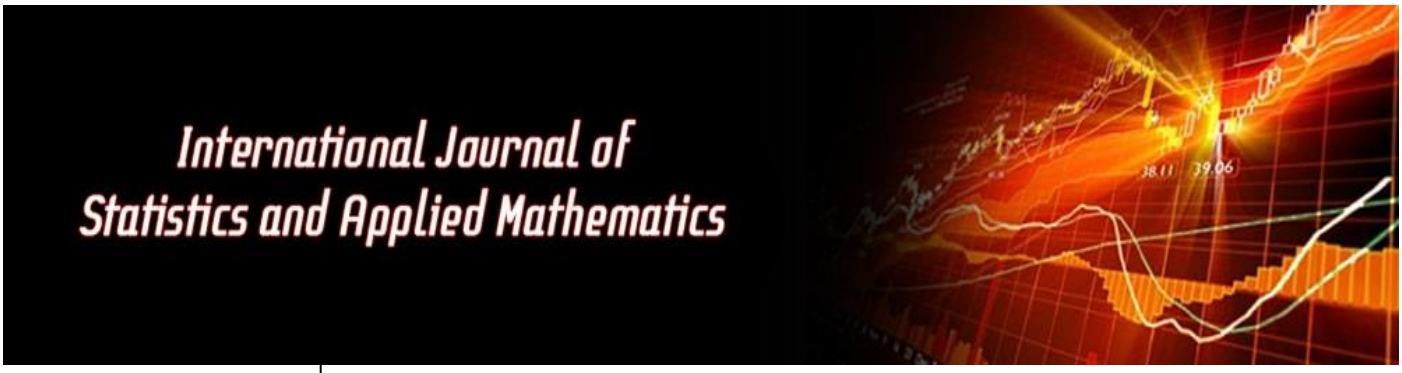

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Alka Singh
Department of Agricultural Engineering, SV Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Suresh Chandra
Department of Agricultural Engineering, S. V. Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Shobhi Chaudhary
Department of Agricultural Engineering, S. V. Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Amit Kumar
Department of Agricultural Engineering, S. V. Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Shaswat Tiwari
Department of Agricultural Engineering, S. V. Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Corresponding Author:
Suresh Chandra
Department of Agricultural Engineering, S. V. Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Mathematical modelling and hydration kinetics of Paddy (PS-5) with varying soaking temperatures

Alka Singh, Suresh Chandra, Shobhi Chaudhary, Amit Kumar and Shaswat Tiwari

Abstract
Moisture diffusion in Paddy (PS-5) during soaking in water at different temperatures *viz*., ambient temperature, 40, 50 and 60 ^{0}C was studied. The moisture content (dry basis) of paddy (PS-5) was increased 11.358 to 34.084 % (Ambient temperature), 40.984 % (40 ^{0}C), 43.328 (50 ^{0}C) and 51.791 % (60 ^{0}C) as soaking in water up to 210 min. Model tested for hydration kinetics are Newton/Lewis, Page and Peleg's equations for soaking of paddy at ambient temperature, 40, 50 and 60 ^{0}C for period of 210 minutes in water. The data were used to determine model parameters. The goodness of fit for models were evaluated by highest value of coefficient of determination (R^2). The weight of paddy during soaking process was determined in terms of moisture content (dry basis). The resulting kinetic data were correlated by means of different modeling equations. Peleg model predicted adequately the hydration kinetics of paddy (PS-5) under given condition. The Peleg model rate constant K_1 and Peleg constant capacity K_2 were affected by the increasing soaking time and temperatures. Among the various models, Peleg model was found to be most suitable for describing the hydration behavior of paddy along with increasing temperature and soaking time.

Keywords: Paddy, hydration ratio, hydration rate, soaking temperature, soaking time

Introduction
Paddy (*Oryza sativa* L.) is second largest major cereal crop a member of grass family (Poaceae/Gramineae), which produces starchy seeds. Paddy is one of the stable and leading food crops in India. About 70% of the paddy produced in India was stored at farm level [1]. Food grain storage technology whether at farm level or commercial level does not fulfill the technical requirements. Food grains are stored in different types of storage structures such as godowns and silo for certain periods till they reach the consumers which play an important role in the proper preservation of food grains. Temperature and moisture content of the grain provide the basis for extension of storage period, alternatively upon further processing of grain. Processing of paddy involves a number of unit operations sizing. These operations change the hydration characteristics of paddy namely (shape, size, volume, surface area, thousand grain weights, density, porosity). Information on these hydration properties of grains is important in design dimensioning, manufacturing and operation of different equipment used in postharvest operations [2]. The knowledge of some important physical properties of different grains is necessary for the design of various processing equipment's and storage chamber. Principal axial dimensions of paddy grains are useful in selecting sieve separators and in calculating power during the rice milling process. They can also be used to calculate surface area and volume of kernels which are important during modeling of grain drying, aeration, heating and cooling. Physical properties of paddy have been investigated and reported by some researchers. However, there is a need for a comprehensive study of the engineering properties of paddy is essential for designing of storage bin for paddy. Hence the present study was conducted to determine the important engineering properties of paddy *viz*., shape and size (axial dimensions, equivalent diameter, aspect ratio and sphericity), volume, surface area, true density, bulk density and porosity at five moisture content levels and also to determine how these properties interconnect with moisture content. Mathematical modelling of hydration process is known to be important for design and optimization of food process operations [3].

Materials and Methods

Experiments were conducted to study hydration kinetics of different varieties of paddy (*Oryza sativa* L) in the laboratories developed under the Agro Processing Centre at College of Post Harvest Technology and Food Processing, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut. Studies were also carried out to evaluate the hydration kinetics and moisture content during soaking process. Fresh and raw paddy (variety: PS-5) from the Seed Processing Center, Old Campus, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut. As per literature, there was no work done on hydration kinetics of paddy (PS-5).

Moisture content: The moisture content of paddy samples was estimated by method[4] , using a hot air oven at 105°C (5 g) of sample was weighed and kept in oven for 8-10 h. The amount of moisture in a product is given on the basis of the weight of water present in the product and is usually expressed in percent. Moisture content (%) is designated by two methods, Wet basis (wb) and dry basis (db).

$$Moisture\ content\ (\%) = \frac{W_i - W_f}{W_i} \times 100 \quad \text{-------- 1}$$

W_i = Initial weight of paddy taken, g
W_f = final weight of paddy after oven drying, g

Experimental Procedure: The soaking test was conducted in an aluminum container. The constant temperature water bath was adjusted to a temperature of 1- 2 ℃ higher than the required temperature of soaking. Water uptake of paddy grain was determined by soaking 50 g samples in screw-tap flasks containing 200 mL of distilled water. The soaking temperatures studied were Ambient temp, 40 ℃, 50 ℃, 60 ℃. Before performing hydration experiments the flasks with water were placed in thermostatically controlled oven fixed at the required soaking temperature for several hours to reach thermal equilibrium. Then, the grains were poured into the screw-tap flasks and experimental procedure was started. These were placed in a constant temperature stirred water bath, controlled within ±0.5 ℃ of the testing temperature. At regular intervals the flasks were withdrawn from the bath for moisture content determination. The soaked grains were filtered through an 80-mesh sieve to remove the surface water and weighed to an accuracy of ±0.1 mg. This procedure was established based on the preliminary test results and other previous studies [5, 6, 7]. Then, the grains were placed in an oven for moisture content determination [4, 8].

Hydration kinetics of paddy

Clean raw paddy was soaked at different temperatures in constant temperature water bath, under atmospheric condition, to determine the hydration behavior of paddy. A constant temperature water bath was used for soaking experimental consist of a water holding chamber with an immersion heating coil for heating the water and a thermostat for control of water temperature. The required temperature can be obtained by adjusting the knob. Hydration rate was calculated using following equation

$$HR = \frac{W_t - W_{(t+Dt)}}{D_t \times W_d} \quad \text{---------- 2}$$

Or

$$HR = \frac{amount\ of\ average\ water\ absorbed\ (g)}{Time\ interval\ (h) \times bone\ dry\ weight\ of\ sample(g)} \quad \text{---------- 3}$$

Where,
HR = Hydration rate (g of water absorbed /h/g of bone-dry matter)
W_t = weight of sample at any time t' (g)
$W_t + _{Dt}$ = weight of sample at any time t'$+_{Dt,}$ (g)
D_t = time interval, h
W = weight of bone-dry material, g

Mathematical Model for hydration

Moisture content (g water/g dry solid) of the sample (M) is calculated by the following equation (7) and recommended [9].

$$\text{Moisture content (g water/g of dry solid)} = \left(\frac{Mt - Md}{M_d}\right) \text{ -- (4)}$$

where M_t is the mass of sample at time *t* and M_d is mass of dry solid.

The moisture content is essential to be the same for all samples in the base measure because of natural and inherent differences in initial moisture content of the samples. Therefore, the moisture ratio (MR) expression is calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad \text{--- (5)}$$

where M_t, M_e, and M_0 are moisture content at any time, equilibrium moisture content, and initial moisture content, respectively. In this method, samples were placed in an environment maintaining relative humidity and temperature constant. When the change in the weight of samples was insignificant, the moisture of the samples was measured and adopted as the equilibrium moisture content (M_e). In order to low humidity in ambient (dry and hot weather), equilibrium moisture content is negligible and

$$MR = \frac{M_t}{M_0} \quad \text{---------- (6)}$$

Hydration curves were constructed by MR versus time. Numerical differentiation of hydration curves is proportional with hydration rate. This concept is used as dimensionless hydration rate (HR) through the paper.
Hydration kinetics models does not take into account the effects of interactions by parameters other than the time of drying. The concept of thin-layer drying models for characterizing the drying behaviour was suggested, initially, by Lewis [10] who derived the semi-theoretical model for porous hygroscopic materials, which is analogous with Newton's law of cooling. The following model was developed and used for hydration kinetics of paddy.

$$\frac{M_t - M_e}{M_0 - M_e} = \exp(-kt) \quad \text{------- (7)}$$

where MR is moisture ratio, k is hydration constant (m^{-1}), t is soaking time, M_t, M_e, M_o is moisture content at any time, equilibrium and initial, respectively. The semi-logarithmic plot of moisture ratio and soaking time represent a straight line for Newton model. Page [11] modified the Lewis model by adding a dimensionless empirical constant (n) and used it for study the drying behaviour of shelled corns. For this model a

log-log graph used to obtain a straight line with a positive slop in case of hydration of paddy.

$$\frac{M_t - M_e}{M_0 - M_e} = \exp(-kt^n) \quad \text{------- (8)}$$

Peleg [12] proposed a two parameters sorption equation and tested its prediction accuracy during water vapour absorption of milk powder and whole rice and soaking of whole rice. This equation has since been known as Peleg model (Eq. 9)

$$M = M_0 \pm \frac{t}{K_1 + K_2 t} \quad \text{---------- (9)}$$

Where M is moisture content (db %) at time (t), M_0 is Initial moisture content (db %), K_1 is the Peleg rate constant (h db%$^{-}$), and K_2 is the Peleg capacity constant (db %$^{-1}$). In equation (9), "±" becomes "+" if the process is absorption or adsorption and "-" if the process is drying or desorption.

This equation is usually written in rather simple way for water absorption to test its ability to fit experimental curve (Eq. 10):

$$\frac{t}{M - M_0} = K_1 + K_2 t \quad \text{----------(10)}$$

According to Eq. (9), a plot of $t/(M - M_0)$ against soaking time (h) gives a straight line, where K_1 is the intercept on the ordinate and K_2 is the slope of the line. The values of K_1 and K_2 were calculated by linear regression by using MS Excel software.

The Peleg model has been used to describe the sorption processes in various foods. The model for studying water absorption of dasheen been leaves has been applied [13]. Peleg's equation to model the water absorption behaviour of green gram during soaking was applied [3]. It was again to study the water absorption in chickpea during soaking [14].

Results and Discussion

The research work was conducted in the laboratories developed under the Agro Processing Centre at College of Post Harvest Technology and Food Processing, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut (UP) India. Six variety of paddy were collected from the Seed Processing Centre, Old Campus, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut. Paddy Variety PS-5 was selected for present study. The soaking of paddy was done with varying temperature i.e. (Ambient, 40°C, 50°C, 60°C) for a constant period of 3.5 h (210 min). The hydration kinetic of varieties of paddy (PS-5) was evaluated. Investigation was carried out to see the hydration kinetics properties of paddy like hydration time, hydration rate and hydration ratio along with application various models.

Hydration kinetic behaviour of Paddy (PS-5)

Preliminary studies indicated that the initial moisture content of the raw paddy (PS-5) was calculated 11.35% (db). A relationship between soaking time and moisture content is shown in (Fig 1). After hydration, final moisture content (on dry basis) of the paddy (PS-5) was observed 34.084 (Ambient temperature), 40.984 % (40 ^{0}C), 43.328 % (50 ^{0}C) and 51.791 % (60 ^{0}C). The moisture content of the paddy increased with increasing hydration time or soaking time (Fig. 1). The result indicates that when the soaking time was increased the moisture content of the paddy similarly it was also increased with increasing soaking temperature from ambient to 60 ^{0}C.

The hydration rate of paddy was increased initially they're after decreased with increasing soaking time. At the soaking time (30 min), hydration rate was found highest followed by decreased gradually during soaking upto 210 min. The hydration kinetic behavior graph was plotted between soaking time and hydration rate (Fig. 2). This might be due to overall result indicate that the hydration rate was decreased as the moisture content of the paddy increased during soaking time. This might be due to the grain absorbed moisture during its initial time and its water absorptivity also increase. Similar result was reported by [15, 16].

The moisture ratio or hydration ratio of the paddy at different temperatures was ranged in between 0.999 to -0.0002 (AT); 0.999 to 0 (40 ^{0}C), 0.999 to -0.079 (50 ^{0}C) and 0.999 to -0.365 (60 ^{0}C). A graphical representation between moisture ratio and soaking time at different temperature is shown in Fig. 3. Initially, at the ambient condition the maximum value of the hydration ratio was found (0.999) while the lowest value was found (-0.365) for 60 ^{0}C of soaking at 210 min (soaking time). The result indicates that as the water absorption by paddy increased, while on other side the hydration ratio of the sample was decreased. The study reveals that the rate of water absorption by paddy at the beginning was high, but when the soaking time increased, the paddy reached its maximum water content at a certain soaking time.

Mathematical modelling for prediction of hydration characteristics of Paddy with soaking temperatures

Newton/Lewis model and Page Model/equations were fitted to experimental data in their linearized forms using regression techniques as well as MS Excel to determine the constant of the models. In order to select the model which had better prediction and coefficient of determination (R^2) were considered.

Table 1: Model's constant of soaked paddy with different soaking temperatures

Models	Variables and Coefficient of fit	Soaking temperatures			
		AT	40 ^{0}C	50 ^{0}C	60 ^{0}C
Newton / Lewis's model [MR = exp (-kt)]	R^2	0.7707	0.8815	0.8241	0.8571
	k	0.0040	0.0045	0.0047	0.0059
Page's model [MR = exp (-kt^n)]	k	0.0017	0.0014	0.0019	0.0022
	n	1.4570	1.4790	1.3710	1.3880
	R^2	0.9213	0.9408	0.8748-	0.8642
Peleg's Model [(t/M-Mo) = K_1+K_2t]	K_1	0.0411	0.0290	0.0277	0.0219
	K_2	0.9186	0.9280	0.9468	0.9575
	R^2	0.9786	0.9280	0.9575	0.9468

Newton / Lewis's model: The hydration constant (k) of this model [MR = exp (-kt)] was obtained from the relationship of moisture ratio and soaking time. A graph between soaking time and moisture ratio on semi-logarithm paper was plotted and represents nearly a straight line (Fig. 3). The hydration constant was determined for all drying methods with temperatures conducted are present in Table 1. The value of k varied from 0.0040 to 0.0059 for all the soaking experiments and with average value of 0.0191. The value of R^2 were varied from 0.7707 to 0.8571 with an average value of 0.8333.

Page's Model: Hydration constant (k and n) obtained from the equation [MR = exp (-kt^n)] are shown in Table 1. The equation [MR = exp (-kt^n)] is graphically presented on log-log paper between [ln (-ln MR)] and [ln t] showed in Fig. 4. It gives a straight line with a positive slope of 'n'. Thus, when experimental data are plotted in graphically by drawing straight line and determining the slope and intercept respectively. This model is two constant empirical modification of Newton's exponent model. Average value of k for all experiment was 0.0018 and ranged between 0.0014 to 0.0022. The value of 'n' was determined between 1.371 to 1.479. The coefficient of determination (R^2) varied between 0.8642 to 0.9908 with an average value of 0.9002. The variation in experimental and prediction moisture ratio of paddy soaking with different temperatures under Page's Model is shown in Fig. 4.

Peleg's Model: The hydration constant i.e. Peleg's rate constant (K_1) and capacity constant (K_2) of paddy (PS-5) determined by the equation [(t/M-Mo) = K_1+K_2t] at different temperatures of ambient temperature (AT), 40, 50 and 60^{0}C are presented in Table 1. The graph is plotted between (t/M-Mo) and soaking time (t) showed in Fig. 5. It gives a straight line where K_1 is the intercept on the ordinate and K_2 is the slope of the line. The value of Peleg's rate constant (K_1) varied from 0.0219 to 0.0411 while capacity constant (K_2) varied from 0.9186 to 0.9575. The coefficient of determination (R^2) ranged between 0.9280 to 0.9786 indicating good fit of experimental data to Peleg's model at different examined temperature. For the four soaking temperatures tested, the constant K_1 shown tendency to decrease while K_2 increased with increasing soaking temperature [3]. In this study, it was found K_1 values were inversely related to temperature that indicated that the increasing of water absorption rate at higher temperatures [17]. Peleg's equation successfully represented the water absorption behavior of paddy during the soaking process at different temperatures and could be used to estimate the moisture content at given soaking time and temperature within the experimental condition considered. The Peleg's constant K_1 is a function of temperature for paddy and decreased with increase in soaking temperature [17]. Similar results were reported for hydration of rice [18] and chickpea [14]. Table 1 shows the value of K_1 and K_2 obtained from fitting of Peleg model at the mentioned temperatures. K_1 is a constant related to mass transfer rate and lowest K_1 has the highest initial water absorption rate [19]. Several investigators also reported that K_1 decreased with increasing temperatures [19, 20].

The constant K_2 increased with increasing soaking temperature (AT to 60 ^{0}C). The constant K_2 is a constant related to maximum water absorption capacity i.e. the lower the K_2, the higher the water absorption capacity. The K_2 was linearly increased with increasing the water absorption capacity of paddy (PS-5) with increasing soaking temperature. Effect of temperature on winter on water absorption capacity of food materials, namely on K_2, is mixed and depends on types of material and if soluble solids loss during soaking is considered in the calculation of moisture content of samples [21, 22]. Water absorption capacity depends upon cell wall structure, composition of the seed and the compactness of the cells in the seed [23].

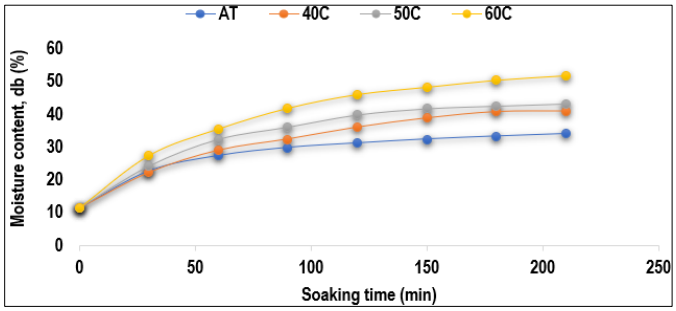

Fig 1: Effect of different soaking temperature on hydration behaviour of Paddy (PS-5)

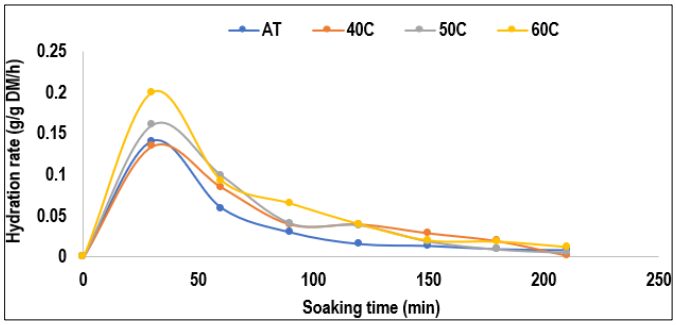

Fig 2: Variation in hydration rate of paddy (PS-5) with soaking period at different water temperatures

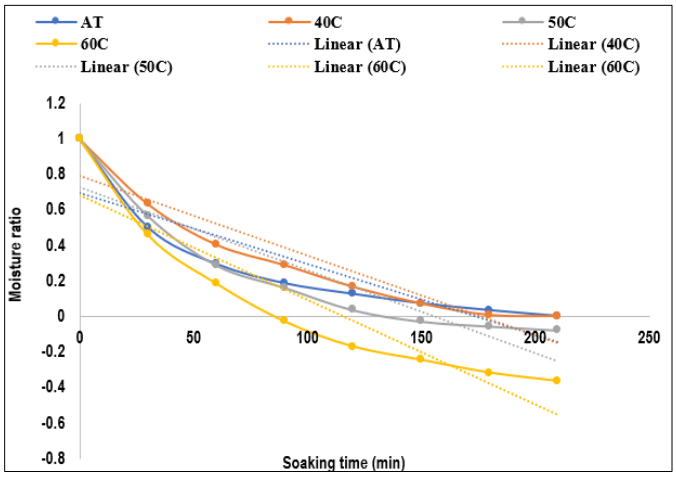

Fig 3: Hydration curve between soaking times and hydration ratio of paddy (PS-5) with different soaking temperatures (Lewis model)

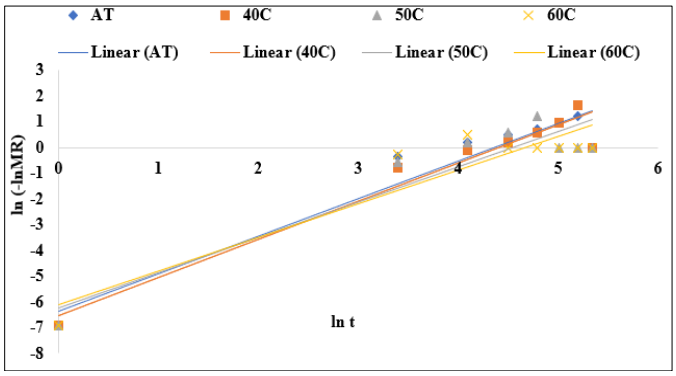

Fig 4: Variation in experimental and prediction data of moisture ratio of soaked paddy at different temperatures (page's model)

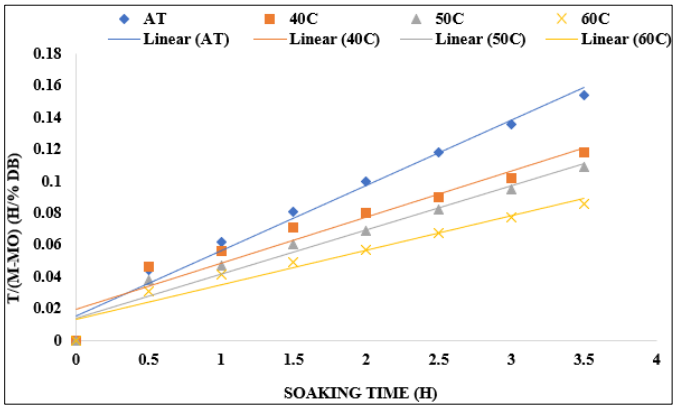

Fig 5: Fitting of the peleg model to water absorption data during soaking of paddy (ps-5) at different temperatures (peleg's model)

Validation of Models

The constant of models for soaking of paddy are presented in Table 1. The best model to describe hydration behaviour of paddy was collected on the basis of high value of coefficient of determination (R^2). It is observed that high value of R^2 is indicative of good fitness of the empirical relationship to represent the variation in moisture ratio with soaking time. The value of coefficient of determination (R^2) were estimated by Lewis's Model (0.7707 to 0.8815), Page's Model (0.8642 to 0.9408) and Peleg's Model (0.9280 to 0.9786) with an average value 0.8333, 0.9087 and 0.9527 respectively. The Peleg model was reported highest Coefficient of determination (R^2) as compared to other using models for soaking of paddy (PS-5) with different soaking temperature. The Peleg model was found fit of soaking of paddy (PS-5) agree with parboiled rice[24], green gram[3] and split chickpea [19].

Conclusion

The paddy (PS-5) was soaked in water at ambient temperature (AT), 40 ^{0}C, 50 ^{0}C and 60 ^{0}C up to 3.5 h (210 min). The moisture content was calculated every 30 min interval. The study revealed that the moisture content of paddy was increased with increasing soaking time and soaking temperatures. Hydration rate of paddy was higher at the initial stage of soaking time. Newton/Lewis, Page and Peleg's equation describe the hydration characteristics of paddy under the experimental conditions i.e. coefficient of determination (R^2) = 0.7707-0.8815; 0.8642-0.9213 and 0.9280-0.9786, respectively. The higher soaking temperature resulted in lesser soaking time in water. The Peleg model can be used to elaborate successfully hydration behavior of paddy as compared to Newton/Lewis, and Page model. By increasing the temperature of soaking medium, Peleg's rate constant (k_1) and Capacity constant (k_2) was decreased and increased respectively with increasing soaking time. In order to control and predict the process, optimizing the hydration condition is vital since hydration governs the subsequent operations and the quality of the final product. The findings have to use in designing of processing machines and equipment for milling, cooking and packaging operations of paddy. The study also revealed that it is possible to predict the water absorption characteristics of paddy which can be help to optimize soaking conditions.

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Conflicts of interest

The authors declare no conflicts of interest regarding the publication of this paper.

Financial Disclosure

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