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Review Article

Kinetics of Water Absorption During Rice Soaking: A Review

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Abstract: Glutinous rice (Oryza sativa var glutinosa) is a rice cultivar with a low amylose content (1-2%). Its cultivation is less extensive than that of non-glutinous rice. Most consumption of glutinous rice is for traditional purposes. Hydration is a crucial step in the processing of glutinous rice. It occurs before the cooking operation. It is understood that soaking techniques require mass transfer parameters of water diffusion into the rice grain. However, due to the complexity of the soaking process, many features are still completely unknown. Consequently, studying the physical changes in rice quality during soaking is essential. Several empirical and semi-empirical models of the soaking process are discussed in this paper. For a more efficient soaking procedure, the behaviour of the hydration kinetics and the mathematical modelling of the quality changes during soaking are critical. In addition, the present limitations and probable future scope of study in this field are discussed.

Keywords: Rice; Soaking; Kinetics; Model for water absorption

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1. Introduction

Glutinous rice is noted for having a low amylose level (1–2%) and a high amylopectin content, providing unique eating qualities unlike ordinary rice. Several factors affected their eating quality, including the digestibility, pasting properties, mineral, sugar, amino acid, and fatty acid content of glutinous rice products (Thomas *et al.*, 2013). Glutinous rice, an essential culinary and cultural commodity throughout East Asia, is typically reserved for festival meals and desserts. However, it is also a staple diet in upland Southeast Asian regions such as Vietnam. The existence of sticky rice has long held cultural significance across a large geographical including parts of China, Japan, Korea, and Southeast Asian countries (Fuller & Castillo, 2016). Glutinous rice (*Oryza sativa* var glutinosa) can be found in traditional Malaysian cakes. In Malaysia, the plantation areas for two local glutinous rice (Susu and Siding) cultivars are 14.76 ha and 24.2 ha (Zainal & Shamsudin, 2021). Glutinous rice grain might be processed into various goods such as rice crackers, snacks, and rice-based bread. Unlike regular rice, sticky rice must be soaked before cooking. Soaking is a standard pre-treatment procedure before cooking glutinous rice to achieve the required softness and texture in the cooked product, particularly before the starch gelatinization process, in water for a while (Hanucharoenkul *et al.*, 2021).

Rice and sensory properties after cooking are linked to the level of starch gelatinization. This could be influenced by the soaking pre-treatment. People in Asia have practised soaking glutinous rice in water for hours before cooking to improve the cooking quality. However, there is still no knowledge regarding the proper soaking temperature or time. During soaking, water absorption into the kernels impacts subsequent operations and the quality of the end product. Pre-soaking allows water to diffuse into the rice kernel, fully swell and gelatinize (Zhu *et al.*, 2019). Soaking is essential because water diffusion increases the moisture content of the kernel. This process would lead the starch to gelatinize during heating. The pre-soaking process is frequently aided by microwave, convective plasma, ultrasonic, and high pressure in laboratory scale development (Hu *et al.*, 2021). Paddy and rice hydration is a complex process, and several factors might influence it, including soaking temperature, soaking time, initial moisture content, and diffusion behaviour. Soaking is also intended to eliminate antinutritional compounds, particularly phytic acid. Soaking has also been a part of the traditional parboiling rice process (Tomita *et al.*, 2019). Cooked rice has been parboiled conventionally to make it sweeter, more nutritious, and easier to digest (Muchlisyiyah *et al.*, 2023). In the preparation of glutinous rice, soaking is a must. Before cooking, the grain must be soaked for an extended period to soften it, allowing the starch to absorb more water during the cooking process. Water diffuses into the rice kernel during soaking, and some components leachut (Sareepuang *et al.*, 2008).

Both phenomena during soaking, namely water diffusion and material leaching, are time and temperature-dependent. Longer soaking times increase water intake, but they may also cause problems. To understand the ensuing procedure and quality, mathematical models are studied to forecast water absorption (Yadav & Jindal, 2007). It is used to match the experimental data and to produce a multi-parameter equation. Numerous empirical models are utilized, including Peleg's equation, Fick's diffusion and derived equation, and the Weibull model (Hu *et al.*, 2021). The diffusion coefficient measures effective diffusivity (D_{eff}), one of the most critical elements in rice grain hydration. The rice grain's physicochemical qualities and microstructure determine the Deff value. The soaking conditions and the glutinous rice processing should be optimized using knowledge of water absorption behaviour (Ji-u & Inprasit, 2019). In addition, the overall effective water diffusivity is dependent on the soaking operation (Megat Ahmad Azman *et al.*, 2020). In this field, substantial work is being conducted all around the world.

This study aims to examine previous investigations on the kinetics and mechanism of rice soaking. In this study, the physical properties of rice are reviewed first, followed by how the soaking process can influence these properties. Then, the different models created by various authors are discussed.

2. Soaking in Rice Processing

Soaking in glutinous rice processing was commonly used in two different ways. First was soaking as a pretreatment process and as part of the parboiling. These procedures were generally defined as follows.

2.1. Soaking as a Pretreatment

Soaking seeds before cooking softens them and conserve energy. It is done by putting the grain inside water for a certain period (usually 2-12 hours) (Hapsari & Eun, 2016). Soaking glutinous rice before cooking requires uniform water absorption and a softer texture (Wiruch *et al.*, 2019). For optimal nutrient retention, cooking and prolonged soaking are suggested (Mannam, 2017). Phytic acid and some enzyme inhibitors, which are responsible for the bioavailability of nutrients, are reduced with soaking (Shanthilal & Anandharamakrishnan, 2013)**.** Soaking as a pretreatment is a method that facilitates chemical transformation, enhances heat transport, and reduces the stiffness of rice.

2.2. Soaking as Part of the Parboiling Process

Rice parboiling is a critical technique that involves three stages: soaking in water (a long process), steaming (to finish starch gelatinization), and drying (to get ideal moisture). The parboiled glutinous rice went through three whole stages before cooking. During soaking and drying, rice kernels' water movement is governed by diffusion. (Shanthilal & Anandharamakrishnan, 2013). Consequently, soaking is crucial as an initial step for optimal gelatinization. Parboiling of glutinous rice was intended to increase the milled rice yield, soften the hard texture, improve the cooking quality and increase the resistant starch (Dutta & Mahanta, 2012; Hanucharoenkul *et al.*, 2021; Hapsari & Eun, 2016; Nawaz *et al.*, 2018)**.**

3. Changes in the Physical Properties of Rice During Soaking

Rice hydration is a complex process due to the simultaneous occurrence of moisture absorption, gelatinization of starch, and swelling in the presence of the soaking medium and temperature. However, soaking rice grains induces physical changes. The amount of these changes within the kernels highly depends on the intensity of the applied hydrothermal treatment (Mir & Bosco, 2013).

3.1. Moisture Content

The amount of water in rice grain is represented by the moisture content. Soaking procedures are highly determined by the initial moisture content of the glutinous rice grain. Rice's moisture content changes from 10–15% to 55–65% (w/w, dB) while soaking, depending on the temperature of the soak water (Mannam, 2017). The initial moisture content will specify the hydration rate of rice soaking procedures (Yadav & Jindal, 2007). The hydration rate is determined by the increasing moisture in the rice grain. It is affected by several factors, including the soaking condition. Hydrogen bonds between amylose and amylopectin inhibit starch granule absorption and swelling in cold water. Furthermore, heat damages granule structure during hot soaking, destroys hydrogen bonds and thus increases starch granule surface water absorption (Rocha-Villarreal *et al.*, 2018). Soaking in warm water frequently reduces cooking time because increasing temperature increases the hydration rate (Tomita *et al.*, 2019). However, soaking below starch gelatinization temperature is recommended to prevent the kernel from breaking and subsequent solids leaching (Zhu *et al.*, 2019).

3.2. Grain Dimension

Rice grain dimensions are categorized as long, medium, or short. The L/B ratio depicts the size of a rice grain. The medium grain ratio is 2.1-3, whereas the quick grain ratio is 2 or less. And the long grain ratio is at least 3.1 (Shinde *et al.*, 2014). It has been discovered that soaking rice grains significantly affects their axial dimensions. This is mainly related to the combination of water diffusion and heat treatment, which causes irreversible thickening and shortening of the starch granules absorption (Rocha-Villarreal *et al.*, 2018). During the soaking process, water molecules gradually move from the exterior medium to the interior rice kernel, and starch granules begin to swell, resulting in a change in milled rice volume. The rate of water migration increases as the temperature rises (Hu *et al.*, 2021). Generally, the hydration is more manageable at higher temperatures, and the starch granules swell more quickly(Ji-u & Inprasit, 2019).

3.3. Colour Properties

Generally, a greater soaking intensity or increased grain moisture content produces rice kernels with more remarkable colour changes. Grain colour variations during heat and moisture treatment are primarily attributable to nonenzymatic browning, pigment migration, and nonenzymatic browning (Lamberts *et al.*, 2008; Messia *et al.*, 2012). The colour of glutinous rice changes from white opaque to white translucent after soaking. The values of L*, a*, and b* were obtained using a colour reader to measure colour intensity(Shafiekhani *et al.*, 2018). The dark-light level is represented by the colour L*, which has a value range of 0-100. A green-red group with a range of -100 to +100 is represented by the colour a*. A blue-yellow level in the range of -100 to +100 is denoted by the colour b*. The soaking process may alter the colour of milled rice L(77 to 1-77.7), a (-0.4 to 1.1), b (15.7 to 20.9) and brown rice (62.0 to 65.1), a (5.3 to 5.4), b (24.3 to 23.8). L*, a*,b* colour characteristics of soaked brown rice suggested that red and yellow bran pigments diffused from the bran into the endosperm, while other components, such as lipids, migrated from the inner to the outer bran layers (Lamberts *et al.*, 2007).

3.4. Textural Properties

The gelatinization of amylose and amylopectin alters the texture of sticky rice after soaking (In *et al.*, 2007). For soaked paddy/rice grain, the texture is decreased as the water increases. However, the leaching of amylose during soaking and cooking controls the hardness of rice. Glutinous rice's low amylose content (1–2%) makes leaching difficult. However, the decrease in the hardness of glutinous rice will increase stickiness (Tao *et al.*, 2019). Starch would display a different textural response as the temperature and soaking time changed. When soaking time was raised, cooked rice became softer and less sticky. The prolonged soaking time appears to cause the rice to absorb more water, which results in the cooked rice being softer (hardness decrease to ±50%) and less sticky (Pansa-Ead *et al.*, 2005). On the other hand, for soaked and dried grains, rice becomes harder than raw rice due to the gelatinization and retrogradation of their starch. The degree of retrogradation of starch relies on the moisture level and temperature throughout the drying process (Paiva *et al.*, 2016). The hardness of rice kernels increases when grains are conditioned at greater moisture levels and temperatures (Mir & Bosco, 2013).

4. Kinetic Models of Rice Hydration

Rice starch gelatinization happens during soaking pretreatment. Water helped heat transfer during the gelatinization process and made the rice less solid. Rice that has not been soaked in water is difficult to digest. Soaking is a crucial step before rice starch gelatinization (Shanthilal & Anandharamakrishnan, 2013). The soaking procedure is governed by diffusion, which regulates water flow into the rice kernel. Comprehending the diffusion process and estimating the moisture gain during paddy soaking is crucial. As moisture moves into and out of the paddy kernel, the physical condition of rice components like protein, starch, and other chemicals changes. Several transport mechanisms, including molecular diffusion of water (in both the liquid and vapour phases), Knudsen flow, and capillary motion are involved in the moisture migration within the kernel (Behera & Sutar, 2018; Liu *et al.*, 2021; Zhu *et al.*, 2019). Balbinoti *et al.* (2018) modelled and simulated rice's hydration step during the parboiling process at 55 C in the 2D model (Figure 1).

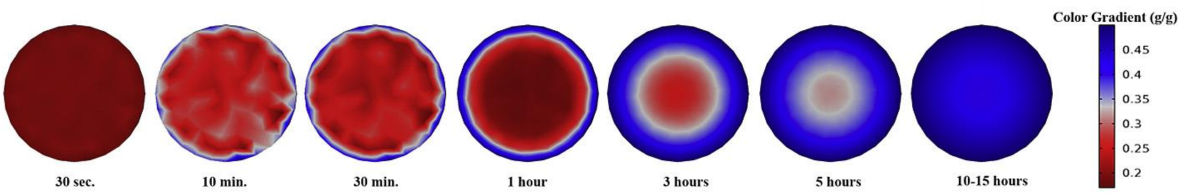

Figure 1. Simulation in 2D of moisture uptake in a process at 55 degrees Celsius. The interior part of rice has a moisture concentration varying from 0.17 g/g (burgundy) to 0.505 g/g (navy blue) (Balbinoti *et al.*, 2018)

Moreover, the grain hydration process is primarily a mass transfer unit in which the water activity differential is the driving force. In other words, diffusion occurs when water moves from a substance with a high-water concentration (soaking water) to a low water concentration (grain). In addition, the complex structure and diverse tissues and cells of the grains create water-permeable channels of various widths, shapes, compositions, and zones with variable permeability. Therefore, water enters the grains not only by diffusion but also by capillary movement. Thus, the hydration process is not as straightforward as it may appear, involving mass transfer and fluid flow mechanisms (Miano & Augusto, 2018). The hydration kinetics data can be fitted to an appropriate mathematical model to estimate the moisture content as a function of time and/or to investigate the process characteristics: the hydration rate, equilibrium moisture content, and lag phase time (in sigmoidal behaviour). Depending on the kinetics of hydration, numerous mathematical models are available. Some are empirical, while others are derived from physical laws. The models used in explaining hydration kinetics can be seen in Table 1. The process for analytical techniques in moisture content can explain water absorption and accurately assess water diffusion rates. The moisture content was calculated using the MR (Moisture Ratio) formula:

$$MR = \frac{M_e - M_t}{M_e - M_o} \quad (1)$$

Where:

M_O= Initial moisture content

M_e= Moisture content in equilibrium

M_t= Moisture in t

Table 2 describes the numerical models used to hydrate (soak and cook) rice under varying conditions. As a result, Peleg's model has been extensively employed in the sorption data for paddy, brown rice, and milled rice (Hanucharoenkul *et al.*, 2021b; Hu *et al.*, 2021; Ji-u & Inprasit, 2019; Saleh *et al.*, 2018). They compared experimental and anticipated water absorption values. They concluded that Peleg's model accurately predicts the hydration behaviour of rice rice. It is a semi-empirical equation (not derived from a physical law or diffusion theory), and it matches the hydration of various products quite well with only two parameters (Peleg, 1988). Both parameters of this model offer physical explanations for the hydration process, which is a benefit. The inverse of the value of k1 corresponds to the hydration rate, and the equilibrium moisture content is the sum of the starting moisture content and the inverse of the value of k2. Furthermore, the initial moisture content can be set during data fitting. Therefore, the projected curve will always pass through the initial moisture content of the experimental sample.

Fick's second rule of diffusion has been used to analyse grains' water sorption and desorption behaviour during soaking and drying. Like drying, researchers have applied semi-theoretical models to the water uptake kinetics of food. The equation models (Table 2), which are similarly based on Fick's second law of diffusion and were derived by simplifying the general series, offer a balance between theory and use (Fick, 1855; Oli *et al.*, 2014). This equation has various solutions in the form of series with distinct terms for regular geometries, such as infinite plates, infinite cylinders, and spheres (Miano & Augusto, 2018). Fick's diffusion and derivative equations are one-parameter models employed with the assumption of continuous water diffusion with an unchanging volume during the soaking process.

However, the dimensions alter depending on the temperature. Bello *et al.* (2007) and Hu *et al.* (2021) studied that this model reasonably estimates the rice hydration process.

Five empirical models (Henderson and Pubis, Exponential, Page, and Two Terms exponential) were used to estimate long-grain white rice's hydration process and density changes (Kashaninejad *et al.*, 2007). The Page model outperformed the other models in terms of prediction and accurately matched the experimental soaking properties of the milled rice. The Page model is extensively used for drying but can also be used for hydration. The equation was empirically generated by adding a shape parameter to the first-order kinetics equation to adapt the data. Page equation parameters could have physical meaning, which can be evaluated using fractional calculus. *Kp* is related to the diffusion coefficient and sample geometry. In contrast, *n* relates to the diffusion type and food microstructure (Simpson *et al.*, 2017).

Meanwhile, Ji-u & Inprasit (2019) studied the effect along grain paddy soaking conditions using 7 empirical models (Peleg, Becker, Lewis, Page, Henderson and Pubis, Modified Page, and Two Terms exponential). Based on the criterion of the highest R2 and the lowest RMSE at all soaking temperatures, the two-term exponential was the best model for characterizing the water absorption of paddy. Because paddy is made up of husk and brown rice, the water diffusivity of each component varies during soaking; thus, paddy should not be treated as a homogenous material in hydration experiments.

Within the rice kernel, water diffuses throughout the hydration process. The temperature gradient is the primary driving force for heat transfer from the medium to the grain. All temperature-dependent procedures were described by an Arrhenius-type equation, whose function is essential for determining the activation energy required for the desired activity (Shanthilal & Anandharamakrishnan, 2013). Consequently, most studies examined the impact of temperature on their respective target processes using an Arrhenius-type equation (Table 3). They discovered that the higher the soaking temperature, the greater the water diffusivity.

Table 1. The Equations used to estimate the hydration process (Adapted and modified from Ji-u & Inprasit, (2019))

Equation used	**Model name**
$M_t = M_0 + \Delta M_0 + k_0 \sqrt{t}$	Becker
$MR = \frac{6}{\pi^2} \exp(\frac{D_{ef}\pi^2 t}{R^2})$	Fick
$M_t = M_0 + \frac{t}{k_1 + k_2 t}$	Peleg
$MR = \frac{M_e - M_t}{M_e - M_0} = exp\ (-kt)$	Lewis
$MR = \frac{M_e - M_t}{M_e - M_0} = exp\ (-k_0 t^n)$	Page
$MR = \frac{M_e - M_t}{M_e - M_0} = A_0 exp\ (-k_0 t)$	Handerson and Pubis
$MR = \frac{M_e - M_t}{M_e - M_0} = exp\ [-(kt)^n$	Modified Page
$MR = \frac{M_e - M_t}{M_e - M_0} = A_0 exp\ (-k_0 t) + A_1 exp\ (-k_1 t)$	Two Term Exponential
$MR = \frac{M_e - M_t}{M_e - M_0} = \frac{6}{\pi^2} - \frac{D_{eff}\pi^2}{R_e^2}]$ $D_{eff} = D_0 exp\ (-\frac{E_a}{RT})$	Arrhenius relationship

Table 2. Previous studies in rice soaking kinetics

Rice Variety	Temperature and time range	Observed Parameter	Hydration models used	Authors
Japonica and Indica	25, 40, 60, 70 °C Every 3 minutes until 5 minutes	Projected area Expansion ratio Moisture sorption ratio	Peleg Fick Weibull Kaptso Ibarz Augusto	(Hu *et al.*, 2021)
RD6 (glutinous rice)	Soaking 30, 40, 50°C 0.25, 0.5, 0.75, 1.0. 1.5, 2.0, 2.5, 3, 5, 8 hours	Moisture and pasting properties	Peleg Model Arrhenius's relationship for Peleg constants	(Hanucharoenkul *et al.*, 2021)
Chocodrie Wells XL-723 XL-729 XL-730 XL-745	23.3, 50, 65, 70 and 75 °C for 1, 2, 4, 6, 8 and 16 h	Water uptake ratio Colour parameter Amylose content Pasting properties Textural properties	Peleg Two-term exponential	(Saleh *et al.*, 2018)
Japonica Rice	10, 25, 40, and 55 °C 2, 5, 10, 20, 30, 40, 50, 60 and 120 minutes	Projected area Brightness NMR spectrophotometer Mean moisture content Correlation between factors	No models used	(Tomita *et al.*, 2019)
Khao Dawk Mali (paddy)	Room temperature, 30, 40, 50 °C 12 hours	Moisture content Dimensional changes Bulk density, effective water diffusivity	Becker Peleg Lewis Page Handerson and Pubis	(Ji-u & Inprasit, 2019)

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Rice Variety	Temperature and time range	Observed Parameter	Hydration models used	Authors
			Modified Page Two-term exponential Arrhenius relationship	
Tarom Mahali (long grain variety of rice)	Soaking 25, 30, 40, 50, 60, 70 °C 5, 10, 15, 20, 25, 30, 40, 50, 60, 70 mins	Moisture content, hydration diffusivity, energy activation	Page Handerson and Pubis Exponential Two-term Exponential Arrhenius relationship	(Kashaninejad *et al.*, 2007)
10 rice varieties	25±1°C, 46 mins and 1 hour 6 mins Different initial moisture content	Moisture content, Dimension changed projected area amylose content gel consistency alkali spreading value protein content	Multiple linear regression	(Yadav & Jindal, 2007)
Long grain	25, 35, 45, 55, 60, 65, 75, 80 and 90°C	Moisture ratio Gelatinization temperature	Ficks Arrhenius relationship	(Bello *et al.*, 2006)
Khaowong khaasin and RD6	Soaking 30, 60, 90 mins 30°C	Moisture content determination	No models used	(Pansa-Ead *et al.*, 2005)
IR-20	25, 35, 45, 55, 60, 65, 75 °C 15 mins	Moisture content Head rice yield	Becker Model Arrhenius relationship	(Sridhar & Manohar, 2003)

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Table 3. Effective water diffusivity of rice from previous studies

Rice Variety	Temperature	Effective water diffusivity (kJ/mole)	Authors
Khao Dawk Mali (paddy)	27.8	$8.85x10^{-12}$	(Ji-u & Inprasit, 2019)
	30	$9.47x10^{-12}$	
	40	$1.32x10^{-11}$	
	50	$1.83x10^{-11}$	
Tarom Mahali (long grain variety of rice)	25	$1.83x10^{-11}$	(Kashaninejad *et al.*, 2007)
	30	$9.15x10^{-11}$	
	40	$1.62x10^{-10}$	
	50	$2.27x10^{-10}$	
	60	$3.06x10^{-10}$	
	70	$3.57x10^{-10}$	
IR-20	25	$4.37x10^{-11}$	(Sridhar & Manohar, 2003)
	35	$5.13x10^{-11}$	
	45	$5.36x10^{-11}$	
	55	$5.58x10^{-11}$	
	60	$5.89x10^{-11}$	
	65	$6.00x10^{-11}$	
	75	$6.33x10^{-11}$	
Long grain	25	$1.40x10^{-11}$	(Bello *et al.*, 2006)
	35	$1.68x10^{-11}$	
	45	$2.77x10^{-11}$	
	55	$3.34x10^{-11}$	
	60	$4.01x10^{-11}$	
	65	$4.31x10^{-11}$	
	75	$7.17x10^{-11}$	
	80	$7.34x10^{-11}$	
	90	$9.36x10^{-11}$	

5. Upcoming Work

The previous section of the paper shows the complexity of the rice hydration study. Different ways of analyzing processes can provide identical or other results. Experimental and predicted results may differ. Brown rice, milled rice, and paddy have different characteristics. Also, different dimensions of rice varieties would result in other soaking processes. Raw material physiochemical impacts results. The rice varieties studied by various writers vary considerably in characteristics. Therefore, in-depth correlations between hydration procedures and the nature of raw materials are required.

In research where cooking or soaking was explored using several models, authors selected one or more models to describe the process, fit the model to experimental data, and estimated the model parameters by regression analysis. It's hard to compare the results of different authors. There must be further review to highlight the significance of the model selection. The model must accurately represent the physical and chemical changes occurring within the system. Some changes, such as the swelling process of the grain and the crack formed during the soaking process, are not yet being studied. Most papers focus on how the water migrates into the rice kernels and the physicochemical changes during the soaking process. However, limited articles are available on the soaking process with the end product required during the cooking.

The preceding review outlines how hydration kinetics of glutinous rice research should be conducted. The following is a general outline:

1. To understand the influential elements, the physicochemical parameters of the glutinous rice under research should be established.
2. The soaking studies should be done at different time intervals in the desired temperature range. A weighing method is the simplest method that can be used to determine the extent of hydration.
3. A proper analysis method (image analysis, NMR, MRI) must be used to obtain information on the differences in the visualisation image of the water absorption process during soaking. This data then can be verified using mathematical models, and vice versa.
4. If a chosen model equation is already determined (e.g., exponential, Peleg, etc.), the experimental data must be fitted into the model to obtain values for the model coefficient, used as the soaking parameters.
5. Finally, compute the Arrhenius energy activation and the diffusivity of the grain of hydration method during soaking.

6. Conclusions

Glutinous rice is a popular commodity in Southeast Asian countries, as well. Soaking is an essential part of the hydration process. Therefore, it is needed to understand the kinetics of the process. The review explains the complication in the soaking kinetics. Soaking is a simple process but involves a complex and dynamic factor. This research demonstrates that modelling rice hydration processes was accomplished by analysing the moisture intake at different intervals. The moisture ratio data can then be plotted into empirical and semi-empirical models. The values of diffusion coefficients determined by another researcher convincingly demonstrated the impact of temperature and moisture content on transport parameters using Arrhenius equations. Problems that arose during the modelling of rice hydration and dehydration, such as swelling and solid leaching, are not covered. Then, more work on the kinetics of glutinous rice soaking is needed to understand the entangled physical, chemical, and thermodynamic processes during soaking.

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