



## Research article

# Influence of soaking temperature and time on the kinetics of water absorption and pasting properties of glutinous rice

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## Abstract

Soaking process is an important pretreatment step affecting on water absorption and gelatinization of rice starch. Glutinous rice (RD6 variety), with whole and broken kernels, was used to investigate the effect of soaking condition on the kinetics of water absorption. Both kernel types were soaked in water (rice kernel: water = 1:1.5) at 30, 40 and 50°C and sampled out at selected soaking times (0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 5 and 8 h). The water absorption of the broken kernel was higher than that of the whole kernel at the same soaking time resulted from the greater surface area for water penetration. The sorption process was described using Peleg model and revealed that mass transfer rate of broken kernel increased with increasing temperature. The obtained water absorption capacity of broken kernel was higher than that of whole sample. Temperature dependence of rate constant from broken kernel was higher than that of whole kernel according to Arrhenius equation. The pasting properties of soaked grains at 30°C were evaluated using a rapid visco-analyzer. Peak and final viscosities of all soaked rice kernel were higher than those of the kernel without soaking. The final viscosity increased with increasing moisture content in the rice kernel. The information gained in this study could be further applied for rice-based product in food industry.

## Introduction

Rice grain could be processed into various products such as rice cracker, rice snack, rice-based bread. Soaking rice in water is one of pretreatments used for rice-based product preparation especially prior to starch gelatinization process. The soaking pretreatment could be used to improve the rice characteristics relating to the extent of starch gelatinization. Water absorption into the kernels during soaking affects succeeding processes and the quality of the final product (Shafaei et al., 2016). There are many factors determining water absorption of the kernel such as amylose and protein contents (Bett-Garber et al., 2007), soaking temperature and time (Perez et al., 2012) including additives added into soaking water (Bello et al., 2004). Soaking temperature and

time are critical parameters affecting the water absorption into the kernel. The moisture absorption behavior of rice kernel at soaking temperature at  $\leq 60^\circ\text{C}$  showed an initial high rate of water absorption and followed by a slower rate in later stages (Bello et al., 2007). The hydration rate increases with increasing soaking temperature (Sharanagat et al., 2018). However, the soaking temperature should be lower than the starch gelatinization temperature to minimize the splitting of the grain kernels and subsequent solid leaching out (Chatakanonda and Sriroth, 2010; Saleh and Meullenet, 2013). A longer soaking time enhances the water uptake of the kernel and results in the kernel softening but may promote the problem of microbial growth from this pretreatment step leading to the lower quality of the final rice products.

Many mathematical models are used to describe and predict the water absorption of kernels or beans as a function of soaking time to understand the subsequent process and quality of the final product.

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Peleg model is a widely used model with the constants of Peleg rate constant ( $C_1$ ) and Peleg capacity constant ( $C_2$ ) indicating the kinetics of water uptake into the cereal kernel and agricultural products. The model constant could be further applied to predict the equilibrium moisture content of the kernels (Shafaei et al., 2016). Application of Peleg model was reported for water absorption prediction such as the soaking of bean and chickpea (Johnny et al., 2015; Shafaei et al., 2016), paddy rice (Corrêa et al., 2017) and brown rice (Foke and Madhava, 2013). Rice is an important staple food crop grown in many countries and is processed into various value-added products. Glutinous rice (*Oryza sativa* var. *glutinosa*) is a cultivar found in Southeast Asia, which has opaque and white kernels with low amylose content in the starch (Ahromrit et al., 2006). RD6 is one of the most popular glutinous rice varieties due to its aroma, starch character and eating quality, which make it very palatable to people (Wongkhamchan et al., 2018) such as rice snack. The effect of Thai glutinous rice cultivars and locations on the rice cracker (*arare*) quality was studied (Keeratipibul et al., 2008) whereas the effect of grain milling on starch structures and flour or starch properties was reviewed by Li et al. (2014). Some studies have reported the water absorption during soaking without the information of pasting properties of the grain such as paddy rice (Corrêa et al., 2017) and brown rice (Foke and Madhava, 2013). Pasting properties are important parameters of the processing quality for starch-based products. It could be used to optimize the starch concentrations and heating conditions (temperature and time) to obtain the desired product quality (Dang and Copeland, 2004). The effect of soaking condition on pasting properties of rice was observed in glutinous rice flour from dry-milling (Nawaz et al., 2016) and in high-amylose indica rice flour from wet-milling using soaking water about 10 times the weight of rice (Chiang and Yeh, 2002). However, there is no report related to the effect of soaking using limited water (for minimizing wastewater) on the pasting properties of glutinous rice (RD6 cultivar) from both whole and broken grains. Therefore, the objectives of this study were to determine the influence of soaking temperature and time on the kinetics of water absorption from both whole and broken rice kernels (RD6 cultivar). The Peleg model and Arrhenius equation were used to describe the water absorption process. The pasting properties of soaked glutinous rice kernel obtained from selected soaking conditions were determined using a rapid visco analyzer (RVA). Finally, the relationship between the water absorption during soaking and pasting properties was investigated. The information gained from this study is expected for further application in design the water absorption and pasting properties of the rice with a more systematic approach to predict and control the process and quality in rice-based product development.

## Materials and methods

### Materials

Commercial glutinous rice (50 kg) of RD6 cultivar was obtained from a rice mill company located in Khon Kaen Province, the northeastern part of Thailand. The separation of broken from whole grain rice was performed by a machine in the rice mill company. Both samples were kept

at 5°C throughout the experiment. The initial moisture contents of whole and broken kernels were 13.7% and 14.0% dry basis (db), respectively, determined according to official method (AOAC, 2012). The amylose contents of glutinous rice determined according to the iodine colorimetric method of Juliano (1971) were  $7.24 \pm 0.05\%$  and  $7.99 \pm 0.06\%$  db for whole and broken kernels, respectively. Usansa et al. (2009), Techarang et al. (2018), and Kunyane and Luangsakul (2018) also reported the amylose content of RD6 about 7%. Since the commercial glutinous rice (RD6) was used in the study, the amylose content about 7%db may be occurred because a part of residual non-glutinous rice was mixed with glutinous rice at the farm level during storage (Keeratipibul et al., 2008) and at the milling plant using the same milling machine.

### Soaking process of whole and broken kernels of glutinous rice

Whole and broken kernels (10 g) were soaked in polyethylene bags containing distilled water (rice: distilled water = 1:1.5 from preliminary test to limit the wastewater) and sealed. The samples after sealing were kept in a controlled temperature chamber (30, 40 and 50°C). The bags containing rice samples were taken out after soaking for 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3, 5 and 8 h. The rice grain was drained on wire sieve and shaken for 30 s. The soaked kernels were spread on tray and blotted with tissue towels for 1 min to remove the residual surface water of soaked rice. Then moisture content of each sample (5 g) was determined using a hot air oven (Binder GmbH, Tuttlingen, Germany) at 130°C until a constant weight was obtained (modified from the method 925.10) (AOAC, 2012). The moisture content (%db) was calculated and plotted as a function of soaking time for each soaking temperature.

### Determination of water absorption kinetics of rice kernels during soaking process

The Peleg model is used to describe sorption process during soaking in this study (Peleg, 1988) as shown in Equation 1:

$$M_t = M_o + \frac{t}{(C_1 + C_2 t)} \quad (1)$$

Where  $t$  was soaking time (h),  $M_o$  was an initial moisture content (%db),  $M_t$  was the moisture content at soaking time  $t$  (%db),  $C_1$  was the Peleg rate constant (h/%) and  $C_2$  was the Peleg capacity constant (1/%). The “+” was used in Equation 1 from the original model using “±” because the process is adsorption (The “−” will be used if the process is drying or desorption) (Turhan et al., 2002). The Peleg (Equation 1) could be modified to be Equation 2 as shown below:

$$\frac{t}{(M_t - M_o)} = C_1 + C_2 t \quad (2)$$

The plot of  $[t/(M_t - M_o)]$  as a function of soaking time was performed for each soaking temperature. The  $C_1$  relates to the mass transfer rate and is linked to the initial water sorption rate ( $R_o$ ) at the beginning soaking process as shown in Equation 3 (Turhan et al., 2002). The equilibrium moisture content ( $M_e$ ) values could be evaluated from  $C_2$  using Equation 4 (Shafaei et al., 2016).

$$R_o = \frac{1}{C_1} \quad (3)$$

$$M_e = M_o + \frac{1}{C_2} \quad (4)$$

The constants ( $C_1$  and  $C_2$ ) of the Peleg model from both whole and broken kernels were determined for each soaking temperature. Then Arrhenius equation was used to describe the effect of temperatures on  $C_1$  and  $C_2$  as shown in Equation 5 and 6, respectively.

$$\ln C_1 = \ln C_{01} - \frac{E_a}{RT} \quad (5)$$

$$\ln C_2 = \ln C_{02} - \frac{E_a}{RT} \quad (6)$$

Where  $C_{01}$  and  $C_{02}$  values were the constants of Arrhenius equation,  $E_a$  was the activation energy (J/mol),  $R$  was the universal gas constant = 8.314 J/mol K and  $T$  was the absolute temperature (K).

#### Pasting properties of soaked glutinous rice

The whole and broken glutinous rice after soaking at a selected temperature (30°C representing as ambient temperature) for 0, 2.5, 3.0, 4.0 and 5.0 h were selected and sampled for investigating the pasting properties because of the recommended soaking temperature for industrial application. The wet-milling was performed using a roller machine for size reduction of the soaked grain without drying prior to grinding. The ground rice was sieved through a 30 mesh flour sieve to obtain rice grit as soon as possible. The moisture content of each rice sample was determined (AOAC, 2012) to calculate the amount of water required for preparing 15%w/w (db) rice samples in RVA experiment. Then, 15%w/w (db) rice grit from both whole and broken kernels was prepared with a total weight of 28 g dispersion in the RVA canisters. To hydrate the starch molecules, the mixtures were stored at room temperature for 30 min and stirred manually to disperse the sample uniformly using RVA plastic paddles before the measurement. The pasting properties were observed using RVA (RVA 4500, Perten Instruments AB, Sweden) by modifying the method of Pongsawatmanit et al. (2007). The pasting profile of the rice samples was monitored during a thermal treatment by equilibrating the grit slurry at 50°C for 1 min, heating to 95°C at a rate of 6 °C/min, then holding at 95°C for 10 min to ensure complete gelatinization of rice grit, decreasing the temperature to 50°C at 6°C/min, and finally holding at 50°C for the remainder of the run (total run

time was 28 min). Agitation speed of RVA paddle was started at 960 rpm for the first 10 s and kept constant at 160 rpm until the end of measurement. Each sample was evaluated in triplicate.

#### Statistical analysis

All measurements were performed in triplicate and reported as the mean and standard deviation. The data were subjected to an analysis of variance (ANOVA) and compared the mean values with a probability of  $p < 0.05$  using Duncan's multiple range test (DMRT) using the SPSS software (version 12; SPSS (Thailand) Co., Ltd.; Thailand). The soaking condition, moisture content of rice kernels and RVA peak and final viscosities were related by Pearson's correlation.

## Results and Discussion

#### The water absorption during soaking of whole and broken kernels of glutinous rice

The moisture contents of both whole and broken kernels as a function of soaking time at different temperatures (30, 40 and 50°C) are shown in Fig. 1. The initial moisture contents of whole and broken kernels were 13.7 and 14.0%db, respectively. After soaking both types of kernels in controlled temperature chambers at 30, 40 and 50°C for 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3.0, 5 and 8 h, the moisture contents of both rice samples increased rapidly with increasing soaking time and temperature at the initial stage (0–1 h). Then relatively slow absorption was observed in later stages (after 2 h of soaking) indicating that the water penetrated into the kernel approaching the equilibrium. After 8 h of soaking, the moisture contents of whole and broken kernels were 57–59%db and 58–60%db, respectively (Table 1). The high water absorption rate at the initial stage could be attributed to filling of the cracks on the grain surface and internal fracture caused by milling process (Ahromrit et al., 2006). The moisture content of the broken kernel was higher than that of whole kernel at the same soaking time (Fig. 1) expected from more surface area for water penetration compared with those of whole kernels. Soaking in higher temperatures resulted to higher moisture content in shorter time. The similar behaviors were also observed during soaking process of whole chickpea (Shafaei et al., 2016) and split chickpea (Johnny et al., 2015).

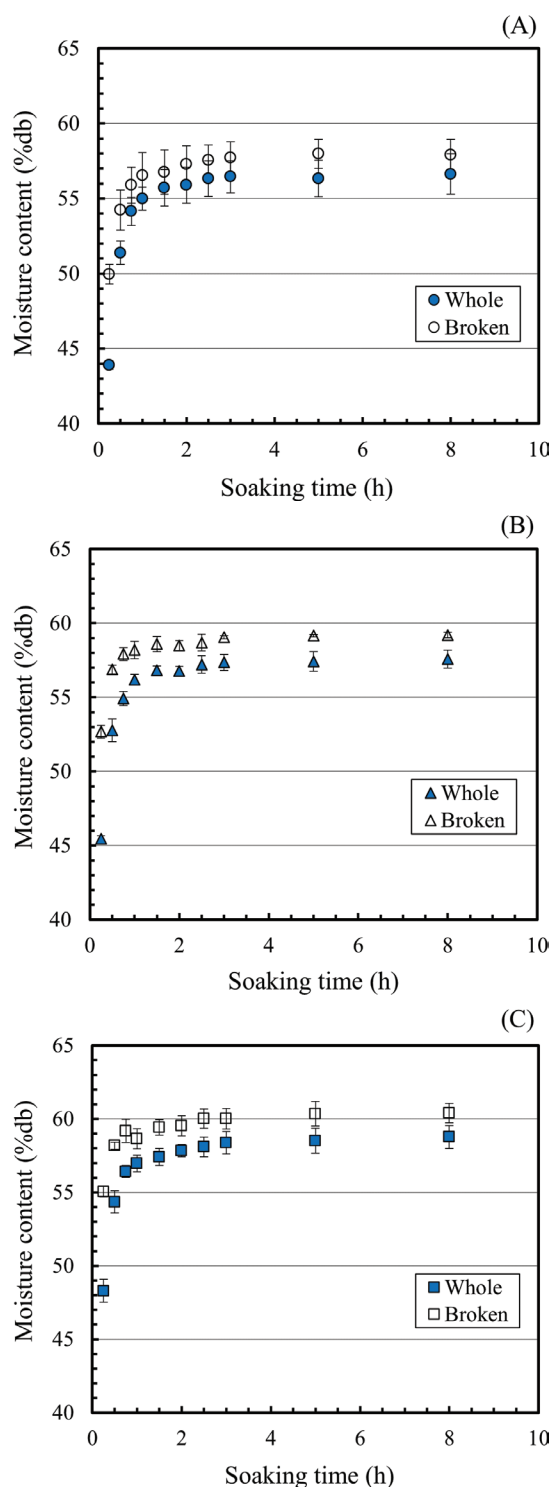
**Table 1** The regression equation obtained from the Fig. 2 to obtain the Peleg model constants ( $C_1$  and  $C_2$ ) for water absorption during soaking process of whole and broken glutinous rice grains at different temperatures with the initial water sorption rate ( $R_o$ ) and equilibrium moisture content ( $M_e$ ) values\*.

| Kernel type | Soaking temperature (°C) | Regression equation    | $C_1$ (h/%)              | $C_2$ (1/%)              | $R_o$ (%/h)        | Calculated $M_e$ (%db) | Experiment $M_e$ (%db)** |
|-------------|--------------------------|------------------------|--------------------------|--------------------------|--------------------|------------------------|--------------------------|
| Whole       | 30                       | $y = 0.0231x + 0.0014$ | $0.0014 \pm 0.0003^a$    | $0.0231 \pm 0.0007^a$    | $730 \pm 148^c$    | $57.0 \pm 1.4^c$       | $56.6 \pm 1.3^c$         |
|             | 40                       | $y = 0.0226x + 0.0013$ | $0.0013 \pm 0.0003^{ab}$ | $0.0226 \pm 0.0003^{ab}$ | $803 \pm 176^{bc}$ | $58.0 \pm 0.5^{bc}$    | $57.6 \pm 0.6^{bc}$      |
|             | 50                       | $y = 0.0220x + 0.0013$ | $0.0013 \pm 0.0002^{ab}$ | $0.0220 \pm 0.0004^{bc}$ | $801 \pm 103^{bc}$ | $59.1 \pm 0.8^{ab}$    | $58.8 \pm 0.8^b$         |
| Broken      | 30                       | $y = 0.0226x + 0.0010$ | $0.0010 \pm 0.0000^{bc}$ | $0.0226 \pm 0.0006^{ab}$ | $1052 \pm 40^b$    | $58.3 \pm 1.1^{bc}$    | $57.9 \pm 1.0^{bc}$      |
|             | 40                       | $y = 0.0220x + 0.0007$ | $0.0007 \pm 0.0001^c$    | $0.0220 \pm 0.0001^{bc}$ | $1452 \pm 285^a$   | $59.3 \pm 0.2^{ab}$    | $59.2 \pm 0.2^{ab}$      |
|             | 50                       | $y = 0.0215x + 0.0007$ | $0.0007 \pm 0.0000^c$    | $0.0215 \pm 0.0003^c$    | $1346 \pm 92^a$    | $60.6 \pm 0.7^a$       | $60.4 \pm 0.7^a$         |

Mean  $\pm$  standard deviation values (n = 3) followed by different superscript letters within the same column are significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

\*  $C_1$  = Peleg rate constant,  $C_2$  = Peleg capacity constant,  $R_o = \frac{1}{C_1}$  and  $M_e = M_o + \frac{1}{C_2}$ .

\*\* experiment  $M_e$  (%db) = the moisture content of soaked rice sample after soaking for 8 h.

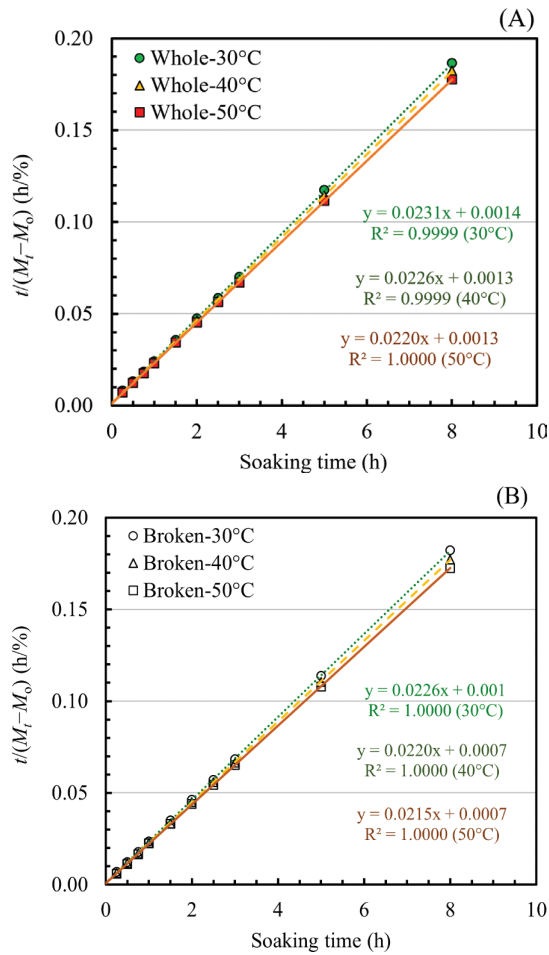


**Fig. 1** Moisture content of whole and broken rice kernels as a function of soaking time at 30°C (A), 40°C (B) and 50°C (C). The initial moisture contents of both whole and broken rice kernels were 13.7 and 14.0%db, respectively.

### Water absorption kinetics of glutinous rice for soaking process using Peleg model

The kinetics of water absorption for rice soaking was investigated using the Peleg model to predict the water sorption kinetics including equilibrium moisture content in soaking process. In this study, the entire absorption data from the beginning of soaking until equilibrium (8 h) was used in the model. The initial moisture content ( $M_0$ ) values (13.7 and 14.0%db, for whole and broken kernels, respectively) and  $M_t$  (%db) values at various soaking time  $t$  were used to calculate the term  $[t/(M_t - M_0)]$  as a function of soaking time. The model revealed a good curve fitting with  $R^2 \geq 0.9999$  (Fig. 2). The regression equations are shown in Table 1. The constant values of  $C_1$  and  $C_2$  (Table 1) were obtained from the intercept and the slope of the plots (Fig. 2), respectively, according to the modified Peleg model. The  $C_1$  (the intercept of the plot) was used to relate the mass transfer rate for water absorption: the smaller  $C_1$  values were the higher the initial water absorption rate (Turhan et al., 2002). The  $C_1$  values of whole kernels (0.0013–0.0014 h/%) were higher than those of broken rice (0.0007–0.0010 h/%) ( $p < 0.05$ ) indicating the lower mass transfer rate of whole kernel due to the lower surface area for water penetration as discussed in the previous section. In this study,  $C_1$  values of soaking of glutinous rice were independent of temperature (30–50°C) ( $p > 0.05$ , Table 1) for both types of kernels. Similar results were observed for split chickpea at soaking temperatures (35–65°C) (Johnny et al., 2015). However, the Peleg constant  $C_1$  was reported to be temperature dependent in the soaking of brown rice (Foke and Madhava, 2013), chickpea (Turhan et al., 2002), amaranth grain (Resio et al., 2006), and sorghum kernels (Kashiri et al., 2010). Since  $C_1$  related to sorption rate at the beginning stage of soaking,  $R_0$  was used to represent the initial water sorption rate and calculated using the term of  $[1/C_1]$  as shown in equation (3). The  $R_0$  value of the broken kernel was higher than that of the whole kernel at the same soaking temperature ( $p < 0.05$ , Table 1) and increased with increasing soaking temperature especially from 30°C to higher than 40°C expected from more softening and expansion of the kernels leading to the higher rate of water migration.

The Peleg rate constant  $C_2$  is used to relate the water absorption capacity. The lower of the  $C_2$  values indicates the higher water absorption capacity of the soaked kernel samples. Water absorption capacity of food materials depends on many factors such as cell wall structure, composition of seeds and compactness of the cells in seeds (Sharanagat et al., 2018). In this study, the  $C_2$  of broken kernel (0.0215–0.0226 1/%) was lower than that of whole kernel (0.0220–0.0231 1/%) indicating the water absorption capacity of the broken kernel was higher than that of the whole grain because of the more surface area for water penetration. The  $C_2$  of both whole and broken kernels decreased with increasing soaking temperatures especially from 30 to 50°C ( $p < 0.05$ , Table 1) suggesting that the higher temperatures enhanced the water absorption capacity of the rice kernels. Similar temperature-dependent phenomena were also observed for brown rice (Foke and Madhava, 2013) and chickpea (Yildirim et al., 2013).



**Fig. 2** The plots of  $[t/(M_t - M_o)]$  as a function of soaking time at 30°C, 40°C and 50°C using the modified Peleg model for whole (A) and broken (B) rice kernels. The  $M_o$  = the initial moisture content (%db),  $M_t$  = the moisture content at soaking time  $t$  (%db).

The Peleg rate constant  $C_2$  could be used to relate the equilibrium moisture content ( $M_e$ ) (maximum attainable moisture content at  $t$  approaching to infinity) as shown in Equation 4. From the experiment, the  $M_o$  values of the whole (13.7%db) and broken kernels (14.0%db) were used in the equation. The calculated  $M_e$  values of soaked glutinous rice for whole and broken were 57.0–59.1%db and 58.3–60.6%db, respectively (Table 1). The percentage difference between the estimated and experimental  $M_e$  values were less than 1% (data not shown) for all soaking conditions. The  $M_e$  values estimated from Peleg capacity constant,  $C_2$ , increased with increasing soaking temperatures. The results confirmed that the dependence of  $C_2$  on temperature resulted to obtain the different equilibrium moisture contents for different soaking temperatures.

#### Effect of temperature on the Peleg constants using Arrhenius model

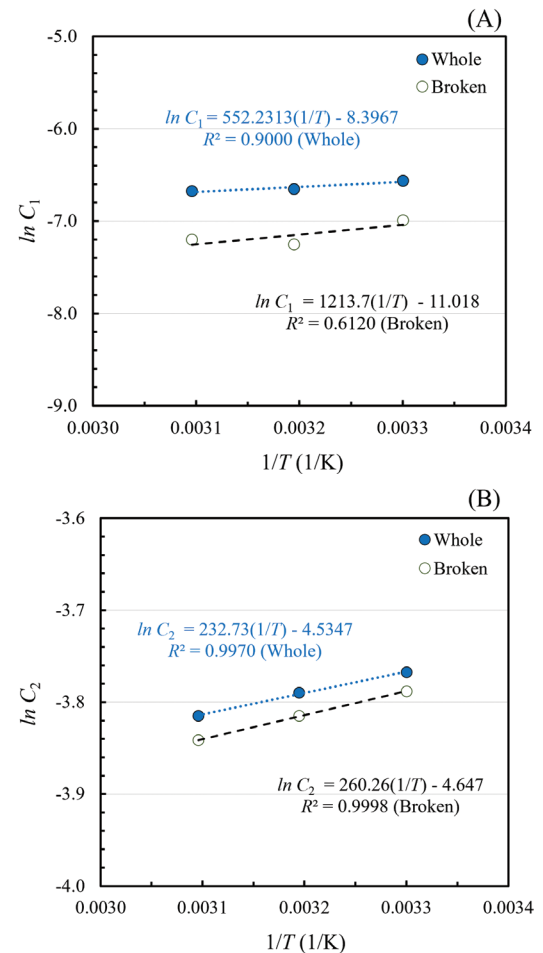
Arrhenius equation was used to confirm the influence of temperature on the Peleg rate constants,  $C_1$  and  $C_2$ , related to water absorption of whole and broken rice kernels. The plots of  $\ln C_1$  and

$\ln C_2$  of both whole and broken kernels versus  $1/T$  were shown in Fig. 3. The slopes of  $\ln C_1$  from the plots of the broken rice were higher than those from whole kernels (Fig. 3A) reflecting the more sensitivity of the changes in  $C_1$  of broken kernels to temperature. However, according to Table 1, the  $C_1$  values of rice soaking in water at 30 to 50°C revealed no significant difference (30–50°C) ( $p > 0.05$ ) for both types of kernels.

Considering the temperature dependency of water absorption capacity,  $C_2$ , from the Arrhenius plot (Fig. 3B), the slopes of  $\ln C_2$  from the curves of the broken rice were also higher than those from whole kernels (Fig. 3B) indicating the higher sensitivity of the changes in  $C_2$  of broken kernels to temperature. The results confirmed with the  $C_2$  of both whole and broken kernels decreased (more water absorption capacity) with increasing soaking temperatures especially from 30 to 50°C ( $p < 0.05$ , Table 1).

#### Pasting properties of soaked glutinous rice

The pasting properties of 15%w/w (db) glutinous rice mixtures from both whole and broken kernels with and without soaking at 30°C were investigated during heating and cooling processes using RVA. The soaking temperature at 30°C was selected to study as the



**Fig. 3** Arrhenius plots of  $\ln C_1$  (A) and  $\ln C_2$  (B) from the Peleg constant values versus  $1/T$  during soaking process of whole and broken rice kernels.

ambient temperature that could be further applied in food industry. The soaking times after 2.5 h were selected for investigating the pasting properties because the moisture content of the rice kernels approached a constant value after soaking for 2.5 h. The pasting properties from RVA curves are related to the gelatinization on heating and short-term retrogradation on cooling of starch-based samples (Pongsawatmanit and Srijunthongsiri, 2008). The selected typical RVA pasting profiles of whole and broken kernels with and without soaking are shown in Fig. 4A. The profiles of raw rice kernels (without soaking representing the soaking time = 0 h) show the lower peak compared to those of the soaked rice suggesting the soaking process could modify the pasting properties of the starch in rice samples. The starch granules are tightly packed in the raw rice kernel. The hardness of the raw glutinous rice decreased after soaking because the absorbed water penetrated into the rice kernel resulting in easily breakage of the grain and the leaching out of the constituents (Cho et al., 2004). With more water absorption during soaking, the soft structure of easily ruptured and fragmented kernels resulted in higher peak viscosity (Han and Lim, 2009) compared to raw kernel. However, the soaking process did not alter gelatinization temperature of all rice kernels because RVA pasting temperatures of all samples were 67.5–68.2°C ( $p > 0.05$ ). During heating of gelatinization process, the increase in starch granule swelling of soaked rice resulted in a pronounced increase in the viscosity of rice mixture at peak (about 45% in comparison with that of raw rice) from about 4700 mPa.s (raw rice) to about 6800 mPa.s (soaked rice). When the rice-water mixtures were maintained at 95°C, the mixtures were subjected to both thermal and shear stress under the RVA experiment, leading to both disruption of the starch granules and leaching out of the starch molecules causing a greater decrease in the viscosity (Fig. 4A). On cooling, each rice sample was subsequently cooled down to 50°C at 6°C/min, the paste viscosity increased to a final viscosity at the end of RVA measurement. The final viscosity is a value that related with not only the simple kinetic effect of cooling on viscosity, but also the re-association of starch (particularly amylose) molecules (Pongsawatmanit and Srijunthongsiri, 2008). The final viscosities obtained from raw rice were 3280 and 3160 mPa.s for whole and broken kernels, respectively ( $p > 0.05$ ). After soaking for 2.5 to 5 h, the final viscosity values of the rice kernels increased to be about 4400 mPa.s and showed no significant difference between the whole and broken samples, including the soaking time ( $p > 0.05$ ). *Similar results of the glutinous rice were also observed in the report of Nawaz et al. (2016) that the duration time of soaking at 30°C did not show a strong effect on peak viscosity of soaked glutinous rice (Thadokkham-11 variety). The results suggest that the soaking*

pretreatment could be used to enhance the peak and final viscosities of the rice-based product.

The final viscosities of both whole and broken rice kernel showed no significant difference ( $p > 0.05$ , Fig. 4) among the samples soaking from 2.5 to 5 h expected from the moisture contents of the soaked rice approaching constant equilibrium moisture content. The result was confirmed by plotting the RVA final viscosity and moisture content of the rice samples after soaking for 0, 2.5, 3 and 5 h as shown in Fig. 5. The lower RVA final viscosity was observed in the lower moisture contents of rice kernels without soaking pretreatment for both whole and broken rice samples. The increase in final viscosity of soaked rice was expected from the water absorption during soaking process. The results suggested that soaking the rice kernels before any heating affected the pasting properties of the rice kernel for both whole and broken kernels.

### Correlation analysis

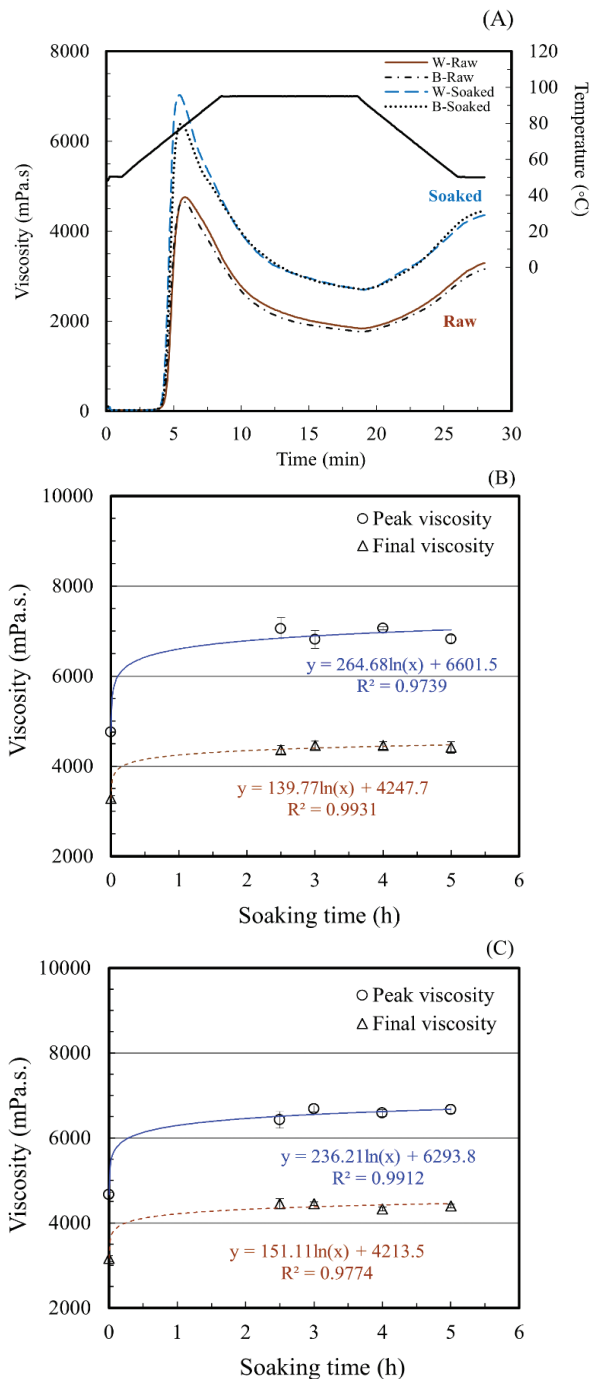
Correlation coefficients ( $r$ ) were investigated to determine the relationship among the soaking time, moisture content of rice kernels, and RVA peak and final viscosities as shown in Table 2 for both whole and broken rice kernels with soaking at 30°C for 0, 2.5, 3 and 5 h. The soaking time, moisture content of rice kernels, and RVA peak and final viscosities have a significant positive correlation to each other ( $r = 0.80$  to  $0.99$ , Table 2) at  $p < 0.01$ . The results confirmed that soaking process could be applied to increase moisture content of rice kernels and enhance peak viscosity and final viscosity of both kernel types of glutinous rice in rice-based products in food industry.

In conclusion, the water absorption of glutinous rice increased faster rate at the beginning of soaking stage and slower rate at the later stage. The Peleg model could be used to predict the kinetics of water absorption and the moisture contents of both whole and broken rice kernels during soaking process. The moisture content of broken rice kernel was higher than that of whole kernel after soaking. The water absorption capacity of both whole and broken kernels increased with increasing soaking temperatures especially from 30 to 50°C with higher sensitivity of the changes of broken kernels to temperature. Soaking process could modify the pasting properties of the raw rice kernels by observing the lower peak compared to those of the soaked rice. The increase in peak and final viscosities of soaked rice was expected from the water absorption during soaking process. The information gained from this study could be further applied to predict and control the water absorption and pasting properties of whole and broken rice kernels in rice-based products in the food industry.

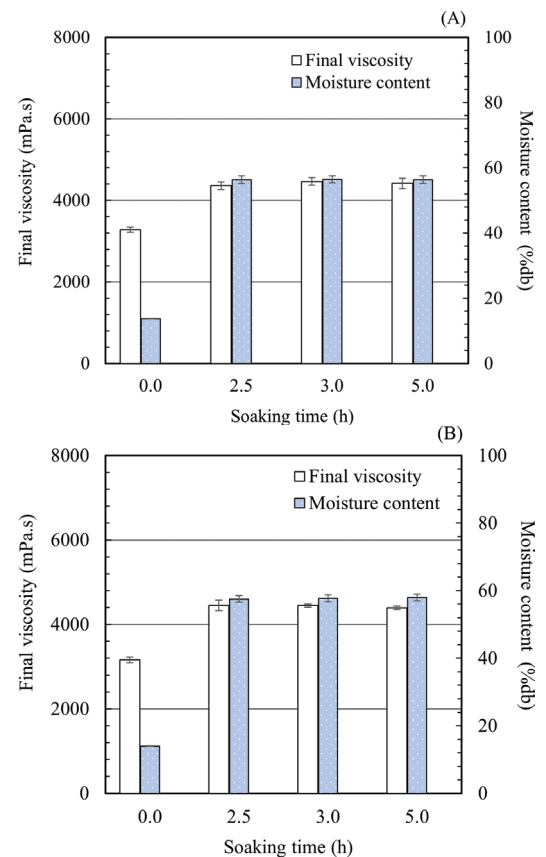
**Table 2** Correlation coefficients ( $r$ ) between the soaking time, moisture content of rice kernels, and RVA peak and final viscosities for both whole and broken rice kernels with soaking at 30°C for 0, 2.5, 3 and 5 h.

|                  | Whole kernel |                  | Broken kernel |                  |
|------------------|--------------|------------------|---------------|------------------|
|                  | Soaking time | Moisture content | Soaking time  | Moisture content |
| Soaking time     | 1.000        |                  | 1.000         |                  |
| Moisture content | 0.850**      | 1.000            | 0.854**       | 1.000            |
| Peak viscosity   | 0.804**      | 0.988**          | 0.877**       | 0.988**          |
| Final viscosity  | 0.848**      | 0.978**          | 0.824**       | 0.993**          |

\*\*Correlation is significant at the 0.01 level (2-tailed),  $p < 0.01$ , ( $n = 12$ ).



**Fig. 4** Typical RVA pasting profiles of 15%w/w db of whole and broken rice kernels with and without soaking (soaking at 30°C for 2.5 h) (A), the peak viscosity and final viscosity of 15%w/w db as a function of soaking time at 30°C for whole (B) and broken (C) rice kernels ( $n = 3$ ).



**Fig. 5** The RVA final viscosity and moisture content of 15%w/w db whole (A) and broken (B) glutinous rice at various soaking times at 30°C.

## Conflict of Interest

The authors declare that there are no conflicts of interest.

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