



Research article

Effect of soaking conditions on properties of Khao Dawk Mali 105

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Abstract

The effects were studied of soaking conditions on the physical properties and water absorption behavior of Khao Dawk Mali 105 (KDML105) paddy. Samples of KDML105 paddy were soaked in water at four temperatures (room temperature ($27.8 \pm 0.98^\circ\text{C}$), 30°C , 40°C , 50°C) for 1–12 hr. The soaking conditions (temperature and time) affected the water absorption of KDML105 paddy. However, the soaking temperature had more influence on the water absorption than the soaking time since the water absorption rate of paddy after the first hour increased from 0.117 kg water/hr/kg solids at room temperature of soaking to 0.159 kg water/hr/kg solids at 50°C soaking temperature. The suitable conditions for soaking were 50°C for 9 hr and the resultant moisture content of the paddy was higher than 45% on a dry basis and sufficient for gelatinization and germination of Khao Hang rice. For the same period of soaking, water absorption increased with increasing soaking temperature. The effective water diffusion was influenced by the soaking temperature increasing with temperature from $8.85 \times 10^{-12} \text{ m}^2/\text{s}$ to $1.83 \times 10^{-11} \text{ m}^2/\text{s}$. An Arrhenius relationship was used to describe the water diffusion dependence on the soaking temperature, and the activation energy for water diffusion was 26.48 kJ/mol. Seven empirical models were developed to explain the hydration behavior of KDML105 paddy. The two-term exponential model produced the best results for goodness-of-fit for any soaking time.

Introduction

Khao Hang is one of the rice types processed in northeast Thailand and some parts of Laos PDR and is a form of parboiled rice (Schiller, 2006) which is made from either glutinous rice or fragrant either normal paddy or sprouted paddy. The demand for Khao Hang has been rising because of its nutritional benefits and there have been many reports mentioning the advantages of Khao Hang (Chamchoi et al., 2008; Pollamai et al., 2008; Tiangboontham, 2008; Worasatsing et al., 2008; Nakornraib, 2012).

Khao Hang is processed hydrothermally, which involves three steps: soaking paddy in water, steaming to complete gelatinization of starch and then drying to reduce the moisture content (Rao and

Juliano, 1970; Gariboldi, 1974). Soaking is a very important step because the moisture content in the kernel is increased by the diffusion of water to provide the starch with sufficient water for gelatinization (Gariboldi, 1974). Soaking is also necessary for paddy germination in the germinated Khao Hang process and the recommended soaking temperature for the germinated Khao Hang process is below 50°C (Wattanachaiyingcharoen, 1999) which is lower than the gelatinization temperature of paddy. At a soaking temperature below 50°C , enzyme activities contribute to the germination stage of paddy; however, if the soaking temperature is too low, the soaking period becomes prolonged and the paddy is spoiled due to fermentation and microbial activity (Luh, 1991; Bhattacharya, 2004; Bhattacharya and Ali, 2015).

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The hydration of paddy is complicated and is affected by many factors, including the soaking temperature, soaking time, initial moisture content and diffusion behavior (Bakshi and Singh, 1980; Bello et al., 2004; Oli et al., 2014). Fick's second law of diffusion is widely used to describe the hydration characteristics of paddy during soaking (Bakshi and Singh, 1980; Elbert et al., 2001; Prakash et al., 2011; Oli et al., 2014). The diffusion coefficient provides a measure of effective diffusivity (D_{eff}) which is one of the important factors in the hydration of paddy (Oli et al., 2014). The D_{eff} value depends on the physicochemical properties and microstructure of the paddy grain; therefore, there is diverse paddy hydration behavior among rice varieties.

While there have been some studies on soaking temperature of parboiling (including Sarepuang et al., 2008 and Kale et al., 2015), this research investigated the effect of soaking temperature on properties of the final product (parboiled rice) and did not consider the properties of the paddy after soaking. Knowledge of the water absorption behavior in KDML105 paddy should be used to optimize the soaking conditions in Khao Hang and germinated brown rice processing. After soaking, the physical properties of paddy, such as dimensions, shape and bulk density, change and understanding this change is a key factor in the design of the equipment used in the process, such as the size of the soaking tank. The objectives of this research were to study the effect of soaking conditions on the water absorption and physical properties of KDML 105 and to develop a suitable hydration model of KDML 105 paddy during soaking.

Materials and Methods

Sample preparation

Khao Dawk Mali 105 (KDML105) paddy was obtained from a paddy field in Chiang Rai province, Thailand. The paddy was cleaned by removing foreign materials and immature seed. The cleaned paddy was stored in an airtight plastic box. The average initial moisture content of the rice grains was $11-14 \pm 1\%$ (wet basis).

Soaking condition

Before soaking, 1,600 g of the sample paddy was rinsed and placed in a percolated nylon bag. Then, the bag was soaked in a thermostatic water bath at four different water temperatures (room temperature ($27.8 \pm 0.98^\circ\text{C}$), 30°C , 40°C , 50°C) for 12 hr. Every hour, a soaked paddy sample (180 g) was removed and quickly blotted with paper towels to remove residual surface moisture. The sampled paddy was measured for its moisture content, dimensional change and bulk density.

Moisture content

The moisture content represents the water absorption of paddy and the applicability of different water absorption models to predict the moisture content of paddy during soaking was determined. The moisture content of paddy samples was determined in triplicate using

the hot-air oven method at 130°C for 22 hr (American Society of Agricultural Engineers, 1998). The water absorption of paddy was calculated from the increase in the moisture content.

Dimensional changes

The dimensional changes of the paddy samples were measured on 100 randomly selected paddy kernels. The length (L), width (W) and thickness (T) of samples were determined using a digital micrometer (Mitutoyo; Kawasaki, Japan). The grain volume (V), equivalent diameter (D_e), geometric mean diameter (D_g) and sphericity (Φ) of samples were determined using the equations described by Mohesenin (1986), Jain and Bal (1997), Jayas and Cenkowski (2006), respectively, as shown in Equation 1–4, respectively:

$$V = \left(\frac{\pi}{6}\right) \frac{WTL^2}{2L - (WT)^{1/2}} \quad (1)$$

$$D_e = \left(\frac{L \times (W + T)^2}{4}\right)^{1/3} \quad (2)$$

$$D_g = (LWT)^{1/3} \quad (3)$$

$$\phi = \frac{(LWT)^{1/3}}{r} \quad (4)$$

Bulk density

The bulk density (ρ_b) of each paddy sample was determined according to the method of Kashaninejad et al. (2007). Bulk density was defined as the ratio of the mass of the sample to the volume of the container. After filling the container, excess kernels were removed by passing a stick across the top surface using five zigzag motions, so the samples were not compacted in any way. The bulk density was expressed in kilograms per cubic meter using Equation 5:

$$\rho_b = \frac{\text{Mass of grain}}{\text{Volume of cylinder}} \quad (5)$$

Estimation of effective water diffusivity

The effective water diffusivity (D_{eff}) of paddy during soaking at different temperatures can be estimated using the simplified form of Fick's second law of diffusion. Assuming that the water diffusivity is constant, the volumetric change during soaking is negligible and the surface of paddy reaches the equilibrium moisture content instantaneously upon immersion in water. Most researchers have assumed rice kernels have a simple spherical shape (Suarez et al., 1982; Bello et al., 2004; Kashaninejad et al., 2007; Cheevitsopon and Noomhorm, 2011) and the general form of Fick's second law in spherical coordinates is given as a mathematical model in Equation 6 according to Crank (1975):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \exp\left(-\frac{D_{eff}\pi^2}{R_e^2}t\right) \quad (6)$$

where MR is the moisture ratio, M_t is the moisture content at time t , M_e is the equilibrium moisture content of water absorption (EMC; % dry basis), M_0 is the initial moisture content (% dry basis), D_{eff} is the effective moisture diffusivity (measured in meters per second squared) and R_e is the equivalent radius of paddy (measured in millimeters).

Equilibrium moisture content of water absorption

The EMC was determined by soaking 60 g of paddy in 200 mL of distilled water. Different water temperatures were used (room temperature ($27.8 \pm 0.98^\circ\text{C}$), 30°C , 40°C , 50°C). The EMC was determined as the moisture content of kernel after 50 hr of soaking (Thakur and Gupta, 2006; Oli et al., 2014).

Modeling of paddy water absorption

Seven common water absorption empirical models (Table 1) were used to predict the water absorption of the KMDL105 during soaking. The kinetics of water absorption were expressed as the moisture ratio (MR) using Equation 7:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (7)$$

Statistical analysis

The constants and coefficients of the models were determined using nonlinear regression analysis facilitated by the SPSS software (version 16; SPSS Inc.; Chicago, IL, USA). The goodness-of-fit between the experimental and predicted amounts of water absorbed was determined using the coefficient of determination (R^2) and the root mean square error (RMSE), which was defined using Equation 8:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \right]^{1/2} \quad (8)$$

where $MR_{exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio and N is the number of observations. The best model for describing the water absorption of paddy was selected based on the criteria of the highest R^2 and the lowest RMSE value. Statistical significance was tested at $p < 0.05$ using Tukey's test.

Results and Discussion

Effect of soaking conditions on grain physical properties

Water absorption characteristics

The water absorption of paddy during soaking at different soaking temperatures for 12 hr is shown in Fig. 1. The water absorption rate in the first period of high soaking temperature was higher than that for a low soaking temperature. The moisture content of paddy soaked at a high temperature was higher than that for a low temperature for the entire soaking period. This peculiar hydration is common in various kind of cereals, including rough rice soaked in water at below the gelatinization temperature (Bello et al., 2007). For soaking at a lower gelatinization temperature, the initial water absorption rapidly increased then gradually increased with soaking time. The results showed that the water absorption rates of paddy in the first hour of soaking temperatures at room temperature, 30, 40 and 50°C were 0.117 kg water/hr/kg solids, 0.121 kg water/hr/kg solids, 0.134 kg water/hr/kg solids and 0.159 kg water/hr/kg solids, respectively. The increasing absorption rate at the very start of soaking was due to water molecules adhering to the husk surface and then penetrating through the microspores of the husk. In the first hour of soaking, water was retained in the voids of the rice kernels due to capillary absorption, after which the water molecules were absorbed into the starch granules and held as water of hydration. In the latter stage of soaking, the water absorption rate decreased until it reached the EMC

Table 1 Empirical models used for prediction of paddy water absorption

Model name	Description	Reference
Becker	$M_t = M_0 + \Delta M_0 + k_0 \sqrt{t}$	(Becker, 1960)
Peleg	$M_t = M_0 + \frac{t}{k_1 + k_2 t}$	(Peleg, 1988)
Lewis	$MR = \frac{M_t - M_e}{M_0 - M_e} = \exp(-kt)$	(Lewis, 1921)
Page	$MR = \frac{M_t - M_e}{M_0 - M_e} = \exp(-k_0 t^n)$	(Page, 1949)
Henderson and Pabis	$MR = \frac{M_t - M_e}{M_0 - M_e} = A_0 \exp(-k_0 t)$	(Henderson and Pabis, 1961)
Modified Page	$MR = \frac{M_t - M_e}{M_0 - M_e} = \exp[-(kt)^n]$	(Overhults et al., 1973)
Two-term exponential	$MR = \frac{M_t - M_e}{M_0 - M_e} = A_0 \exp(-k_0 t) + A_1 \exp(-k_1 t)$	(Sharma, 1981)

after prolonged soaking. This result was similar to the observations of Miah et al. (2002), Bello et al. (2007), Mir and Bosco (2013) and Oli et al. (2014) who reported that the water absorption rate rapidly increased in the first stages of soaking and after that it gradually increased in the later stages and increased with an increasing temperature.

Dimensional changes

The dimension parameters of soaked paddy (width, length, thickness, grain volume, equivalent diameter, geometric mean diameter, sphericity) at various temperatures and times of soaking are presented in Table 2. All dimension parameters of soaked paddy at the EMC were significantly greater than for raw paddy. When the moisture content of paddy reached the EMC, the soaked paddy at 50°C had significantly higher dimension parameters than the paddy that was soaked at lower temperatures (room temperature, 30°C, 40°C), except for the length and sphericity. The length-width ratio of KDML105 in this experiment was 3.84 which conformed with its long grain rice classification (United States Department of Agriculture, 1994; Naivikul, 2004). The dimensions of soaked samples rapidly increased in the first hour of soaking and then gradually increased (Fig. 2). The highest dimensional increase rate was at 50°C soaking temperature (0.02 mm/hr in width, 0.14 mm/hr in length, 0.07 mm/hr in thickness). The increase in the dimensions of paddy occurred because water penetrated into the amorphous starch granules and formed hydrates through hydrogen bonding. (Ali, 1974).

Bulk density

The bulk density of paddy during soaking at different temperatures for 12 h is shown in Fig. 3. The initial bulk density of paddy (538.35 kg/m³) increased after soaking at room temperature, 30°C, 40°C and 50°C to 593.70 kg/m³, 600.31 kg/m³, 616.52 kg/m³ and 619.67 kg/m³, respectively. The bulk density of paddy rapidly increased with initial soaking and gradually increased later. Even though there was volumetric expansion of the paddy kernel volume during soaking, the bulk density of paddy still increased due to the mass of water gain in the paddy.

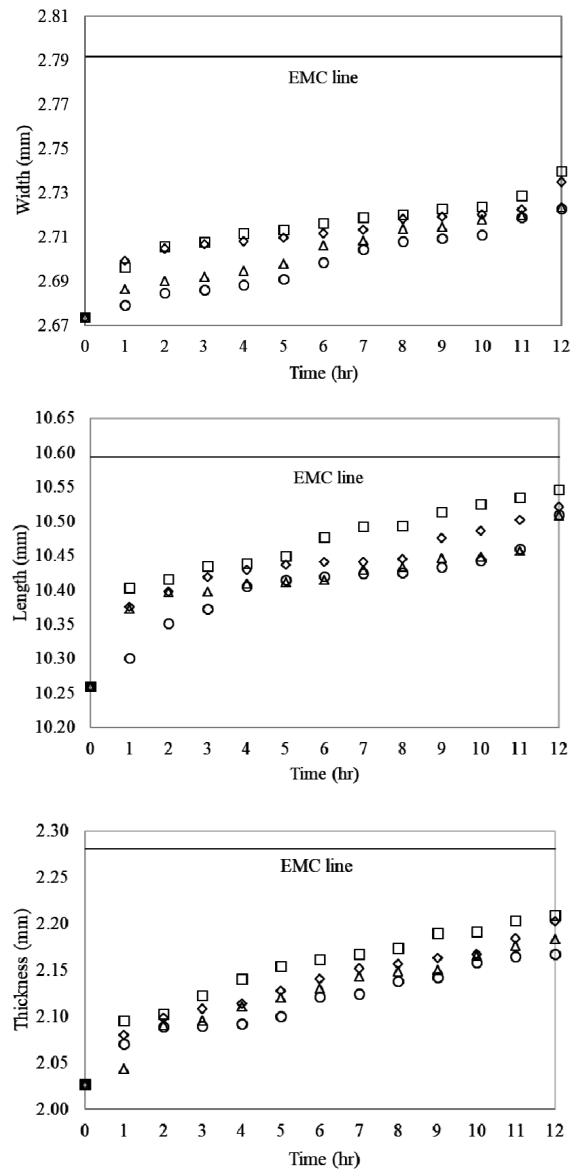


Fig. 2 Effect of soaking conditions on dimensional changes of KDML 105 paddy, where ○ = room temperature (27.8±0.98°C), 30° = △C, 40° = ◇C, □ 50° = C and EMC = equilibrium moisture content

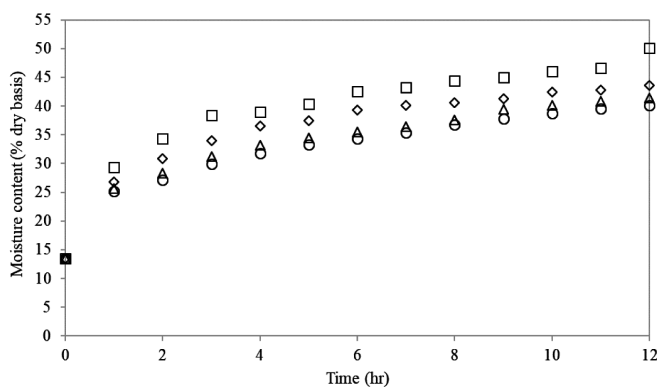


Fig. 1 Effect of soaking condition on water absorption of KDML 105 paddy, where ○ = room temperature (27.8±0.98°C), 30° = △C, 40° = ◇C, 50° = □C

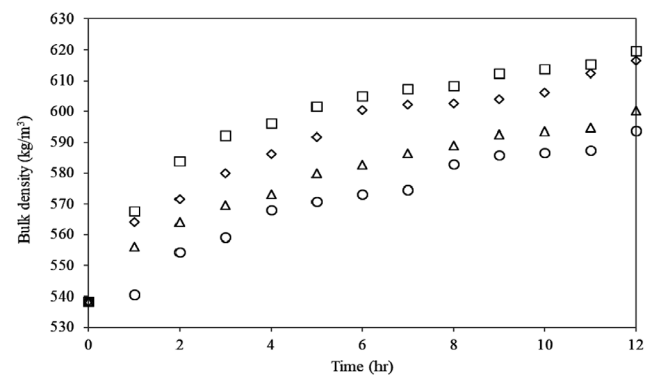


Fig. 3 Effect of soaking condition on bulk density of KDML 105 paddy, where ○ = room temperature (27.8±0.98°C), 30° = △C, 40° = ◇C, 50° = □C

Table 2 Dimensional changes of raw and soaked KDML 105 paddy

Parameter	Raw paddy	Soaked paddy (at equilibrium moisture content)			
		Room temperature (27.8 ± 0.98°C)	30°C	40°C	50°C
W (mm)	2.67 ± 0.01 ^a	2.72 ± 0.01 ^b	2.73 ± 0.01 ^b	2.74 ± 0.01 ^b	2.79 ± 0.01 ^c
L (mm)	10.26 ± 0.07 ^a	10.54 ± 0.01 ^b	10.54 ± 0.02 ^b	10.57 ± 0.02 ^b	10.59 ± 0.03 ^b
T (mm)	2.03 ± 0.01 ^a	2.22 ± 0.01 ^b	2.22 ± 0.01 ^b	2.22 ± 0.01 ^b	2.28 ± 0.01 ^c
V (mm ³)	16.42 ± 0.08 ^a	18.84 ± 0.06 ^b	18.92 ± 0.10 ^b	19.05 ± 0.06 ^b	20.05 ± 0.21 ^c
D _e (mm)	3.84 ± 0.01 ^a	4.01 ± 0.01 ^b	4.01 ± 0.01 ^b	4.02 ± 0.01 ^b	4.08 ± 0.01 ^c
D _g (mm)	3.82 ± 0.01 ^a	3.99 ± 0.01 ^b	4.00 ± 0.01 ^b	4.01 ± 0.01 ^b	4.07 ± 0.01 ^c
Φ	0.37 ± 0.00 ^a	0.38 ± 0.00 ^b	0.38 ± 0.00 ^b	0.38 ± 0.00 ^b	0.38 ± 0.01 ^b

W = width; L = length; T = thickness; V = grain volume; D_e = equivalent diameter; D_g = geometric mean diameter and Φ = sphericity.

Mean values (± SD) with different lowercase superscripts within each row denote significant differences ($p < 0.05$) for each soaking temperature.

Water absorption modeling

The moisture contents of the paddy samples were used to determine the applicability of each water absorption model for the prediction of the moisture content of paddy during soaking. The water absorption data for several conditions were fitted to the seven empirical models (Table 1). The results of the nonlinear regression analyses and statistical analyses of the different models including the constants and coefficients of models were used to evaluate the goodness-of-fit (R^2 and RMSE) and these results are presented in Table 3. The statistical parameters of the empirical models showed that

the R^2 and RMSE values were in the ranges 0.643–0.998 and 0.0100–1.1586, respectively. The two-term exponential was the best model for describing the water absorption of paddy based on the criteria of the highest R^2 and the lowest RMSE at all soaking temperatures. Several researchers have reported that the two-term model was suitable for explaining the hydration and dehydration behavior of paddy (Sharma et al., 1982; Noomhorm and Verma, 1986). Since paddy consists of husk and brown rice, during soaking, the water diffusivity of each component is different; therefore, paddy should not be considered as a uniform material in hydration studies.

Table 3 Comparison of different models for water absorption at different temperatures

Temperature (°C)	Model	Model constant and coefficients	R^2	RMSE
Room temperature (27.8±0.98°C)	Becker's	$\Delta M_0 = 5.548, k_0 = 6.205$	0.996	0.3173
	Peleg's	$k_1 = 0.079, k_2 = 0.033$	0.948	1.1586
	Exponential (Lewis)	$k = 0.173$	0.643	0.0877
	Page	$k_0 = 0.377, n = 0.565$	0.986	0.0173
	Henderson and Pabis	$A_0 = 0.716, k_0 = 0.110$	0.997	0.0100
	Modified Page	$k = 0.178, n = 0.565$	0.968	0.0173
	Two-term exponential	$A_0 = 0.079, k_0 = 0.465, A_1 = 0.665, k_1 = 0.102$	0.998	0.0100
30	Becker's	$\Delta M_0 = 6.191, k_0 = 6.419$	0.994	0.4225
	Peleg's	$k_1 = 0.072, k_2 = 0.031$	0.954	1.1326
	Exponential (Lewis)	$k = 0.183$	0.488	0.0990
	Page	$k_0 = 0.394, n = 0.562$	0.987	0.0173
	Henderson and Pabis	$A_0 = 0.706, k_0 = 0.114$	0.993	0.0141
	Modified Page	$k = 0.191, n = 0.562$	0.987	0.0173
	Two-term exponential	$A_0 = 0.130, k_0 = 0.918, A_1 = 0.663, k_1 = 0.106$	0.996	0.0100
40	Becker's	$\Delta M_0 = 8.697, k_0 = 6.479$	0.963	1.0329
	Peleg's	$k_1 = 0.054, k_2 = 0.030$	0.986	0.6487
	Exponential (Lewis)	$k = 0.237$	0.638	0.0889
	Page	$k_0 = 0.477, n = 0.564$	0.997	0.0100
	Henderson and Pabis	$A_0 = 0.670, k_0 = 0.144$	0.977	0.0245
	Modified Page	$k = 0.269, n = 0.564$	0.997	0.0100
	Two-term exponential	$A_0 = 0.356, k_0 = 0.522, A_1 = 0.449, k_1 = 0.096$	0.997	0.0100
50	Becker's	$\Delta M_0 = 10.576, k_0 = 7.202$	0.967	1.0923
	Peleg's	$k_1 = 0.044, k_2 = 0.026$	0.946	1.3891
	Exponential (Lewis)	$k = 0.311$	0.715	0.0831
	Page	$k_0 = 0.548, n = 0.603$	0.963	0.0316
	Henderson and Pabis	$A_0 = 0.651, k_0 = 0.190$	0.967	0.0300
	Modified Page	$k = 0.369, n = 0.603$	0.963	0.0316
	Two-term exponential	$A_0 = 0.591, k_0 = 0.174, A_1 = 0.702, k_1 = 2.309$	0.974	0.0300

ΔM_0 = initial moisture gain; k, k_0 , k_1 = hydration rate constants; A_0 , A_1 = coefficients; n = experimental constant; R^2 = coefficient of determination.

Effective water diffusivity

Fick's second law of diffusion (Equation 6) was used for D_{eff} estimation of KDML 105 paddy soaked at different temperatures as shown in Table 4. The D_{eff} values during soaking of paddy varied from 8.85×10^{-12} to $11.83 \times 10^{-11} \text{ m}^2/\text{s}$ in the temperature range from room temperature ($27.8 \pm 0.98^\circ\text{C}$) to 50°C . The D_{eff} of paddy increased with increasing soaking temperature; therefore, the increasing water absorption of paddy was an outcome of the rising D_{eff} as shown in Table 5. The effect of temperature on the D_{eff} values in this result was similar to observations made by Bello et al. (2004), Thakur and Gupta (2006) and Bello et al. (2007) who reported that the effective water diffusivity was temperature dependent.

Generally, the relationship between the D_{eff} value and soaking temperature of paddy can be described using the Arrhenius relationship as shown in Equation 9:

$$D_{\text{eff}} = D_0 \exp(-E_a / RT) \quad (9)$$

where D_{eff} is the diffusion coefficient (measured in square meters per second), D_0 is a constant (measured in square meters per second), E_a is the activation energy (measured in kilojoules per mole), R is the gas constant (8.314 J/moleK) and T is the temperature (measured in degrees kelvin). The logarithm of D_{eff} and absolute temperature was plotted (Fig. 4) and D_0 and E_a were calculated using linear regression as shown in Table 4. The activation energy for diffusion of KDML 105 paddy (Table 4) was 26.48 kJ/mole , which was lower than the 31.50 kJ/mole for PR 116 paddy (Thakur and Gupta, 2006) and the 30.46 kJ/mole for KDML 105 brown rice (Cheevitsopon and Noomhorm, 2011). A lower activity energy implies faster water absorption of grain; with its husk layer, paddy has more resistance to water movement than brown rice.

Table 4 Effective water diffusivity (D_{eff}) and energy of activation (E_a) of KDML 105 paddy at different temperatures

Temperature ($^\circ\text{C}$)	D_{eff} (m^2/s)	E_a (kJ/mole)	Empirical equation	R^2
27.8	8.85×10^{-12}	26.48	$D_{\text{eff}} = 3.47\text{E-}07\exp(-26,480/RT)$	0.999
30	9.47×10^{-12}			
40	1.32×10^{-11}			
50	1.83×10^{-11}			

R^2 = coefficient of determination; RT = room temperature.

Table 5 Literature values for diffusion coefficient of paddy during soaking

Variety	Temperature ($^\circ\text{C}$)	Effective water diffusivity (m^2/s)	Reference
Gallo, RP2 (Long grain)	25	1.56×10^{-11}	Bello et al. (2004)
	35	1.78×10^{-11}	
	45	2.08×10^{-11}	
	55	2.59×10^{-11}	
	65	7.20×10^{-11}	
PR116 (Long grain)	30	2.56×10^{-11}	Thakur and Gupta (2006)
	45	4.24×10^{-11}	
	60	7.92×10^{-11}	
	25	1.40×10^{-11}	
Long grain	35	1.68×10^{-11}	Bello et al. (2007)
	45	2.77×10^{-11}	
	55	3.34×10^{-11}	
	60	4.01×10^{-11}	
	65	4.37×10^{-11}	

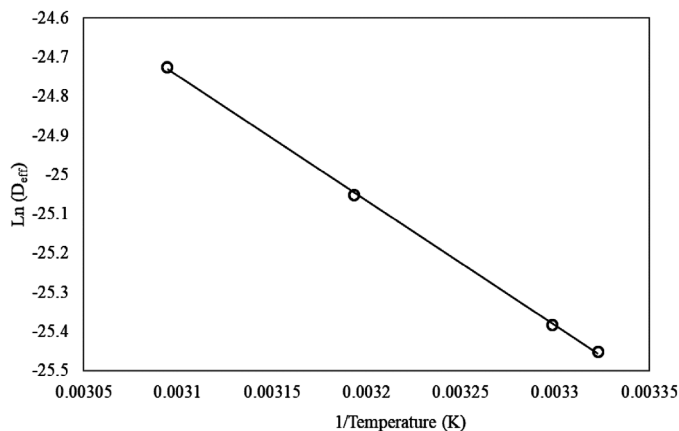


Fig. 4 Arrhenius plot for the effective diffusion coefficients

With the Arrhenius relationship, the mathematical model in Equation 6 could be used to predict the moisture content of paddy (KDML 105) as a function of the soaking temperature and time. The observed data and the predicted moisture content using the two-term exponential and the mathematical model were in good agreement (Fig. 5).

Conflict of Interest

The authors declare that there are no conflicts of interest.

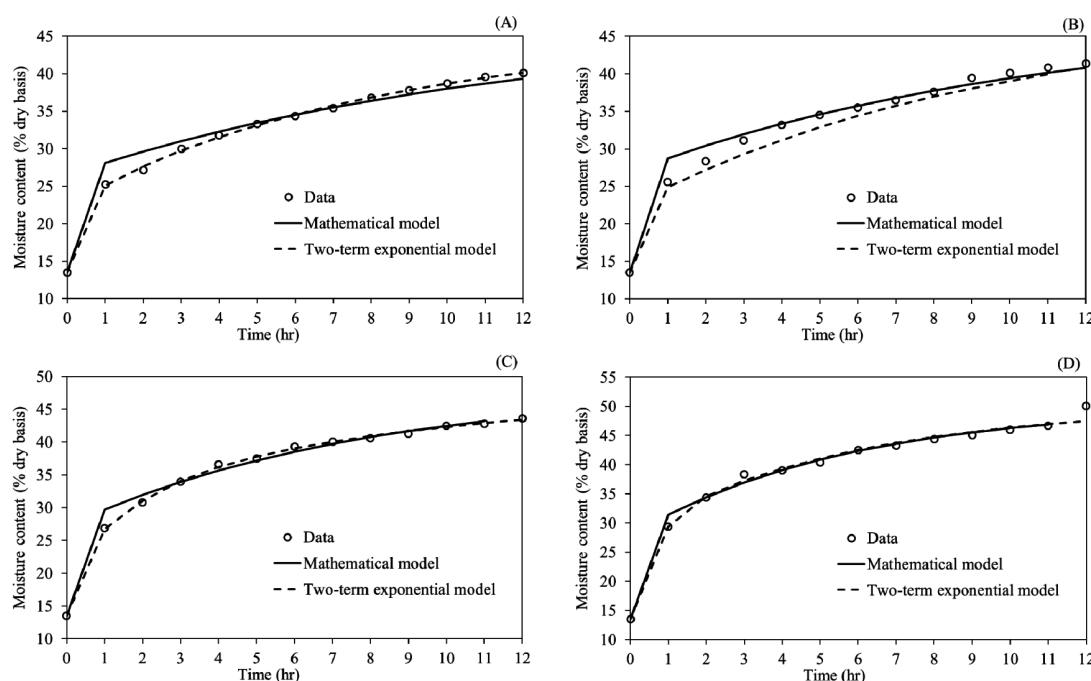


Fig. 5 Comparative fit of data using mechanistic and two-term exponential models: (A) room temperature ($27.8 \pm 0.98^\circ\text{C}$); (B) 30°C ; (C) 40°C ; (D) 50°C

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