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Application of different mathematical models to determine hydration characteristics of paddy grain

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ABSTRACT

In this article study of water absorption kinetics of paddy grain was carried out at 10ºC, 20ºC, and 30ºC. Three mathematical models namely Henderson and Pabis model, Exponential model and Page model were used for describing the soaking behavior of paddy grain. Among these models Henederson and Pabis model was found to be the most suitable for describing hydration kinetics of paddy grain at lower temperature. Effective diffusivity of water during soaking of paddy grain varied from 1.68×10^{-11} m^2/s to 2.14×10^{-11} m^2/s with activation energy of 9.97 KJ/mol.

KEYWORDS

Absorption kinetics; Moisture diffusivity; Paddy grain; Hydration.

INTRODUCTION

Cereals are important source of functional ingredients which are potential components for many processed foods. Processing of cereals often requires that the seeds be hydrated first to facilitate operations such as cooking or canning. Thus, absorption of water to these materials is of both theoretical and practical interest to processing industries[1,2]. Cereal like rice is (*Oryza sativa* L.) considered as a main staple food and is a major source of nutrients in many parts of the world. Prior to processing, the rice undergoes some kind of hydrothermal treatment such as soaking[3]. Processing of grain and quality of finished product depend on proper soaking procedure. Soaking is a slow process controlled by the diffusion of water in the grain[4]. Warm water is used for soaking purpose to shorten the soaking time because increasing temperature increases hydration rate. Usually hydration temperature below gelatinization temperature is prescribed for minimizing the splitting of kernels.

In order to optimize the process parameter and present diffusion as a function of time and temperature equation modeling of soaking behavior is needed. But currently, there is no basic understanding of the physics behind the moisture transport in food systems[5]. Virtually, all models concerning this problem are empirical. They build upon Fick's law with effective moisture diffusivity, which is an unknown empirical function of temperature and moisture content[6]. Empirical models are often used instead of the theoretical ones, due to their ease of computability and interpretation.

Reports are there on prediction of moisture content distribution within a wheat kernel from a finite element diffusion model[7]. The relationship between moisture movement in the wheat kernel and the shape and composition of the kernel with an analytical solution of the diffusion equation had been described earlier[8]. Tagawa et al. evaluated the diffusion coefficients of water in wheat kernels at various temperatures ranging from 10 to 50°C and mentioned that water absorption of wheat kernel was in the second falling rate period[9]. As the drying and water absorption phenomena are reversible in nature, therefore water absorption process in paddy grain could be explained using the theory of diffusion in the same manner and drying models can be used to describe water absorption behavior of paddy grain.

The objective of the present study is to determine the effect of temperature and time on hydration of paddy grain, to determine moisture diffusivity and activation energy in paddy and to find out the best mathematical model that can describe the soaking characteristics of paddy at lower temperature.

EXPERIMENTAL

Materials: Paddy grains were collected from local market. Then the grains were manually screened to remove foreign particles, chaff and broken kernels, immature and damaged seeds. Only paddy grains that were in good condition were selected for the experiment.

Moisture determination: Moisture content of paddy grains was measured by standard air oven method. Known amount of sample was taken in aluminum cup and weighed, and then it was placed in hot air oven for moisture determination at 130±3°C untill constant weight was obtained[10].

Water absorption study: To study the hydration characteristics of paddy grains a definite amount of clean raw paddy were soaked into distilled water (1:10 w/v) at different temperature. The soaking temperature studied were 10°C, 20°Cand 30°C. Paddy grains were taken in a glass beaker containing distilled water at the desired temperature. During hydration the samples were taken out at definite interval of time (initially 30 min, then 1 h and then 2 h). Filter paper was used to remove surface water and then placed in hot air oven for moisture determination (% d.b). For equilibrium moisture content a separate set of sample was soaked for 24 hours.

THEORETICAL CONSIDERATION

Modeling of water absorption curve

For determining water absorption characteristics of paddy grain three commonly used mathematical models (TABLE 1) were selected. In this analysis MR or moisture ratio is needed to describe different soaking model, i.e $MR = \frac{M - M_e}{M_0 - M_e}$ where M is the moisture content (% dry basis) of the paddy at each moment. M_0 is the initial moisture content (% dry basis) of paddy. M_e is the equilibrium moisture content (% dry basis). This moisture ratio was then fitted to different models namely Henderson and Pabis model, exponential model and Page model.

TABLE 1: Mathematical model for describing paddy soaking data

No.	Model Name	Equation
1.	Henderson and Pabis	$MR = B\exp(-kt)$
2.	Exponential	$MR = \exp(-kt)$
3.	Page	$MR = \exp(-kt^n)$

Correlation coefficient and error analysis

The goodness of fit of the tested mathematical model to the experimental data was evaluated with the correlation coefficient (R^2), the estimated mean error (SE). The average percent difference between the experimental and predicted values or the mean relative deviation modulus (P) has also been used as a measure of model adequacy. The mean relative deviation modulus (P) and the estimated mean error for each model were calculated by the following equation

$$P = \frac{100}{n}\sum_{i=1}^{n}\frac{|MR_{actual} - MR_{predicted}|}{MR_{actual}} \quad (1)$$

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(Y - Y_0)^2}{DF}} \quad (2)$$

Where n is the number of observations, MR_{actual} is the experimental moisture ratio, $MR_{predicted}$ is the predicted moisture ratio. Y is experimental values observed; Y_0 is value estimated though the model; DF is degrees of freedom (number of observations minus the number of the parameters of the model). The best model describing the soaking characteristics of paddy grain was chosen as the one with the highest correlation coefficient (R^2) and the least estimated mean error (SE) and mean relative deviation modulus (P)[11]. In this study the regression analysis was performed using Microsoft Excel.

RESULTS AND DISCUSSION

Modeling of soaking characteristics of paddy

Three selected models were fitted to the water absorption data of paddy. Water absorption constants, correlation coefficient (R^2) and residual mean square (SE) were calculated and the models were evaluated based on correlation coefficient (R^2), mean error (SE) and mean relative deviation modulus (P). The details of the statistical analysis for three models are presented in TABLE 2.

Acceptable R^2 value of greater than 0.90 was obtained for all three models fitted to all hydration data. From TABLE 2 it is evident both Henderson and Pabis model and Page model showed lower SE value as compared to the exponential model. But P values were lower for Henderson and Pabis model as compared to the other two models. Value of correlation coefficient was also higher for Henderson and Pabis model. Hence Henderson and Pabis model gave better predictions than others, and satisfactorily described the water absorption characteristics of paddy grain at low steeping temperature.

TABLE 2 : Statistical result for henderson and pabis, exponential and page model

Temperature	Henderson and Pabis			Exponential			Page		
(ºC)	R2	SE	P	R2	SE	P	R2	SE	P
10	0.979	0.047	9.84	0.979	0.052	10.08	0.975	0.046	14.24
20	0.961	0.068	17.13	0.959	0.089	17.94	0.938	0.058	25.99
30	0.949	0.057	19.03	0.932	0.141	23.78	0.925	0.057	35.04

Determination of effective diffusivity

In order to predict moisture diffusivity during soaking of rice, the second Fick's law solution for diffusion out of sphere was used. For this purpose the following assumptions were made:(i) the effective diffusion coefficient is independent of moisture concentration, (ii) the volume of grain does not change during water absorption, (iii) the surface of grain reaches the equilibrium moisture content instantaneously upon immersion in absorption media. General series solution of Fick's second law in spherical coordinates is given below[12].

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2 D_{eff}\pi^2}{R^2}t\right) \quad (3)$$

Where D_{eff} is the effective diffusivity (m^2/s) and R is the equivalent radius of paddy grain(1.68mm). The slope (k) of this model is related to effective diffusivity and determined by the Equation (4)

$$k = \frac{D_{eff}\pi^2}{R^2} \quad (4)$$

The effective diffusivity was calculated by Equation (3) using slopes derived from the linear regression of ln MR against absorption time data. The effective diffusivity of paddy grain during water absorption varied from 1.68×10^{-11} m^2/s to 2.14×10^{-11} m^2/s in the temperature range from $10^{\circ}C$ to $30^{\circ}C$ (TABLE 3). It is evident from the table that effective diffusivity increases with increase in absorption temperature. This trend is similar to the earlier reports for rice[11] and wheat kernel[13].

TABLE 3 : Effective diffusivity of paddy grain during in different soaking temperature

Temperature ($^{\circ}C$)	Effective diffusivity (m^2/s)
$10^{\circ}C$	1.68×10^{-11}
$20^{\circ}C$	1.88×10^{-11}
$30^{\circ}C$	2.14×10^{-11}

Determination of activation energy

Effect of temperature on effective diffusivity is generally described using Arrhenius-type relationship to obtain better agreement of the predicted curve with experimental data

$$D_{eff} = D_0 \exp\left(-\frac{E}{RT}\right) \quad (5)$$

Where D_0 is diffusivity constant at infinitely high temperature, E is activation energy(KJ/mol) T is the absolute temperature. $\ln D_{eff}$ is plotted(Figure 1) as a function of reciprocal of absolute temperature in order to obtain diffusivity constant and activation energy. The resultant curve shows a linear relationship between $\ln D_{eff}$ and (1/T). The diffusivity constant (D_0) and activation energy (E) calculated from linear regression are 1.12×10^{-9} and 9.97(KJ/mol) respectively. These values are comparatively low to those reported in the literature for water absorption in some other grain like amaranth[14] grain (32.1KJ/mol), lupin seeds[15] (60.44KJ/mol) etc. This may be due to that at low steeping temperature rate of water absorption was lower, as a result energy requirement for water absorption was also less, hence activation energy of paddy grain was lower as compared to other grain's activation energy at higher temperature.

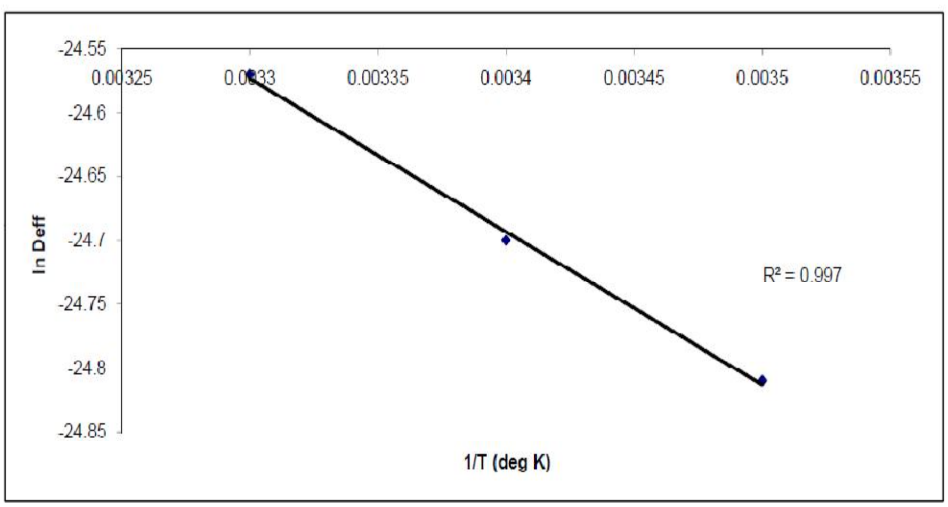

Figure 1 : Arrhenius type relationship between effective diffusivity and hydration temperature of paddy grain

CONCLUSION

The present study gives us the following conclusions

Increase in soaking temperature increases moisture diffusion and thus moisture content of paddy.

The Henderson and Pabis model satisfactorily described the hydration kinetics of paddy grain at lower steeping temperature.

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