dipole rotation and ionic conduction. The heat is generated particularly in the wet area of the sample because water is a dipolar molecule. Subsequently, the moisture inside the sample vaporizes rapidly. This vapor pressure helps accelerating moisture movement from inside to the sample surface. This phenomenon is the so-called “pumping effect”.

True density

The relationships between the true density of cooked brown rice and drying time for single-stage drying are illustrated in Figures 5(a) and 5(b). For the single-stage drying in the HAD, the true density of the sample appeared to increase with the drying time due to the shrinkage taking place after water loss in the sample. The differences in the true density between the drying

temperatures of 50, 70 and 90 °C were not obvious. In contrast to this, drying in the MWD resulted in the true density of the sample dropping through the drying process, especially after a period of drying. This was caused by the moisture within the sample being rapidly heated and accumulating vapor pressure after a period of time; as a result, the puffing or volume expansion led to a decrease in the true density. The higher the microwave power applied, the lower the true densities that resulted. This puffing effect is usually required for quick-cooking or instant food products as the porous structure is needed to facilitate the rehydration process (Prasert and Suwannaporn, 2009). As illustrated in Figures 5(c) to 5(e), the true density of cooked brown rice was quite stable throughout the drying process; moreover, the dissimilar drying methods in the second stage of drying did not lead to any noticeable variation in the true density because the samples were dried in the first stage by the MWD at 850 W to a somewhat low moisture content level and then exposed to the tempering step to equilibrate the moisture and temperature within the kernels; as a result, the removal of the remaining moisture did not cause much shrinkage and any difference in the structure of samples.

Images captured by stereomicroscopy

The images of 1) freshly cooked brown rice, 2) brown rice after cooking and pretreatment and 3) brown rice after cooking, pretreatment and drying taken by stereomicroscopy are depicted in Figure 6. The structure of the cooked brown rice became spongier after the freezing and thawing pretreatment indicating that the pretreatment helped enhancing the porosity of the sample structure. As a consequence, the moisture transfer in either the drying or rehydration process would be facilitated. This finding confirmed the report of Ozai-Durrani (1965) claiming that instant rice would be more porous and faster to rehydrate if, after cooking, the cooked rice is frozen and slowly thawed prior to the drying process due to

the influence of volume expansion of ice crystals during freezing. Additionally, it is noticeable from Figure 6 that microwave drying caused the puffing

or volume expansion of the rice structure leading to greater porosity and a lower true density of the rice than resulted from ordinary hot-air drying.

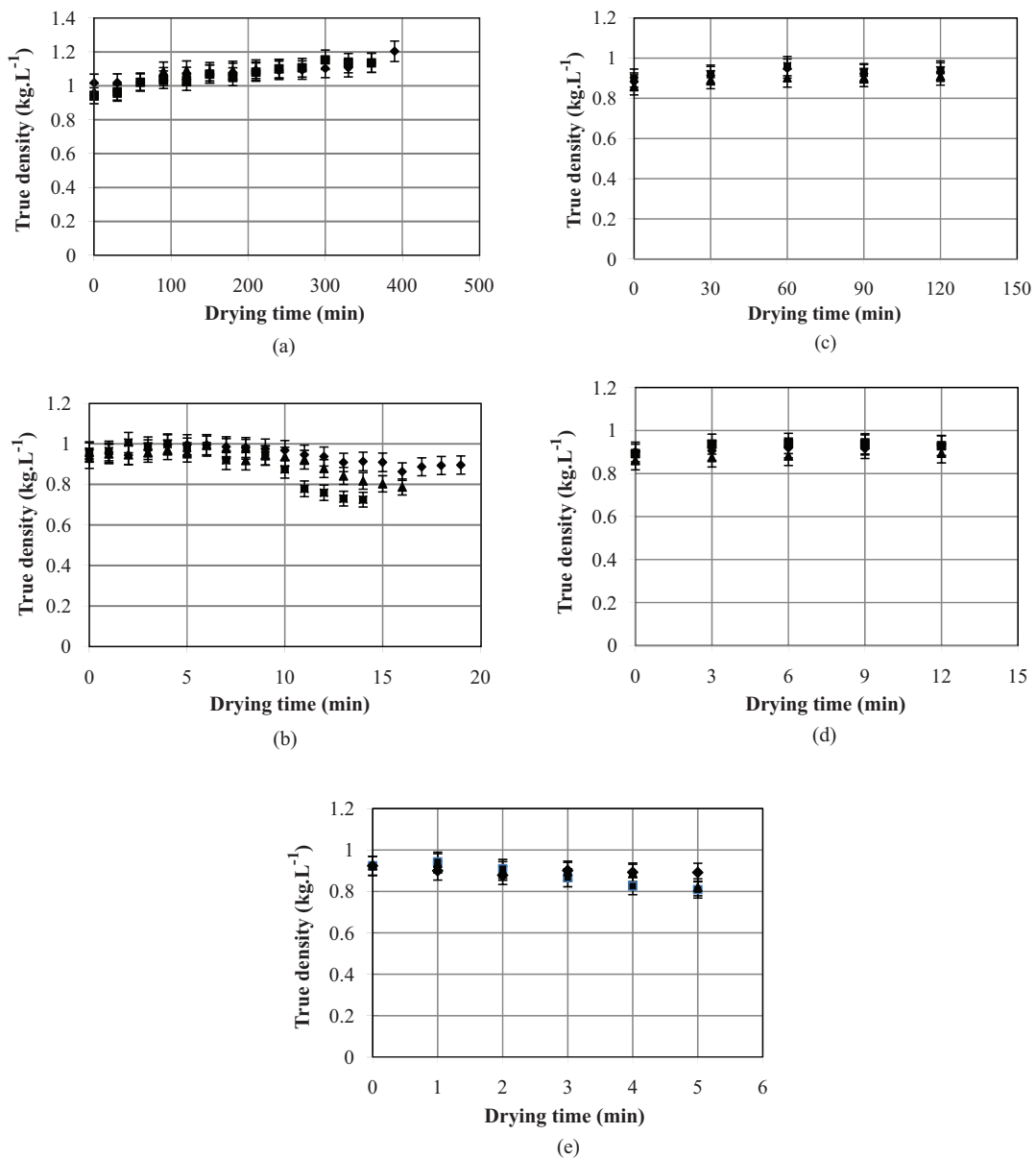


Figure 5 True density of cooked brown rice after drying by: (a) Single-stage drying in HAD (♦ = 50 °C; ▲ = 70 °C; ■ = 90 °C); (b) Single-stage drying in MWD (♦ = 425 W; ▲ = 595 W; ■ = 850 W); (c) Second-stage drying in HAD (♦ = 50 °C; ▲ = 70 °C; ■ = 90 °C); (d) Second-stage drying in FBD (♦ = 160 °C; ▲ = 180 °C; ■ = 200 °C); (e) Second-stage drying in MWD (♦ = 425 W; ▲ = 595 W; ■ = 850 W). (Vertical bars indicate the SE of the mean values.)

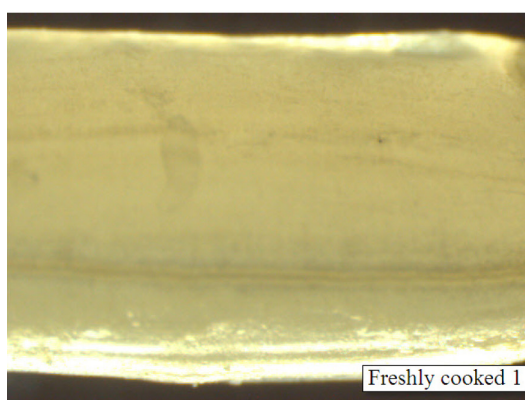
CONCLUSION

In order to produce quick-cooking brown rice, the cooked sample should be dried by the MWD since the MWD provides a high drying rate and porous structure of product. The thin-layer drying models developed in this study can effectively estimate the moisture content change of cooked brown rice during the drying process. The moisture diffusivities of cooked brown rice during drying depended on the moisture transport mechanism occurring inside the rice kernel. The moisture diffusivities were much higher for microwave drying than hot air drying. The true densities of samples that were dried in the HAD were higher than those dried in

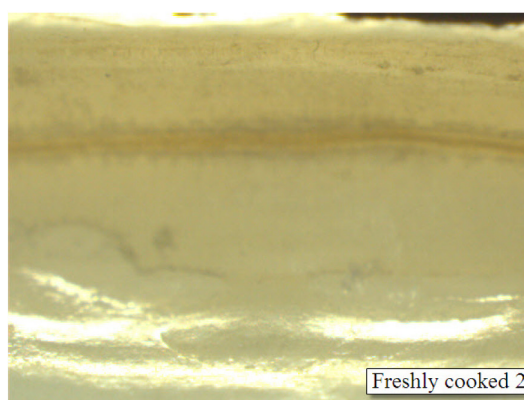
the MWD indicating a more porous structure in the microwave-dried samples. The images taken by stereomicroscopy confirmed the effect of freezing pretreatment and drying on the product structure. Nevertheless, in order to determine a suitable process for producing high quality, quick-cooking brown rice, further studies on the textural and sensorial qualities of rehydrated rice and the rehydration time are needed.

ACKNOWLEDGEMENTS

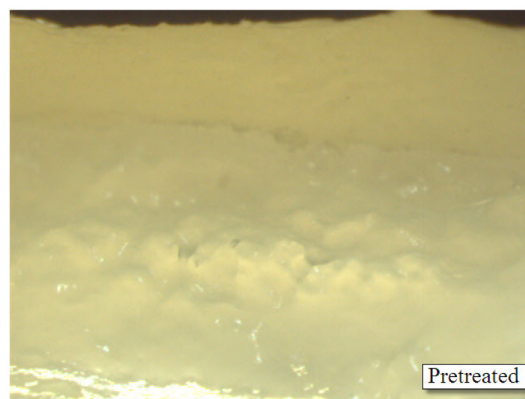
A part of this research was funded by Center for Advanced Studies in Agriculture and Food, KU Institute for Advanced Studies, Kasetsart University.



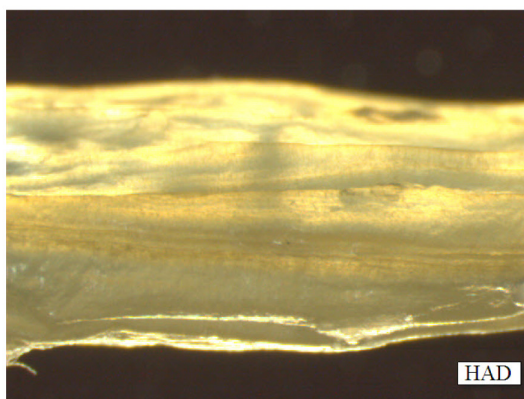
(a)



(b)



(c)



(d)

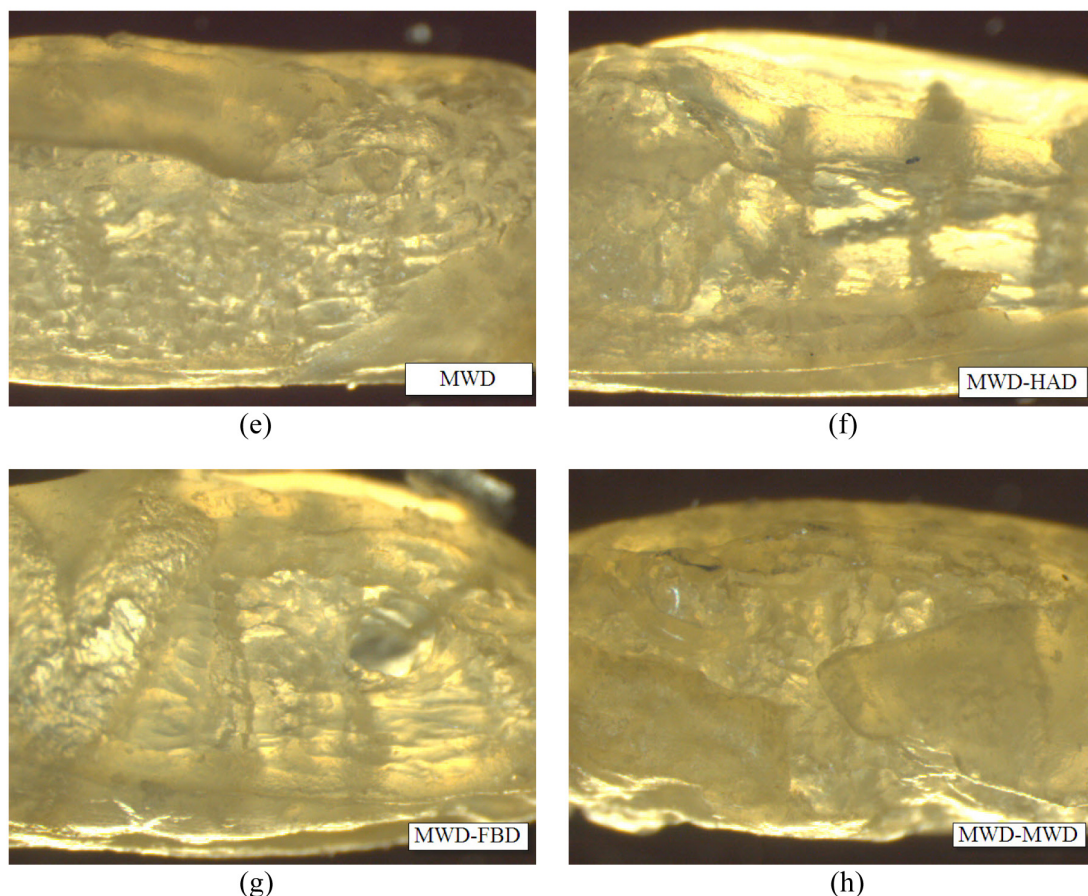


Figure 6 Images of samples captured from stereo microscope at 16 \times magnification: (a) Freshly cooked brown rice sample no.1; (b) Freshly cooked brown rice sample no.2; (c) Cooked brown rice after freezing and thawing pretreatment; (d) Sample after single-stage drying in hot-air dryer (HAD); (e) Sample after single-stage drying in microwave dryer (MWD); (f) Sample after two-stage drying in MWD and HAD; (g) Sample after two-stage drying in MWD and fluidized bed dryer (FBD); (h) Sample after two-stage drying in MWD and MWD.

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