Food Science and Engineering
http://ojs.wiserpub.com/index.php/FSE/

Research Article

Physicochemical Properties and Hydration Kinetics of Kenaf (*Hibiscus cannabinus*) Seed

Shafa'atu Giwa Ibrahim[1,2], Nor Aini Mat Noh[1], Nur Syamimi Zaini[3], Wan Zunairah Wan Ibadullah[3], Nazamid Saari[3], Roselina Karim[1*]

[1]Department of Food Technology, Faculty of Food Science and Technology, University of Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[2]Department of Biochemistry and Molecular Biology, Faculty of Science, Usmanu Danfodiyo University, Sokoto, P.M.B 2346 Sokoto, Nigeria
[3]Department of Food Science, Faculty of Food Science and Technology, University of Putra Malaysia, 43400 Serdang, Selangor, Malaysia
E-mail: rosaz@upm.edu.my

Received: 14 March 2022; **Revised:** 20 May 2022; **Accepted:** 10 June 2022

Abstract: Hydration of kenaf seed was studied at 25, 35 45, 55 and 65 °C by the method of weight gain until equilibrium was achieved along with the physicochemical properties of the seed. The results showed that the kenaf seed had a small dimension and brownish surface color. Water absorbed during soaking was a function of soaking time and temperature. Soaking at higher temperatures increased the hydration rate constant and decreased the soaking time needed to reach equilibrium. Sigmoidal, Peleg and Page models effectively described the hydration characteristics of the seed under the soaking temperatures. The half-saturation time; τ, Peleg's rate constant; K_1 and Page rate constant K_3 decreased from 199.78-32.97 min, 2.55-0.47 min/% and 3.14-2.74 min/%, respectively, while the sigmoidal rate constant; K increased from 0.85-6.83 min^{-1} with an increase in soaking temperature from 25-65 °C. The rate of water absorption of the seed at a higher temperature was faster. The temperature dependence of K was explained by the Arrhenius equation, from which activation energy of 71.31 KJ/mol was obtained.

***Keywords*:** hydration, kenaf seed, soaking temperature, soaking time, water absorption

1. Introduction

Kenaf (*Hibiscus cannabinus* L.) is an herb of sub-Saharan Africa, an important fiber crop initially used to produce inedible materials. It is a multipurpose crop that has been utilized as a source of raw material for industrial and energy applications [1] an alternative fiber crop for paper pulp production, is normally grown during the entire summer growing season (150 days and longer. On a dry weight basis, the seed contains 18.9-24.8% of fat, 24.9-30.5% of protein, 23.2-33.1% of carbohydrates and 12.5-13.5% of fiber [2-3]. The seed is usually dried after harvesting to a moisture content of around 9.00-12.00%. A review on kenaf seed has discussed its possible uses as a value-added ingredient in food processes [4]. In an effort towards optimum utilization of this seed, soaking plays an important role, which facilitates subsequent operational processes. Soaking is often a long-time process, especially at ambient temperature. Increasing the temperature of the soaking medium has been reported as an effective means of reducing soaking time [5]. The

DOI: https://doi.org/10.37256/fse.3220221401

physical characteristics of seeds are vital factors that affect the behavior of seeds during hydration, intrinsic (physical and chemical) and extrinsic (soaking medium and soaking temperature) factors are known to affect the water absorption kinetics of seeds [6].

Hydration is an essential process in dried foods [7]. Knowledge of the physical properties and hydration behavior of kenaf seed is crucial for the design of equipment such as for storing, handling and processing. Furthermore, the knowledge of the hydration behavior of seeds during soaking is essential, since it affects the subsequent processing conditions such as fermentation, extraction and the quality of the final products [8]. Empirical models such as first-order kinetics, exponential, Weibull and Peleg are often used in the rehydration of plant seeds and are usually considered important for the designing and optimization of food processing [6].

Several studies have been conducted on the water absorption properties of different seeds such as chickpea seeds [9-10], navy beans [11], Andean lupin [12], red lentil [13] and whole moong grain [5]. No work has been carried out on the physical characteristics and water hydration model of kenaf seed. Studying the hydration kinetics of KB6 kenaf seed could provide useful information on the appropriate soaking temperature and time and will provide valuable information on process optimization. Thus, this study was conducted to determine the physical characteristics of KB6 kenaf seed, the effect of soaking temperature on hydration capacity, hydration time and to develop a model for water absorption kinetics of the seed.

2. Materials and methods

KB6 kenaf seeds were obtained from National Tobacco and Kenaf Board, Pasir Putih, Kelantan, Malaysia. The seeds were cleaned, and the moisture content of the seed was determined. The seed flour of 2.00 g was dried to a constant weight in an oven (Gallenkamp, Japan) at 105 °C for 24 h and the moisture content was expressed as a percentage dry basis (% d.b.).

2.1 *Determination of physical characteristics of kenaf seed*

The physical characteristics of the seed were determined according to Kaptso et al. [6]. Hundred healthy seeds were randomly selected in triplicates and the mean weight was determined using an electrical weighing balance of 0.001 accuracy. The bulk density (ρ_b) of the seed was evaluated as the weight of the seed to the volume occupied (g/mL), and the true density (ρ_g) was evaluated as the ratio of the seed weight to the volume of water displaced (g/mL). The porosity (ε) of the seed was calculated from the values of the seed's true density and bulk density using the expression in equation (1). Length (L), width (W) and thickness (T) of each seed were measured using a Digimatic caliper (Mitutoyo Corp. CD-15APX, Japan) with an accuracy of 0.01 mm. The L was defined as the distance from the eye's seed to the other end. The W was defined as a direction perpendicular to the eye's seed and the T was considered as the dimension of the fullest side of the seed. The geometric mean diameter (mm), D_g was calculated using the expression in equation (2).

$$\varepsilon = \frac{(\rho_g - \rho_b) * 100}{\rho_g} \tag{1}$$

$$D_g = (LWT)^{\frac{1}{3}} \tag{2}$$

The sphericity, ϕ was calculated using the expression in equation (3)

$$\phi = \frac{(LWT)^{\frac{1}{3}}}{L} \tag{3}$$

The volume of the seed was computed using equation (4)

$$V_g = \frac{\pi * WT * L2}{6[2L-(WT)^{0.5}]} \tag{4}$$

The surface area, S(mm^2) was equally calculated using the expression in equation (5)

$$S = \pi D_g{}^2 \tag{5}$$

2.2 *Hydration capacity of kenaf seed*

The effect of water-soaking temperature on the hydration capacity of kenaf seed was determined following the method of Clemente et al. [14]. Ten (10) gram of kenaf seed was separately soaked at different water temperature of 25, 35, 45, 55 and 65 ^{o}C. The gain weight was monitored at 1 h interval for a period of 5 h. Hydration capacity was determined as the difference between weight after soaking (W_s) and weight before soaking (W_{DS}) divided by weight of dry seeds (W_{DS}).

$$Hydration\ capacity\ \left(gH2O/gDS\right) = \frac{W_s - W_{DS}}{WDS} \tag{6}$$

2.3 *Determination of water absorption of kenaf seed*

Water absorption of kenaf seed was conducted according to the previous method reported by Maskan [15]. Following this method, 20 g of kenaf seeds were weighed into a conical flask. The flask plus the seed was equilibrated in a water bath to the desired soaking temperature (25, 35, 45, 55 and 65 °C), after which the seed was transferred into another conical flask containing 250 mL of distilled water already pre-set at the required temperature in a water bath and the temperature was maintained at the desired soaking temperature throughout the experimental study. The conical flasks were removed at 10, 20 30 min intervals at the initial and subsequently at 30 min interval until a constant weight was obtained, the soaked seeds were drained and then blotted on an absorbent towel 3 times to remove excess water at the surface of the seeds as previously reported by Gowen et al. [16]. The seeds were then weighed on a weighing balance and the difference between the weight measured at a given time and the initial weight (20 g) was recorded as weight gain due to water absorption and the seeds were returned to the soaking water at the desired temperature. The gain weight was added to the initial moisture content and was converted to the instantaneous moisture content (% d.b.). The instantaneous moisture content was then used to plot the kinetic curve of water absorption. This experiment was carried out in triplicate for each experimental temperature at 10 min intervals for the initial 30 min and subsequently 30 min interval until equilibrium was attained in the absorbed moisture content of the soaked seeds.

2.4 *Mathematical modeling of water-soaking kenaf seed*

Mathematical modeling of water absorption of kenaf seed during different soaking temperatures 25, 35, 45, 55 and 65 °C was carried out using the Peleg, Page, and Sigmoidal kinetics as described by Sharanagat et al. [5]. Model parameters were estimated, and the performances of models were evaluated according to coefficient of determination (R^2) and standard error of estimation (SEE). The Peleg's model for water absorption of the seed assumed the form of equation (7).

$$M_t - M_0 = \frac{t}{K_1 + K_2} \tag{7}$$

where: M_t = moisture content at time t (% d.b.), M_0 = initial moisture content (% d.b.), t = soaking time (min), K_1 = Peleg rate constant (min/%), K_2 = Peleg capacity constant (1/%).

In addition to Peleg's model, Page mathematical model was also evaluated for its suitability in explaining the water absorption of the seed using the expression in equation (8).

$$MR = \frac{M_t - M_0}{M_0 - M_s} = \exp(-K_3 t^{0.5}) \tag{8}$$

where MR is moisture ratio, M_t (% d.b.) is moisture content at time t, M_0 (% d.b.) is initial moisture content, M_s (% d.b.) is saturation moisture content, t is soaking time (min) and K_3 (min^{-1}) is the absorption rate of the process.

A sigmoidal mathematical model was also evaluated based on the expression in equation (9).

$$M_{(t)} = \frac{M_{eq}}{1 + \exp[-k * (t - \tau)]} \tag{9}$$

$M_{(t)}$ is the moisture content of kenaf seed as a function of the soaking time, M_{eq} is the equilibrium moisture content and k (min^{-1}) is the constant rate of hydration. The soaking time (t, min), τ (min), is defined as the time needed to attain half-saturation (50%) of the kenaf seed.

2.5 *Determination of effective diffusivity and activation energy*

The rate constant obtained from equation (9) was used in conjunction with the seed radius (r) using the Fick's law of diffusion with a constant moisture diffusivity for spherical shape as described in equation (10).

$$k = \frac{\pi^2 D_{eff}}{r^2} \tag{10}$$

where k (s^{-1}) is the constant rate of diffusion for the sigmoidal obtained in equation (9). D_{eff} (m^{2}s^{-1}) is the effective diffusivity and r (m) is the seed radius which is half of D_g.

The diffusivity coefficients obtained for each temperature were related to the reciprocal of absolute temperature using the Arrhenius equation (11). The energy of activation was determined by linear regression of Ln(D_{eff}) versus 1/T.

$$D_{eff} = D_0 \exp\left[\frac{E_a}{R(T + 273.15)}\right] \tag{11}$$

where D_0 is the diffusivity for an infinite temperature, E_a (KJ/mol) is the activation energy for water diffusion, R is the molar gas constant (8.314 J/mol K) and T the absolute soaking temperature expressed in Kelvin (K).

2.6 *Data analysis*

Minitab version 17.0 was used for descriptive and inferential statistics and results were presented as mean ± standard deviation. The modeling of hydration kinetics was studied using Curve Expert Professional version 2.6.5 and GraphPad prism version 7.0.

3. Results and discussion

Table 1. Physicochemical characteristics of KB6 kenaf seed

Parameters	Values
Length, L (mm)	2.92 ± 0.07
Width, W (mm)	1.08 ± 0.13
Thickness, T (mm)	0.24 ± 0.02
Hundred seeds mass (g)	2.61 ± 0.19
Geometric mean diameter, D_g (mm)	0.88 ± 0.04
Sphericity, ϕ	0.33 ± 0.03
Surface area, S (mm^2)	2.86 ± 0.58
Volume, V_g (mm^3)	0.22 ± 0.04
True density, ρ_g (g/ml)	0.97 ± 0.02
Bulk density, ρ_b(g/ml)	0.64 ± 0.01
Porosity, ε (%)	34.57 ± 1.35
Surface colour	Brownish
Lightness, L	31.68 ± 0.38
Redness, a*	2.86 ± 0.08
Yellowness, b*	6.41 ± 0.10
Moisture (%)	9.00 ± 0.00
Crude protein (%)	21.88 ± 0.42
Crude fat (%)	24.69 ± 0.15
Crude fiber (%)	18.67 ± 0.80
Carbohydrates (%)	18.61 ± 0.95
Ash (%)	6.17 ± 1.18

The physicochemical properties of KB6 kenaf seed were presented in Table 1. The length, width, thickness, geometric mean diameter and hundred seeds mass were found to be 2.92 mm, 1.08 mm, 0.24 mm, 0.88 mm and 2.61 g, respectively. These values were significantly less than values reported for other seeds such as lupin [17], cowpea and Bambara groundnut seeds [6]. These implied that the kenaf seed has a smaller dimension. The hundred seeds mass (2.61 g) of the KB6 kenaf seed cultivar at moisture content 9.00% was like the other kenaf varieties such as Everglades

(2.95 g) at moisture content of 7.67%, Tainung (2.88 g) at moisture content of 7.35% and SF-459 (2.81 g) at moisture content of 7.27% [18]. The degree of sphericity of kenaf seed was found to be 0.33 at moisture content of 9.00%, which is significantly lower than the sphericity values (0.75-0.77) of Everglades, Tainung and SF-459 kenaf seed varieties at moisture range of 7.27-26.21% [18], this indicates that KB6 kenaf seed cultivar has an angular shape different from the oviform of the other kenaf cultivars. As reported by Izli [18], the sphericity of the earlier studied kenaf seed cultivars increased linearly as the moisture content increased. Thus, the differences observed in this study to that of the earlier reports might be attributed to variations in cultivar and differences in moisture content. The surface area for KB6 kenaf seed (2.86 mm) at moisture content of 9.00% was found to be significantly lower than what has been reported for other kenaf seed cultivars (4.69-6.49 mm) at moisture content of 7.27-26.21% [18]. It has been reported that a direct positive association existed between the moisture content of seeds and the surface area [19]. This might have accounted for the significant variations in the surface area of KB6 kenaf seed to the variants studied earlier. The bulk density of KB6 kenaf seed at moisture content 9.00% was 0.64 g/mL. A similar result for bulk density has been reported for kenaf seed Tainung variety (0.64-0.69 g/mL), as the moisture content decreased from 25.96-7.67%. Also, 0.61-0.67 g/mL for Everglades variety as the moisture content equally decreased from 26.21-7.67% [18]. The similarity in the density of KB6 cultivar to the Tainung and Everglades varieties might be due to the variations in the moisture content, that positively affected the mass of the seed without a corresponding expansion in the volumetric of the bulk [20]. The true density of KB6 kenaf seed variant at moisture content 9.00% was 0.97 g/mL. This value was significantly lower than the values (1.25-1.36 g/mL) reported for Everglades, Tainung and SF-459 kenaf seed variants at moisture content of 7.27-26.21% [18]. The difference in the true densities of KB6 cultivar and kenaf seed cultivars in earlier studies might be due to variation in moisture content and bigger dimensions of seeds used in earlier studies. The porosity of KB6 kenaf seed 34.57%, was 41.13-47.23% less than the porosity values of the other cultivars (Everglades, Tainung and SF-459) found by Izli [18] at moisture range of 7.27-26.21%.

Visual observation of the surface color of the seed revealed a brownish color. This concurred with the dark greyish brown reported by LeMahieu et al. [21]. The low values of L (31.68), a* (2.86) and b* (6.41) of the seed further suggested that the kenaf seed was less bright in appearance. Compared to cowpea seed which has higher values of L (48.14-55.06), a* (3.41-8.47) and b* (16.58-25.23) manifesting its brighter/yellowish color [6]. The composition of KB6 kenaf seed used in this study was 9.00% moisture content, crude protein 21.88%, crude fat 24.69%, crude fiber 18.67%, carbohydrates 18.61% and ash 6.17%. The moisture content and crude fat content of this seed were comparable to the values reported for QP3 and V36 [3]. In contrast, the crude protein (29.8-30.5%) and carbohydrates (19.2-23.2%) of QP3 and V36 were higher than the values reported in this study. However, the crude fiber (11.5-12.5%) and ash (4.5%) of both QP3 and V36 were lower than the values found in this study. These variations might be due to differences in geographical location, planting season and soil type.

3.1 *Effect of soaking temperature and time on the hydration capacity of kenaf seed*

The effect of different soaking temperatures and time on the hydration capacity of kenaf seed was presented in Figure 1. The hydration capacity for the seeds soaked at 25 °C and 35 °C ranged from 0.144 to 0.563 g H_2O/g DS and 0.17 to 0.815 g H_2O/g DS respectively. These values are like values reported for different cultivars of kidney beans [22-23]. However, the hydration capacity of seeds soaked at 45 °C, 55 °C and 65 °C ranged from 0.291 to 0.997 g H_2O/g DS, 0.566 to 1.02 g H_2O/g DS and 0.864 to 1.015 g H_2O/g DS respectively. The hydration capacity significantly ($P < 0.05$) increased as the duration of soaking was prolonged. There was a significant increase ($P < 0.05$) in the hydration capacity of the soaked kenaf seeds as the soaking temperature increased from 25 to 65 °C. At 1 h soaking time, there was no significant ($P > 0.05$) difference in the hydration capacity of the seeds soaked at 25 and 35 °C. Temperature and time have significant effects on the hydration capacity of the kenaf seed. Signifying that, hydration capacity is both a function of soaking temperature and time. At a high soaking temperature of between 55 and 65 °C, the seeds reached maximum water absorption capacity at 2 h of soaking, with hydration capacity greater than 1.0 g H_2O/g DS and continuing soaking at the temperatures above soaking time 2 h does not significantly increase the hydration capacity of the seeds. The hydration capacity of seeds is important for the determination of the technological application of food. It would provide useful information for designing appropriate instruments for packaging, transporting, cooking and formulation of different food products from kenaf seed. It is also, a vital property that determines the degree of water absorption by soaked seeds and is a function of chemical constituent of the seed coat and cotyledons [24].

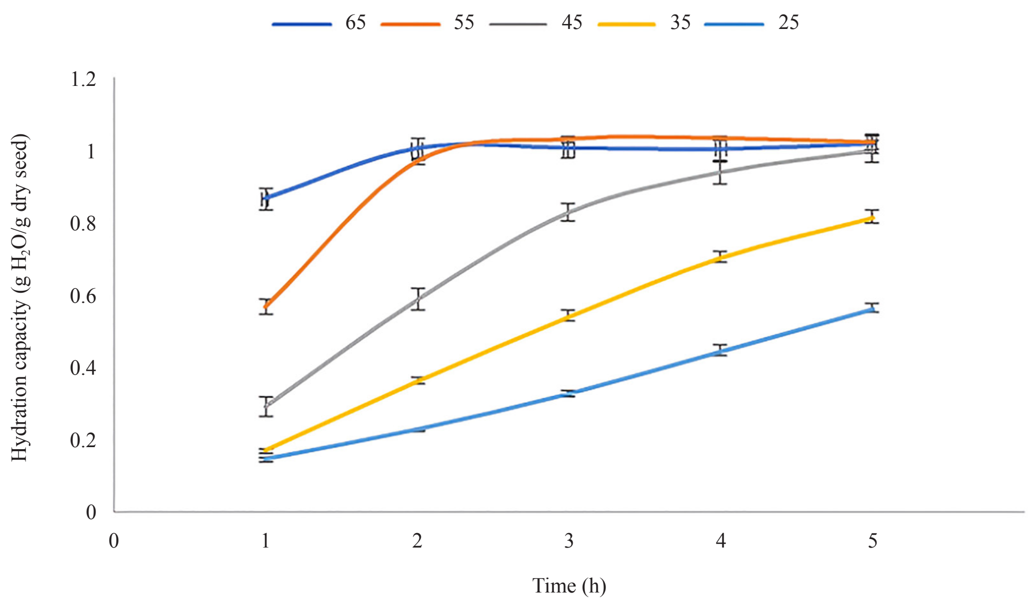

Figure 1. Effect of soaking temperature and time on hydration capacity of kenaf seed
Values are means of triplicates. The bars at each data point represent the standard deviation

3.2 *Hydration kinetics of water soaking kenaf seed*

Table 2. Effect of soaking temperature on saturation moisture content and required soaking time

Temperature (°C)	Saturation moisture content (% d.b.)	Soaking time (h)
25	110.95 ± 0.38^{a}	10.27
35	109.35 ± 0.13^{b}	7.00
45	108.40 ± 0.24^{bc}	5.00
55	111.07 ± 0.43^{a}	3.50
65	107.79 ± 0.58^{c}	2.67

Data are mean ± SD of triplicates. Values with the same superscripts letters down the column are statistically not significant at α = 0.05. Note: d.b.: dry basis; h: hour.

The temperature of this experiment was between 25 to 65 °C, these were based on the commonly used temperature at home for soaking grains. The high temperature selected was because the lower temperature required additional cost in terms of refrigeration which is more expensive than heating and more time would be needed. Elevated temperature above 65 °C can be of disadvantage like denaturation of proteins. The effect of soaking temperature on saturation moisture content and required soaking time (Table 2). The saturation moisture content for the temperature 25 to 65 °C ranged from 107.79% to 111.07%. Soaking temperature 25 °C and 55 °C had significantly ($P < 0.05$) higher saturation moisture content of 110.95% and 111.07%, respectively. It took 10 h:16 min for the kenaf seeds soaked at 25 °C to attain saturation and 7 h for the seeds soaked at 35 °C. Whereas, the seeds soaked at 45 °C, 55 °C and 65 °C required

5 h, 3 h:30 min and 2 h:40 min, respectively to attain saturation. These indicate that soaking at a higher temperature increased the rate of water absorption and reduced the soaking time required for the seeds to be saturated. This finding corroborates with the previous report of Miano et al. [12] that increasing operational temperature speed-up the hydration process of grains.

The moisture content of the soaked seed increased with an increase in soaking temperature and time (Figure 2). The optimum moisture content of between 100 to 120% was achieved between temperature 47 °C to 67 °C and soaking time of 150 to 200 min. However, prolonging the duration of soaking above 200 min does not have a significant increase in the moisture content of the seeds soaked between 47 to 67 °C. This implied that the amount of water absorbed upon hydration was both the function of soaking temperature and time.

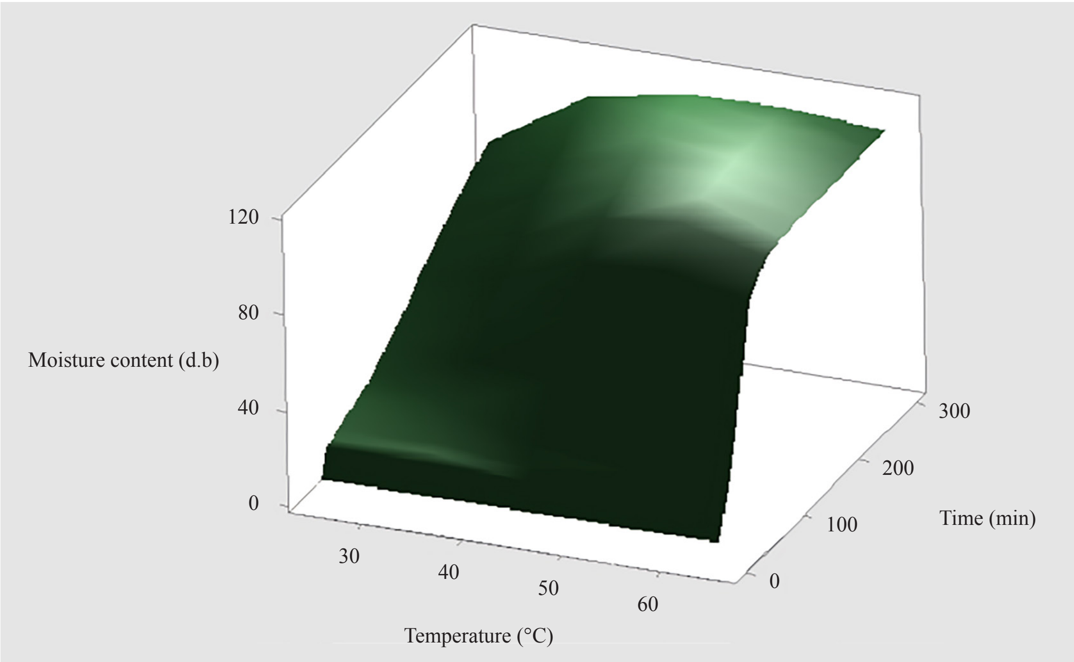

Figure 2. Surface plot of moisture content versus soaking time and temperature

Note: d.b.: dry basis

3.2.1 *Kinetics of water absorption*

The kinetics of the water absorption curve of kenaf seed at the different soaking temperature was presented in Figure 3. The hydration process of the seed showed a higher rate of water absorption in the diffusion stage. Followed by a slower rate of absorption in the relaxation stage and reaching maximum moisture content as the soaking time is prolonged especially at 45, 55 and 65 °C. These indicate that saturation condition was achieved much faster at higher temperatures than lower temperatures. The water absorption curve of the seed demonstrated a sigmoidal behavior with a non-linear regression coefficient value ($R^2 > 99.61\%$). This was similar to previous curves reported for other seeds [7, 12, 25].

The kinetics parameters of the different mathematical models (Sigmoidal, Page and Peleg's) of water absorption of the seed are presented in Tables 3&4. For all the models the correlation coefficients (R^2) were higher (82.10-99.86%) with a low standard error of estimation, SEE (0.05-2.67). These justified the accuracy of the models in explaining the water absorption characteristics of the seed at the different soaking temperatures.

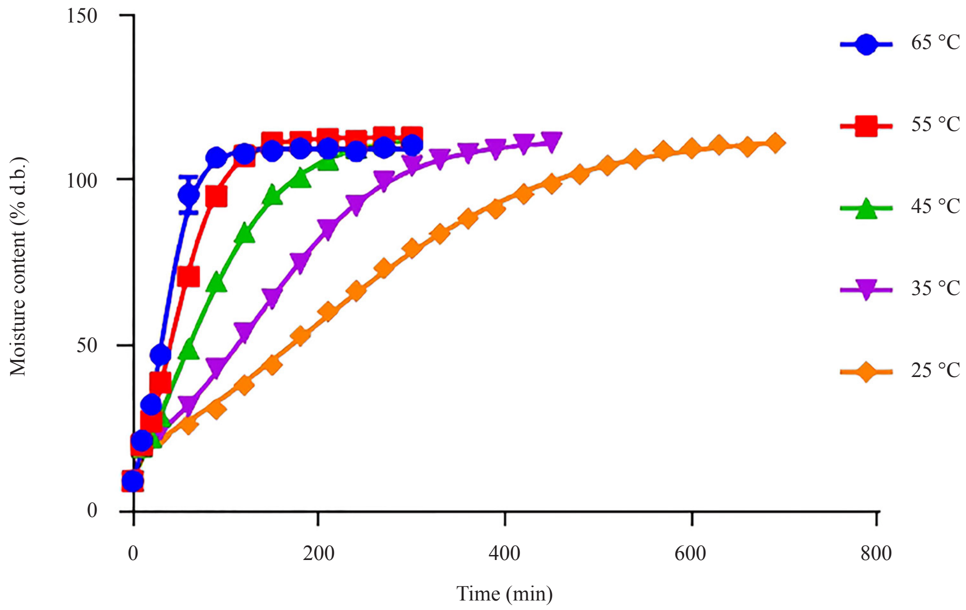

Figure 3. Water absorption curves of kenaf seeds at different soaking temperatures
Data are mean ± SD (vertical bars of n = 3). Note: d.b.: dry basis.

3.2.2 *The kinetics rate of hydration*

The constant rate of hydration for each of the models differs significantly from the variation in the soaking temperature. The sigmoidal rate of hydration, K (Table 3) consistently increased with an increase in soaking temperature. The soaking temperatures 25 °C and 65 °C had 0.0085 min^{-1} and 0.0683 min^{-1}, respectively. Accordingly, a high temperature leads to a higher water absorption rate. This observation has been reported by Solomon [17] for lupin seeds, Thakur & Gupta [26] for cereal grains and Turhan et al. [8] for peas and beans.

Table 3. Water absorption characteristics of KB6 kenaf seed following sigmoidal model

Soaking temperature (°C)	Meq (Exp % d.b.)	Meq (Obs % d.b.)	K ($\times 10^{-2} min^{-1}$)	τ (min)	R^2 (%)	SEE
25	112.15 ± 0.73aA	110.95 ± 0.38aA	0.85 ± 0.02d	199.78 ± 3.87a	99.65	2.16
35	112.48 ± 1.49aB	109.35 ± 0.13bC	1.39 ± 0.03d	128.24 ± 2.74b	99.65	2.34
45	110.37 ± 0.41abD	108.40 ± 0.24bcE	2.58 ± 0.06c	72.28 ± 1.94c	99.61	2.67
55	112.33 ± 0.36aF	111.07 ± 0.43aG	4.25 ± 0.15b	46.54 ± 0.30d	99.85	1.72
65	109.43 ± 0.29bH	107.79 ± 0.58cI	6.83 ± 0.60a	32.97 ± 1.80e	99.86	1.69

Note:
Meq: equilibrium moisture content;
Exp: expected moisture content;
d.b: dry basis;
Obs: observed moisture content;
K: sigmoidal rate constant;
τ: half saturation time;
R^2: regression coefficient;
SEE: standard error of estimation.
The values with the same lower-case letter down the column are not statistically significant and values with the same upper-case letter between the rows of expected moisture content and observed moisture content are not significantly different $P \geq 0.05$.

An opposite effect of soaking temperature was observed for the Page (K_3) and Peleg's (K_1) constant rate of hydration. The Page constant rate (K_3) of hydration varied from 3.15 min^{-1} at 25 °C to 2.74 min^{-1} at 65 °C. The Peleg's rate constant (K_1) is in the same order of variations but lower than the Page rate constant. The K_1 relates to the mass transfer rate and its values under the soaking conditions (25 to 65 °C) decreased linearly from 2.55 to 0.47 min/% (Table 4). This indicates that an increase in the soaking temperature leads to a corresponding increase in the water absorption rate. This finding agreed with earlier reports for other seeds [5, 11, 27-28]. The Peleg's capacity constant (K_2) ranged from 0.00587 to 0.0078 1/% (Table 4). This is an indication that the water absorption rate increased, and water absorption capacity decreased as the soaking temperature increased. K_2 relates to maximum water absorption capacity [8, 27].

Table 4. Water absorption characteristics of KB6 kenaf seed following Peleg's and Page models

Soaking Temperature (°C)	Peleg's model				Page		
	K_1 (min/%)	K_2 (× 10^{-3} 1/%)	R^2 (%)	SEE	K_3 (min/%)	R^2 (%)	SEE
25	2.55 ± 0.05a	5.87 ± 0.06c	83.19	0.58	3.14	97.5	0.05
35	1.69 ± 0.02b	5.67 ± 0.15c	85.95	0.34	2.90	97.1	0.06
45	1.12 ± 0.05c	5.30 ± 0.20d	90.17	0.19	2.70	96.7	0.07
55	0.68 ± 0.04d	6.67 ± 0.12b	94.07	0.2	2.69	89.8	0.13
65	0.47 ± 0.03e	7.80 ± 0.10a	94.98	0.19	2.74	82.1	0.17

Note:
K_1: Peleg's rate constant of hydration;
K_2: Peleg's capacity constant;
R^2: regression coefficient;
SEE: standard error of estimation;
K_3: Page rate constant of hydration.
The values with the same letter down the column are not significantly different $P \geq 0.05$.

The observed saturation moisture content of the seed varied significantly. The seed soaked at temperatures 25 °C and 55 °C had the highest saturation moisture content of 110.95% and 111.07%, respectively. However, the seed soaked at 65 °C has the least saturation moisture content of 107.79%. The predicted saturation moisture content obtained by the sigmoidal model varied significantly from the observed saturation moisture content, except for seed soaked at 25 °C (Table 3). Soaking at a higher temperature reduces the time required for the seeds to reach half saturation. The seed soaked at 65 °C required 32.97 min and the one soaked at 25 °C required 199.78 min to be half saturated. These correlate with previous findings on rice [29], adzuki beans [30], guar splits [31] and for lens culinaris [7]. The various soaking time obtained for the experimental temperature could be helpful during food formulation processes. The decrease in saturation moisture content has been reported to be related to the higher extraction of water-soluble components of the seed at a higher temperature [7]. Also, the behavior of saturation moisture could be related to the cell integrity and mass transfer phenomenon of the seed. It was observed that higher temperature damage cell membrane of seeds and lead to lower water holding capacity [7]. Likewise, as the absorption rate of the seed was faster at higher temperatures. The seed edges and rapidly absorb water. Consequently, the external layer becomes saturated and the mass transfer from the soaking water to the surface of the seed was reduced [7, 30].

3.3 *Effective diffusivity and activation energy*

The effective diffusion coefficient (D*eff*) of KB6 kenaf seed increased (2.78 × 10^{-12} to 22.35 × 10^{-12} m^2/s) with the increase in soaking temperature (Table 5). A similar observation has been reported for soybean [16], rice [32], chickpeas [33] and sorghum [34]. The differences in the D*eff* of the kenaf seed at the different soaking temperatures was found to be linearly correlated to the reciprocal of their absolute temperature.

Table 5. Effective diffusivity of KB6 kenaf seed at different soaking temperatures

Soaking Temperature (°C)	Diffusion coefficient (m^2s^{-1})	Activation energy Ea (KJ/mol)	R^2 (%)
25	2.74×10^{-12}	71.31	99.84
35	4.55×10^{-12}		
45	8.44×10^{-12}		
55	1.39×10^{-11}		
65	2.24×10^{-11}		

Note: R^2: regression coefficient

The activation energy (Ea) of hydration of the kenaf seed was computed by the linear relationship of effective diffusivity and absolute temperature; T (Figure 4). The plot showed linear relation with a high R^2-value (99.84%). The logarithm of the reciprocal of D_{eff} decreased linearly with an increase in the reciprocal of T. This is like previous reports on hydration studies for different seeds [5, 27]. The seed possesses a high activation energy 71.31 KJ/mol. This value is like the activation energy (78.81 KJ/mol) reported for GC variety of cowpea seed [6] and higher than values reported for sorghum (24.21 KJ/mol) [35] and 51.67 KJ/mol for Barley [36].

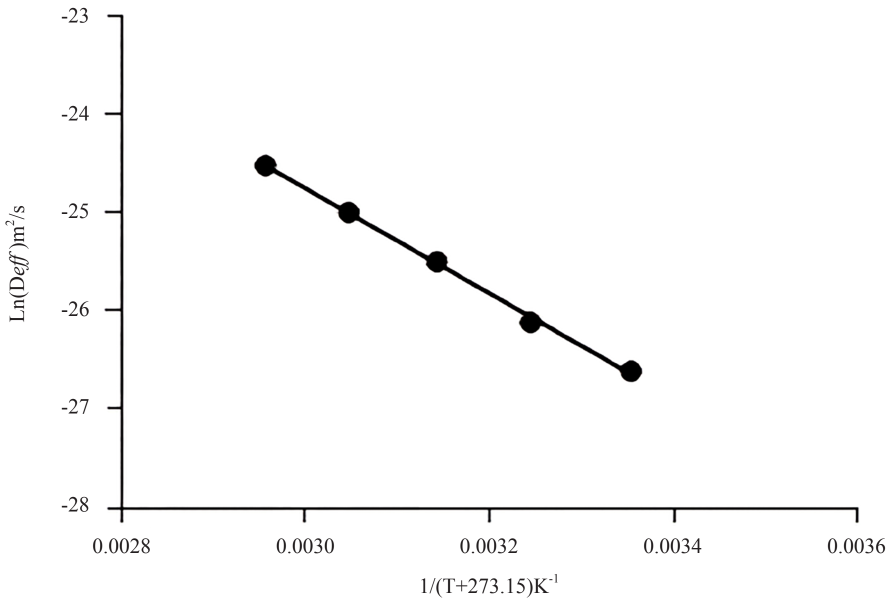

Figure 4. Arrhenius plot for determination of activation energy of hydration of kenaf seed

4. Conclusion

This study disclosed the physicochemical properties of KB6 kenaf seed. The seed has a small dimension and a brownish surface color. Temperature and time had a significant ($P < 0.05$) effect on the hydration capacity of the seed. An increase in the soaking temperature decreased the soaking time required to achieve saturation moisture content. The optimum soaking time for the seed is 160 min at 65 °C, 210 min at 55 °C, 300 min at 45 °C, 420 min at 35 °C and 616 min at 25 °C. The water absorption curve of the seed assumed a sigmoidal with an increased rate of absorption as the soaking temperature increased. The sigmoidal model produced the half-saturation time (τ), which decreased as the soaking temperature increased. All the models; sigmoidal, Page and Peleg's were accurate at describing the water absorption of the seed. The D*eff* of the seed increased as the soaking temperature increased. This signified that the rate of diffusion of water into the seed at higher temperatures was faster.

Acknowledgements

The authors would like to acknowledge the financial support from the National Kenaf and Tobacco Board (LKTN), Malaysia and Tertiary Education Trust Fund, Nigeria. The authors are grateful to the Faculty of Food Science and Technology, Universiti Putra Malaysia for providing laboratory facilities for this research.

Conflict of interest

The authors have no conflict of interest to declare.

References

[1] Webber CL, Bledsoe VK. Plant maturity and kenaf yield components. *Industrial Crops and Products*. 2002; 16(2): 81-88.

[2] Omenna EC, Uzuegbu DC, Okeleye DD. Functional and nutritional properties of kenaf seed. *EC Nutrition*. 2017; 11(4): 166-172.

[3] Mariod AA, Fathy SF, Ismail M. Preparation and characterisation of protein concentrates from defatted kenaf seed. *Food Chemistry*. 2010; 123(3): 747-752. Available from: http://dx.doi.org/10.1016/j.foodchem.2010.05.045.

[4] Giwa IS, Karim R, Saari N, Wan AWZ, Zawawi N, Ab Razak AF, et al. Kenaf (*Hibiscus cannabinus* L.) seed and its potential food applications: A review. *Journal of Food Science*. 2019; 84(8): 2015-2023. Available from: https://doi.org/10.1111/1750-3841.14714.

[5] Sharanagat VS, Kansal V, Kumar K. Modeling the effect of temperature on the hydration kinetic whole moong grain. *Journal of the Saudi Society of Agricultural Sciences*. 2018; 17(3): 268-274. Available from: https://doi.org/10.1016/j.jssas.2016.05.005.

[6] Kaptso KG, Njintang YN, Komnek AE, Hounhouigan J, Scher J, Mbofung CMF. Physical properties and rehydration kinetics of two varieties of cowpea (*Vigna unguiculata*) and bambara groundnuts (V*oandzeia subterranea*) seeds. *Journal of Food Engineering*. 2008; 86(1): 91-99. Available from: https://doi.org/10.1016/j.jfoodeng.2007.09.014.

[7] Oroian M. The temperature hydration kinetics of Lens culinaris. *Journal of the Saudi Society of Agricultural Sciences*. 2017; 16(3): 250-256. Available from: http://dx.doi.org/10.1016/j.jssas.2015.08.004.

[8] Turhan M, Sayar S, Gunasekaran S. Application of Peleg model to study water absorption in chickpea during soaking. *Journal of Food Engineering*. 2002; 53(2): 153-159. Available from: https://doi.org/10.1016/S0260-8774(01)00152-2.

[9] Ranjbari A, Kashaninejad M, Aalami M, Khomeiri M, Gharekhani M. Effect of ultrasonic pre-treatment on water absorption characteristics of chickpeas (*Cicer arietinum*). *Latin American Applied Research*. 2013; 43(2): 153-159.

[10] Shafaei SM, Masoumi AA. Studying and modeling of hydration kinetics in chickpea seeds (*Cicer arietinum* L.). *Agricultural Communications*. 2014; 2(2): 15-21.

[11] Ghafoor M, Misra NN, Mahadevan K, Tiwari BK. Ultrasound-assisted hydration of navy beans (*Phaseolus*

vulgaris). *Ultrason Sonochemistry*. 2014; 21(1): 409-414. Available from: https://doi.org/10.1016/j.ultsonch.2013.05.016.
[12] Miano AC, García JA, Augusto PED. Correlation between morphology, hydration kinetics and mathematical models on Andean lupin (*Lupinus mutabilis* Sweet) grains. *LWT-Food Science and Technology*. 2015; 61(2): 290-298.
[13] Kumar MM, Prasad K, Chandra TS, Debnath S. Evaluation of physical properties and hydration kinetics of red lentil (*Lens culinaris*) at different processed levels and soaking temperatures. *Journal of the Saudi Society of Agricultural Sciences*. 2018; 17(3): 330-338.
[14] Clemente A, Sa R, Vioque J, Bautista J, Milla F. Effect of processing on water absorption and softening kinetics in chickpea (*Cicer arietinum* L.) seeds. *Journal of the Science of Food and Agriculture*. 1998; 78(2): 169-174. Available from: https://doi.org/10.1002/(SICI)1097-0010(199810)78:23.3.CO;2-G.
[15] Maskan M. Effect of processing on hydration kinetics of three wheat products of the same variety. *Journal of Food Engineering*. 2002; 52(4): 337-341.
[16] Gowen A, Abu-Ghabbam N, Frias J, Oliveira J. Modelling the water absorption process in chickpeas (*Cicer arietinum* L.): The effect of blanching pre-treatment on water intake and texture kinetics. *Journal of Food Engineering*. 2007; 78(3): 810-819.
[17] Solomon WK. Hydration kinetics of lupin (*Lupinus albus*) seeds. *Journal of Food Process Engineering*. 2007; 30(1): 119-130.
[18] Izli N. Effect of moisture on the physical properties of three varieties of kenaf seeds. *Journal of Food Science and Technology*. 2015; 52(6): 3254-3263.
[19] Milani E, Seyed M, Razavi A, Koocheki A, Nikzadeh V, Vahedi N, et al. Moisture dependent physical properties of cucurbit seeds. *International Agrophysics*. 2007; 21(2): 157-168.
[20] Sologubik CA, Campañone LA, Pagano AM, Gely MC. Effect of moisture content on some physical properties of barley. *Industrial Crops and Products*. 2013; 43: 762-767.
[21] LeMahieu PJ, Oplinger ES, Putnam DH. Kenaf. *Alternative field crops manual*. Madison, Wisconsin, USA: University of Wisconsin-Extension; 1991. Available from: https://hort.purdue.edu/newcrop/afcm/kenaf.html.
[22] Saha S, Singh G, Mahajan V, Gupta HS. Variability of nutritional and cooking quality in bean (*Phaseolus vulgaris* L.) as a function of genotype. *Plant Foods for Human Nutrition*. 2009; 64(2): 174-180. Available from: https://doi.org/10.1007/s11130-009-0121-4.
[23] Wani IA, Sogi DS, Wani AA, Gill BS. Physical and cooking characteristics of some Indian kidney bean (*Phaseolus vulgaris* L.) cultivars. *Journal of the Saudi Society of Agricultural Sciences*. 2017; 16(1): 7-15. Available from: https://doi.org/10.1016/j.jssas.2014.12.002.
[24] Bewley JD, Black M, Halmer P. *The encyclopedia of seeds: science, technology and uses*. CAB Internetional, Wallingford; 2006.
[25] Bello M, Tolaba MP, Aguerre RJ, Suarez C. Modelling water uptake in a cereal grain during soaking. *Journal of Food Engineering*. 2010; 97(1): 95-100.
[26] Thakur AK, Gupta AK. Water absorption characteristics of paddy, brown rice and husk during soaking. *Journal of Food Engineering*. 2006; 75(2): 252-257.
[27] Jideani VA, Mpotokwana SM. Modelling of water absorption of Botswana bambara varieties using Peleg's equation. *Journal of Food Engineering*. 2009; 92(2): 182-188. Available from: https://doi.org/10.1016/j.jfoodeng.2008.10.040.
[28] Khazaei J, Mohammadi N. Effect of temperature on hydration kinetics of sesame seeds (*Sesamum indicum* L.). *Journal of Food Engineering*. 2009; 91(4): 542-552.
[29] Shittu TA, Olaniyi MB, Oyekanmi AA, Okeleye KA. Physical and water absorption characteristics of some improved rice varieties. *Food and Bioprocess Technology*. 2012; 5(1): 298-309. Available from: https://doi.org/10.1007/s11947-009-0288-6.
[30] Oliveira AL, Colnaghi BG, da Silva EZ, Gouvêa IR, Vieira RL, Augusto PED. Modelling the effect of temperature on the hydration kinetics of adzuki beans (*Vigna angularis*). *Journal of Food Engineering*. 2013; 118(4): 417-420. Available from: https://doi.org/10.1016/j.jfoodeng.2013.04.034.
[31] Vishwakarma RK, Shivhare US, Nanda SK. Water absorption kinetics of guar seeds and unhulled guar splits. *Food and Bioprocess Technology*. 2013; 6(5): 1355-1364.
[32] Kashaninejad M, Maghsoudlou Y, Rafiee S, Khomeiri M. Study of hydration kinetics and density changes of Tarom Mahali rice during hydrothermal processing. *Journal of Food Engineering*. 2007; 79(4): 1383-1390. Available from: https://doi.org/10.1016/j.jfoodeng.2006.04.019.
[33] Prasad K, Vairagar PR, Bera MB. Temperature dependent hydration kinetics of *Cicer arietinum* splits. *Food*

Research International. 2010; 43(2): 483-488.
[34] Silva DAROD, Jorge LMDM, Jorge RMM. Kinetics study and modelling of sorghum grain hydration. *Revista Ciência Agronômica*. 2019; 50(1): 44-53.
[35] Kashiri M, Kashaninejad M, Aghajani N. Modeling water absorption of sorghum during soaking. *Latin American Applied Research*. 2010; 40(4): 383-388.
[36] Montanuci FD, Jorge LMM, Jorge RMM. Effect of time and temperature on the hydration process of barley grains. *Heat and Mass Transfer*. 2015; 51(3): 363-372.