Hydration kinetics and changes in some physical properties of wheat kernels

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Abstract

Hydration characteristics of wheat kernels was studied at different soaking temperatures. Some physical properties were also evaluated as a function of soaking temperature in the range of 25 to 65 ºC. Five models for describing the soaking behaviour of wheat kernels were investigated. Among them, Page model was found to be the most suitable for describing the soaking behavior of wheat kernels. Effective diffusivity of water during soaking of wheat kernels varied from 2.80×10^{-12} to 1.36×10^{-11} m^2/s with an activation energy of 34.26 KJ/mol. In the soaking temperatures from 25 to 65 ºC, studies on soaked samples showed that the kernel density decreased linearly from 2458.18 to 985.58 kg/m^3 and porosity also decreased linearly from 72.33% to 27.55%, while kernel volume increased linearly from 0.022 to 0.066 cm^3. A quadratic relationship between bulk density and soaking temperature of wheat kernels was developed. The amount of solids leached increased with temperature particularly for higher soaking temperatures.

Keywords: Density; Hydration kinetics; Modeling; Moisture diffusivity; Water uptake; Wheat kernel.

Introduction

Cereals and legumes are important sources of functional ingredients which are potential components for many processed foods. Processing of cereals and legumes 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 theoritical and practical interest to processing industries [1,2]. Wheat is one of the major staple foods in all over world because of its agronomical adaptability; ability of its flour to be made into various food materials and ease of storage. In the malting process, carefully selected barley is soaked in water at about 17 °C until saturation before germination [3]. Recently, production of wheat malt or cereal mixture other than barley has initiated in some countries [3]. Adding water is also a pretreatment for the flour milling process (tempering). Tempering is a wheat moistening process that enhances milling efficiency. Control of this process may be improved with better knowledge of the distribution and movement of moisture within the wheat kernel. In tempering, temperature, variety, kernel size, and time of exposure affect the rate at which moisture enters into the wheat kernel. Among these factors, temperature has been shown to have the greatest effect, with an increase in temperature resulting in an increase in the rate of moisture absorption.

From a processing and engineering point of view, one is interested not only in knowing how fast the absorption of water can be accomplished, but also how it will be affected by processing variables [4], and also how one can predict the soaking time under given conditions. Thus, quantyitative data on the effect of processing variables are necessary for practical applications to optimize and characterise the soaking coditions.

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design food processing equipments and predict water absorption as a function of time and temperature [2,5,6]. Water diffuses into the grain and some components leach out during soaking. Both phenomena are functions of time and temperature [7]. Soaking is a slow process controlled by the diffusion of water in the grain [8]. Thus soaking at room temperature may provoke microbial contamination, which affects quality attributes (such as color, taste and flavor) of the product [9]. Warm water soaking is a common method to shorten the soaking time, because higher temperature increases hydration rate. However, soaking temperature below of starch gelatinization is recommended to minimize leaching of solids [10]. Many researchers have studied the drying of wheat kernels from different points of view but there is less information about soaking of wheat kernels. Moisture content distribution within a wheat kernel was predicted from a finite element diffusion model, and moisture diffusion coefficients for wheat kernel during isothermal moisture soaking were determined [11]. Kang and Delwiche (2000) described 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 [12]. Tagawa *et al.* (2003) determined 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 [13]. If the two phenomena (i.e., drying and water absorption of wheat kernel) are reversible, then the water absorption process of wheat kernel could be explained using the theory of diffusion in the same manner and drying models can be used to describe water absorption behavior of wheat kernels. The objectives of the present study were to determine the effect of temperature and time on the hydration of wheat kernel, to study effect of soaking variables on leaching of solids, to explore the effect of soaking temperature on some physical properties of wheat kernel, and to find out the best mathematical model to describe the soaking behavior of wheat kernels.

Materials and methods

Sample preparation

The wheat kernels used in this research were obtained from Seed and Plant Breeding Institute, Gorgan, Iran. Tajan variety was used in this study because it is one of the most important varieties grown and consumed in Golestan province, Iran. Before conducting the hydration experiment the sample was cleaned to remove foreign materials and broken kernels in order to obtain kernels of uniform size. The initial moisture content of samples was determined by drying about 5 g of samples in an air convection oven at 103 ±2 °C until a constant weight [14] and was found to be 11.80 (% w.b.).

Determination of physical properties

Some physical properties (bulk density, kernel density, volume and porosity) of wheat kernels were determined separately before and after soaking experiment (15 hours) for different temperatures (25, 35, 45, 55 and 65 °C). Bulk density was calculated from the mass and volume of a circular container with known volume (0.5 l). The seeds were poured in this container up to the top and excess seeds were removed by strike-off stick. The samples were not compacted in any way [15].

Kernel density is the weight per unit volume of an individual seed. Kernel density and volume of wheat kernel was determined using the liquid displacement method. Toluene (C_7H_8) was used instead of water because it is absorbed by kernels to a less extent [16].

The porosity (ε) of the wheat kernel is the ratio of the volume of the voids between the grains to its bulk volume and was determined using the following relationship [16]:

$$\varepsilon = \frac{\rho_k - \rho_b}{\rho_k} \times 100 \qquad (1)$$

where ρ_b and ρ_k are the bulk and kernel density, respectively, in kilogram per cubic meter.

Size characterization

As wheat kernel is irregularly shaped, the equivalent sphere radius was employed to represent wheat kernel size for the mathematical model used in this study. For this purpose the total volume of 50 kernels was measured with a pycnometer using toluene as fluid. The average wheat kernel volume was calculated by dividing the total volume by the total number of wheat kernels. The equivalent sphere radius was then computed from the formula for the volume of a sphere using the average wheat kernel volume [9].

Soaking procedure

Approximately 10±0.5 g of wheat kernels were placed in 200 ml of distilled water at five different soaking temperatures of 25, 35, 45, 55 and 65 °C. The samples along with the soaking water were placed in a water bath (WNB 14, Memmert GmbH Co., Germany) with a temperature control accuracy of ±0.5°C fixed at the required soaking temperature. The wheat kernels were soaked at each temperature for up to 15 hours and soaked samples were withdrawn from the water at different time intervals (15 min at the first 5 hours and 30 min at the rest of soaking process). After reaching the required soaking time, the sample was drained on a tissue paper and the excess water eliminated with adsorbent paper, and the soaked wheat kernels were weighed with a digital balance (TE313S, Sartorius, Germany) with 0.001 g accuracy to determine moisture content. These operations were conducted at each predetermined time untill the test was terminated. The increase in sample mass during soaking in water was considered to reflect the increase of moisture in the sample. All experiments were conducted three times. The weight uptake was calculated as:

$$WU(\%) = \frac{(W - W_0)}{W_0} \times 100 \tag{2}$$

where WU is weight uptake, W is weight of wet wheat kernel at any time (g) and W_0 is initial weight of wheat kernel (g).

Leaching loss

Leaching loss was determined after each hydration experiment. The water in the filtrate was allowed to evaporate by keeping in an oven maintained at 105 °C for at least 10 hours untill constant weight and then the dry residue was calculated. The leaching loss was calculated as the weight of solids present in the filtrate divided by the intial weight and expressed as percent solids to initial sample weight [17].

Analysis of soaking data and soaking models

The effect of soaking temperature on physical properties and equilibrium moisture content of wheat kernel was determined using the analysis of variance (ANOVA) method and significant differences of means were compared using the Duncan's test at $\alpha<0.05$. The best relationship between soaking temperature and physical properties of wheat kernel was also determined using regression analysis. The effect of soaking time and temperature on water uptake and leaching loss of wheat kernel were studied statistically.

Five selected models, which might be adequate to describe soaking behavior of wheat kernels are presented in Table 1. In the analysis of water absorption data of wheat kernel, the moisture ratio (MR) is essential to describe different soaking models:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{3}$$

Table 1.Selected equations for describing wheat kernel soaking data

No.	Model name	Equation
1	Henderson and Pabis	$MR = B\exp(-At)$
2	Exponential	$MR = \exp(-kt)$
3	Page	$MR = \exp(-kt^N)$
4	Two-term exponential	$MR = A_0\exp(-k_1t) + A_1\exp(-k_2t)$
5	Modified Page	$MR = \exp(-kt)^N$

where MR is moisture ratio (decimal), M is the moisture content at time t (% d.b.), M_0 is the initial moisture content (% d.b.), M_e is equilibrium or saturation moisture content (% d.b.) and t is time (min). The moisture ratio was then fitted to the different models (exponential model, Henderson and Pabis model, Page model, modified Page model and two-term exponential model). There are several criteria such as coefficient of determination (R^2), residual mean square (MSE) and residual plotting to evaluate the fitting of a model to experimental data. 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 [18]:

$$P = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|MR_{actual} - MR_{predicted}\right|}{MR_{actual}} \qquad (4)$$

Non- linear regression procedure was performed on all soaking runs to estimate the parameters associated with five considered models from the experimental data using SLIDWRITE software.

The model constants were then related to the soaking temperatures to obtain functional relationship, which were determined using regression technique. The best model describing the soaking characteristics of wheat kernel was chosen as the one with the highest coefficient of determination (R^2) and the least mean square error (MSE) and mean relative deviation modulus (P).

Determination of equilibrium moisture content

The experimental determination of the equilibrium moisture content is time consuming, since the transient values converge very slowly towards an equilibrium state. It was therefore not possible to determine this parameter experimentally. Hence, the equilibrium moisture content was estimated by extrapolating a linear plot of the rate of change of moisture (dM_t/d_t) against the moisture content (M) to the point where $dM_t/d_t=0$. Table 2 shows the equilibrium moisture content of wheat kernels at different soaking temperatures.

Results and discussion

Effect of soaking temperature on physical properties

Fig. 1 shows the relationship between bulk density and soaking temperature of wheat kernels after 15 hours soaking at different temperatures. As shown in Fig. 1, the bulk density of wheat kernels during water absorption can be predicted as a quadratic function of soaking temperature that has maximum value (727.40 kg/m^3) at the soaking temperature of about 55°C. The effect of soaking temperature on the bulk density of wheat kernels was statistically significant ($P<0.05$). The increase in bulk density of wheat kernels with increase of soaking temperature till 55°C indicates that the increase in mass owing to moisture gain in the sample is higher than the accompanying volumetric expansion of the bulk and after 55°C is vice versa. Therefore, it was assumed the following quadratic equation to represent the relationship between bulk density and soaking temperature of wheat kernels:

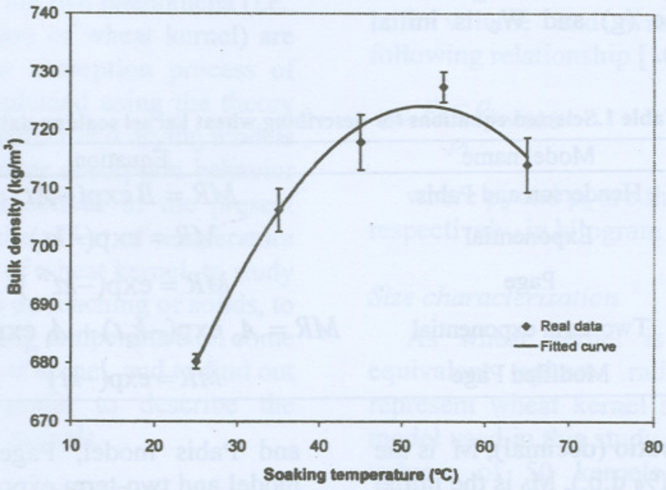

Fig. 1. Effect of soaking temperature on bulk density of wheat kernels after 15 hours soaking.

$$\rho_b = -0.058\,T^2 + 6.084\,T + 563.89, \quad (R^2 = 0.982) \qquad (5)$$

The variation of kernel density with soaking temperature after 15 hr soaking for wheat kernel is shown in Fig. 2. Analysis of variance showed that the increasing soaking temperature had significant effect on kernel density of wheat kernels (P<0.05). The kernel density of soaked samples was found to decrease linearly from 2458.18 to 985.58 kg/m^3 when soaking temperature increasead from 25 to 65 °C. The decreasing trends of the kernel density of sample at different soaking temperatures may be attributed to the higher volumetric expansion of the kernel as compared to the kernel weight gain. The variations in kernel density with soaking temperature of wheat kernel can be represented by the following relationship:

$$\rho_k = -38.805\,T + 3340.8, \quad (R^2 = 0.923) \qquad (6)$$

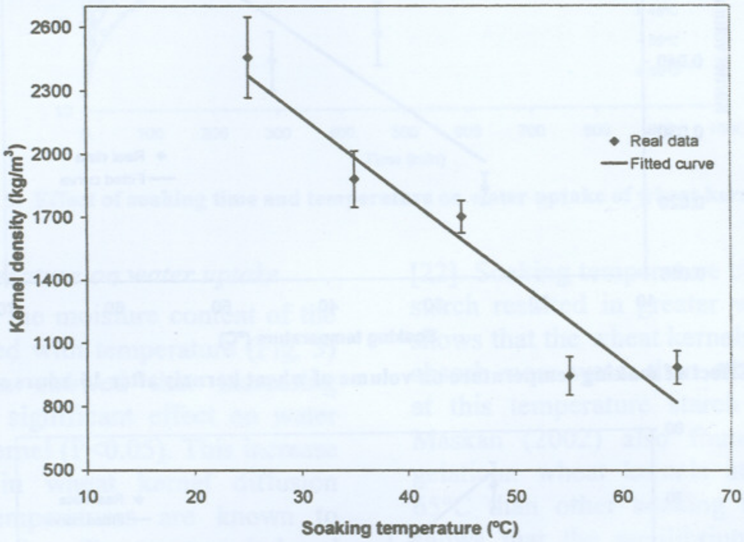

Fig. 2. Effect of soaking temperature on kernel density of wheat kernels after 15 hours soaking.

The increase in volume of wheat kernel during hydrothermal soaking at different temperatures (25-65°C) is shown in Fig. 3. It indicates that when the soaking temperature increased from 25 to 65°C, the volume of wheat kernel increased linearly from 0.022 to 0.066 cm^3 (P<0.05). A linear relationship has been reported by Muramatsu *et al.* (2006) between specific volume (sample volume to the mass of dry material) and soaking temperature of wheat and barley over a wide range of moisture content from the initial to saturated level (10-90 %d.b.) although the effect of temperature on the specific volume was comparatively weak within the range of measured temperatures (10-60°C) [19]. Maskan (2001) reported that the volume of wheat, dovme and firik increased significantly with temperature and volumetric changes/expansion in the samples was similar with respect to the water uptake. Studies on the volume changes of corn semolina during hydrothermal treatment at different temperatures (30-100°C) showed that the volume increase for raw semolina was higher than for the roasted semolina at all hydration temperatures. Up to a hydration temperature of 70°C, the volume increase was low for both type of semolina, but it was distinctly higher at 90°C and 100°C [6].

The volume of wheat kernel (V_k) was found to bear the following relationship with its corresponding soaking temperature:

$$V_k = 0.001\,T + 0.0005, \quad (R^2 = 0.890) \qquad (7)$$

Since the porosity depends on the bulk as well as kernel densities, the magnitude of variation in porosity depends on these factors only. The porosity changes of wheat kernels soaked at different temperatures is shown in Fig. 4. Analysis of data showed that the effect of soaking temperature on porosity of wheat kernels was statistically significant (P<0.05). It decreased linearly from 72.33% at temperature of 25°C to 27.55% at soaking temperature of 65°C. The porosity and soaking temperature of wheat kernels can be correlated as below:

$$\varepsilon = -1.24\,T + 105.43, \quad (R^2 = 0.904) \qquad (8)$$

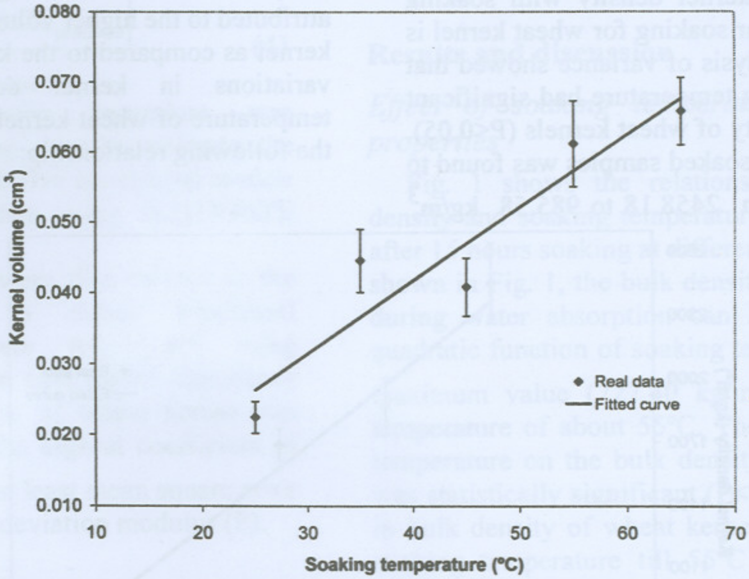

Fig. 3. Effect of soaking temperature on volume of wheat kernels after 15 hours soaking.

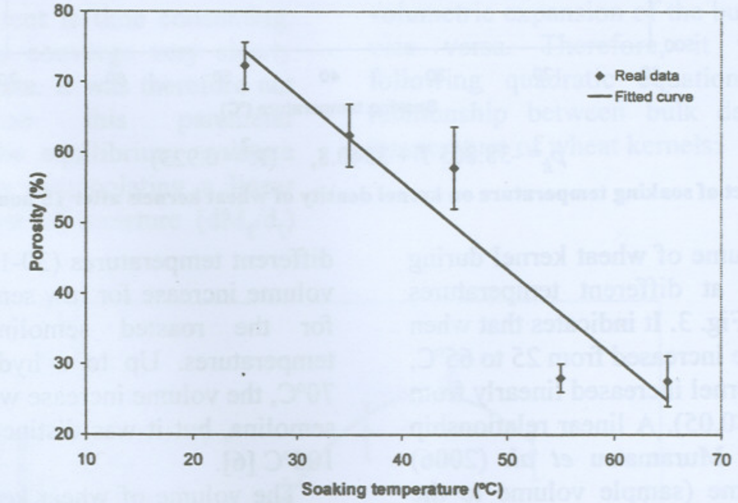

Fig. 4. Effect of soaking temperature on porosity of wheat kernels after 15 hours soaking.

Effect of soaking time on water absorption

Fig. 5 shows the time variation in water absorption by wheat kernels at different temperatures. Wheat kernels soaked at higher temperatures absorbed more water than samples soaked at lower temperatures (P<0.05). Although the moisture content increased progressively with time, a closer examination of data revealed some interesting patterns, valid for all temperatures. The samples exhibited the characteristics moisture absorption behaviour. During the first 30 min, the moisture content increased sharply. Between 30 and 300 min, depending on temperature, the rate of increase in moisture content is, more or less, uniform. For soaking times more than 40 min, the rate of increase drops progressively, and the moisture content eventually comes to a constant value. It was found that the trend of water absorption by other cereals and seeds was the same [5,6, 13, 20, 21,22].

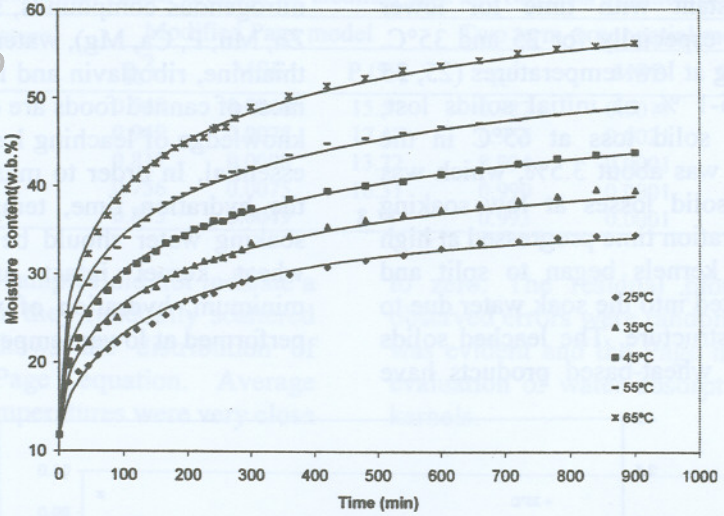

Fig. 5. Effect of soaking time and temperature on water uptake of wheat kernels.

Effect of soaking temperature on water uptake

At any given time, the moisture content of the wheat kernels increased with temperature (Fig. 5) and analysis of data showed that increasing moisture content had significant effect on water absorption of wheat kernel ($P<0.05$). This increase is due to changes in wheat kernel diffusion resistance. Higher temperatures are known to expand and soften grains. Temperature induced softening has been reported for soybean [23], chickpea [24], kidney bean [5], wheat [20], rough rice (paddy), milled rice [25,26] and white rice [22]. Soaking temperature closer to the gelation of starch resulted in greater water uptake. Figure 5 shows that the wheat kernels soaked at 65°C could absorb more water than other conditions, because at this temperature starch gelation commences. Maskan (2002) also found that due to starch gelatioan wheat kernels attained more water at 65°C than other soaking temperatures. Table 2 shows that the equilibrium moisture content of wheat kernels increased significantly ($P<0.05$) when the soaking temperature incresed from 25 to 65 °C.

Table 2.Equilibrium moisture content of wheat kernel at different soaking temperatures

Temperature (°C)	Equilibrium moisture content (% w. b.)
25	37.29^{e}
35	42.28^{d}
45	46.34^{c}
55	51.45^{b}
65	59.76^{a}

Superscript letters indicate that means with the same letters designation in a column are not significantly different at $P=0.05$.

From the above discussion, it is evident that temperature affects water uptake characteristics of wheat kernel. The rate of water uptake is higher at higher temperatures. Thus the application of higher temperature has potential to shorten the soaking time necessary to reach a given moisture content.

Leaching loss

The variation of solids leached with time during the soaking of wheat kernel at different temperatures is shown in Fig. 6. At any given time, the amount of sloids leached increased with temperature particularly for the soaking temperatures of 55 and 65°C ($P<0.05$). This Figure shows the amount of solids leached remain low and practically constant with time for lower soaking temperatures especially for 25 and 35°C. After 900 min soaking at low temperatures (25, 35 and 45°C) about 0.5-1 % of initial solids lost, while the maximum solid loss at 65°C in the measured time range was about 3.5%, which was more than 4 times solid losses at low soaking temperatures. As hydration time progressed at high temperatures, wheat kernels began to split and some parts disintegrated into the soak water due to the softened sample structure. The leached solids in wheat kernel and wheat-based products have been reported to be phytic acid, non-protein nitrogenous compounds, sugars, minerals (Fe, Cu, Zn, Mn, P, Ca, Mg), water soluble vitamins such as thiamine, riboflavin and niacin [27, 28, 29]. Since most of canned foods are drained before eating, the knowledge of leaching loss in the soaking water is essential. In order to maximise nutrient retention, the hydration time, temperature and amount of soaking water should be optimised. To keep the wheat kernel intact and soaking lossess at minimum, hydration of wheat kernels should be performed at lower temperatures.

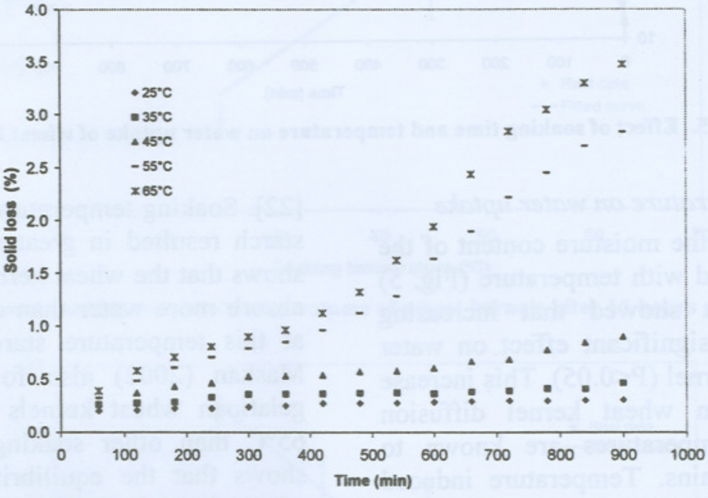

Fig. 6. Total solids leached during soaking of wheat kernels at different soaking temperatures and times.

Modeling of water absorption

Tables 3 and 4 show the statistical analysis results for the five models fitted to the soaking data of wheat kernels. These models were evaluated based on the coefficient of determination (R^2), mean square error (MSE), mean relative deviation modulus (P) and residual plotting.

Acceptable R^2 of greater than 0.95 was obtained for some models fitted to all soaking runs while Page model presented higher values than other selected models. As well as Page model showed lower MSE values than other models. P value indicates the deviation of the observed datafrom predicted values and R^2 was stated not to be only and good criteria for evaluation non-linear mathematical models. Page model showed lower P values than other models. Hence, the Page model gave better predictions than others, and satisfactorily described soaking characteristics of wheat kernel.

Table 3.Statistical results obtained for exponential, henderson & pabis, and page models

Temperature	Exponential model			Henderson & Pabis model			Page model		
(°C)	R^2	MSE	P (%)	R^2	MSE	P (%)	R^2	MSE	P (%)
25	0.949	0.0046	15.51	0.982	0.0011	4.62	0.989	0.0006	4.62
35	0.909	0.0075	17.47	0.955	0.0020	7.02	0.996	0.0002	1.52
45	0.817	0.0095	13.72	0.877	0.0023	5.33	0.995	0.0001	1.00
55	0.756	0.0073	10.31	0.775	0.0020	4.61	0.957	0.0004	2.07
65	0.815	0.0048	8.14	0.881	0.0011	3.20	0.992	0.0001	0.66

Table 4.Statistical results obtained for modified page and two term exponential model

Temperature (°C)	Modified Page model			Two term exponential model		
	R^2	MSE	P (%)	R^2	MSE	P (%)
25	0.949	0.0048	15.51	0.982	0.0011	4.62
35	0.949	0.0078	17.47	0.955	0.0021	7.04
45	0.817	0.0098	13.72	0.994	0.0001	1.00
55	0.756	0.0075	10.31	0.990	0.0001	0.83
65	0.815	0.0049	8.14	0.993	0.0001	0.67

The residuals for the samples did not indicate a visual pattern and rather they randomly scattered around zero. Fig. 7 shows the distribution of residual errors for Page equation. Average residuals for different temperatures were very close to zero. The residual plots suggested that the observed errors were random and no residual trend was evident and the Page model is usable for the evaluation of water absorption behavior of wheat kernels.

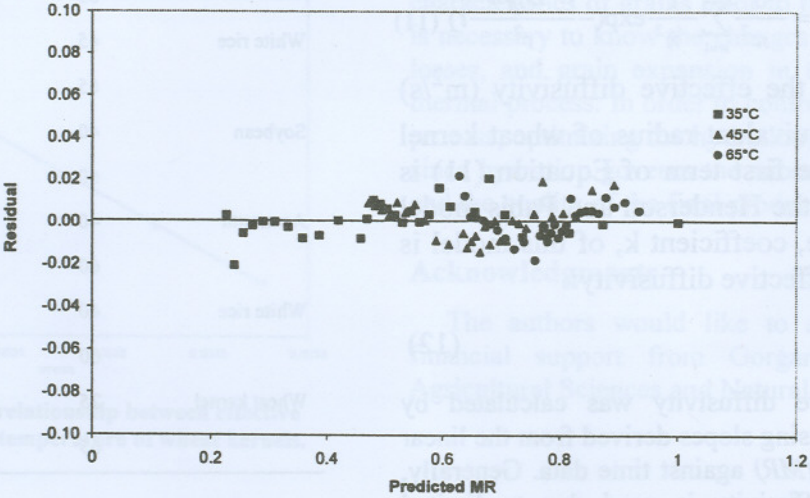

Fig. 7. Distribution of residual errors for Page equation for soaking of wheat kernel at 35, 45 and 65 °C.

The Page model coefficients (K and N) for each soaking run were calculated (Table 5). A regular increase in K coefficient was observed as temperature increased from 25 to 45°C. However, an abnormal behavior was observed at 55 and 65°C. It may be due to effect of high temperature inducing softening or absorption more water than expected at higher temperatures, probably due to starch gelation [20]. Further analysis was performed to describe the temperature dependence of K and N. Several equations were tested in the linaer or non-linear regression procedure to find out *K* and *N*. Criteria such as R^2, MSE, P value and residual plotting were used to evaluate the equations. The equations that provided the best results were:

$$K = 0.0034\times T + 0.034, \quad (R^2 = 0.83) \tag{9}$$

$$N = -0.0038\times T + 0.758, \quad (R^2 = 0.91) \tag{10}$$

Table 5.Page model parameters in different soaking condition of wheat kernel

Temperature (°C)	K	N
25	0.018	0.687
35	0.028	0.584
45	0.033	0.461
55	0.029	0.405
65	0.019	0.471

Moisture contents predicted with the generalized model are compared to observed moisture contents at different soaking temperatures in Fig. 5. These results demonstrate that the model tracks the observed moisture contents well throughout the entire period of each run.

Calculation of effective diffusivity and activation energy

In order to predict moisture diffusivity during soaking of wheat kernel, 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 wheat kernel does not change during water absorption, (iii) the surface of wheat kernel 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 [30]:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-\frac{n^2 D_{eff} \pi^2}{r^2} t) \quad (11)$$

Where D_{eff} is the effective diffusivity (m^2/s) and r is the equivalent radius of wheat kernel (1.98 mm). The first term of Equation (11) is also known as the Henderson and Pabis model [30]. The slope, coefficient k, of this model is related to the effective diffusivity:

$$k = \frac{D_{eff} \pi^2}{r^2} \quad (12)$$

The effective diffusivity was calculated by Equation (11), using slopes derived from the linear regression of *ln(MR)* against time data. Generally, an effective diffusivity is used due to limited information on the mechanism of moisture movement during soaking process. The effective of diffusivity during soaking of wheat kernel varied from 2.80×10^{-12} to 1.36×10^{-11} m^2/s in the temperature range from 25°C to 65°C (Table 6). The comparison of the diffusion coefficients for water soaking obtained in this study for wheat kernel with those reported in the literature for other grains is shown in Table 7. It can be concluded that effective diffusivity of wheat kernel is very similar to other agricultural materials.

Table 6.Effective diffusivity of wheat kernel in different soaking temperatures

Temperature (°C)	Effective diffusivity (m^2/s)
25	2.80×10^{-12}
35	4.18×10^{-12}
45	6.24×10^{-12}
55	1.06×10^{-11}
65	1.36×10^{-11}

Table 7.Effective diffusivity for wheat kernel soaking compared with other grains

Material	Temperature (°C)	D_{eff} (m^2/s)	Reference
Maize	52	4.86×10^{-11}	[31]
Wheat kernel	10	1.1×10^{-12}	[13]
	50	1.0×10^{-11}	
Rough rice	40	6.67×10^{-9}	[8]
	50	9.03×10^{-9}	
Raw rice	45	2.08×10^{-11}	[9]
	65	7.20×10^{-11}	
Brown rice	45	7.90×10^{-11}	[9]
	65	8.82×10^{-11}	
White rice	45	2.33×10^{-10}	[9]
	65	4.70×10^{-10}	
Soybean	40	1.08×10^{-10}	[1]
	60	2.00×10^{-10}	
Amaranth	40	3.84×10^{-12}	[32]
	60	8.25×10^{-12}	
White rice	40	1.62×10^{-10}	[22]
	60	3.06×10^{-10}	
Wheat kernel	25	2.80×10^{-12}	This research
	65	1.36×10^{-11}	

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

$$D_{eff} = D_0 \exp(-\frac{E_a}{RT_a}) \quad (13)$$

where D_0 is a diffusivity constant equivalent to the diffusivity at infinitely high temperature and E_a is the activation energy (KJ/mol). The logarithm of D_{eff} as a function of reciprocal of absolute temperature (T_a) is plotted in Figure 8. The results show a linear relationship between (log D_{eff}) and ($1/T_a$) or an Arrhenius-type relationship (Equation 13). The diffusivity constant (D_0) and activation energy (E_a) calculated from the linear regression are 2.79 $\times10^{-6}$ (m^2/s) and 34.26 (KJ/mol), respectively. This value is comparable to those reported in the literature for water absorption in some grains. This activation energy is in reasonable agreement with the data presented by several authors for other grains. For example Engels *et al.* (1986) found E_a values ranging from 22.5 to 64.51 KJ/mol, depending on the moisture concentration of rice kernel, while Haros *et al.* (1995) reported an activation energy value of 39.41 KJ/mol for water absorption in corn [31]. Resio *et al.* (2003) find out an activation energy of 32.1 KJ/mol for amaranth grain [32] and Solomon (2007) reported an activation of energy of 60.44 KJ/mol for lupin seeds.

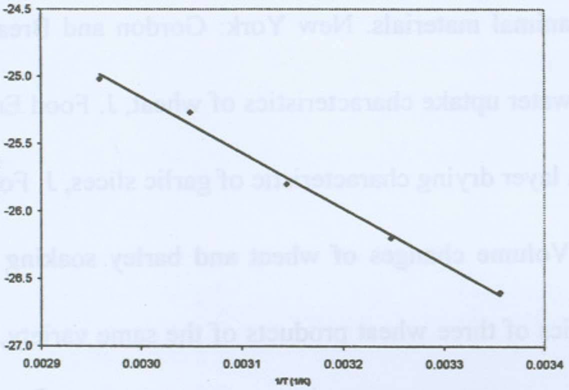

Fig. 8. Arrhenius type relationship between effective diffusivity and soaking temperature of wheat kernels.

Conclusions

Soaking of wheat kernel is an important part of processing operations like germination, cooking, flour milling process (tempering) and preparing a product from it. Hydration is a complex process and indicates the physical and chemical changes caused by processing. Processing of cereals often requires that the seeds be hydrated first to facilitate the consecutive extraction or cooking. Thus penetration of water into these materials is of theoretical and practical interest to the processing industry. The rate of water absorption has significance in the formulation of foods. In the canning industry too, knowledge in hydration characteristics of grains prior to further processing is necessary to know the changes such as leaching losses, and grain expansion in the can during a thermal process. 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.

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