Hydration Kinetics of Some Durum and Bread Wheat Varieties Grown in South-Eastern Region of Turkey

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Summary: Hydration kinetics of wheat varieties grown in South-Eastern Region of Turkey, covering a temperature range from 25 to 50 ºC was examined. Peleg's model together with Arrhenius relationship were successfully used to evaluate water uptake of some Durum (Local names; Zenit and BurgosBurgos) and Bread (Local names; Dariyel and Karatopak) wheat varieties during soaking at a temperature range of 25-50 ºC. Model was found to be suitable for describing the soaking behaviour of wheat kernels with a coefficient of determination (R^2) and Root mean square error (RMSE) greater than 0.9805, and less than 0.051, respectively. The Peleg rate and capacity constants, K_1 and K_2, were affected by temperature and wheat varieties. Activation energy values of Zenit, BurgosBurgos, Dariyel and Karatopak wheats were found as 39.94, 38.03, 36.25 and 29.54 kJ mol^{-1}, respectively. Zenit wheat was the least hydrated while Karatopak was the most hydrated one due to kernel size and protein content. General equations to describe the water uptake of wheat varieties as a function of soaking time, temperature and initial moisture content were developed. These derived equations can be used for wheat operations such as tempering, mixing, knedding etc.

Keywords: Durum and Bread wheat varieties; Water uptake; Soaking; Peleg's model; Activation energy

Introduction

Cereals and legumes are important sources of protein and carbohydrates that are potential components for many processed foods. Cereal grains contribute 50% of the world's dietary calories. Wheat provides slightly less than 20% of total calories [1]. Wheat is one of the major staple foods in all over world due to its agronomical adaptability; ability of its flour to be made into various food materials (pasta, bread, biscuits, fortified cereals foods and other special food products) and ease of storage. Wheat is one of the world's most important grains, with annual world production of 728,966,757.00 tonnes in 2014. Total annual wheat production of Turkey was 19,000,000.00 tonnes in 2014 [2].

In general, three major steps in pre-cooking process *i.e.* soaking or hydration, steaming has great influence on the final characteristics and quality of the end product. Therefore, hydration of water in to these materials is of both theoretical and practical interest to processing industries [3]. Hydration (tempering) is also a pre-treatment for the milling process. Tempering is a wheat moistening process that enhances milling performance. Control of this process may be improved with better knowledge of the distribution and movement of moisture within the wheat kernel. In tempering, temperature, wheat variety, kernel size, and time affect the rate at which moisture penetrates the wheat. Among them, temperature has been shown to display the most dramatic effect, with an increase in temperature resulting in an increase in the rate of water hydration during food preparations.

From engineering point of view, one is interested not only in knowing how fast the hydration 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, quantitative data on the effect of processing variables are necessary for practical applications to optimize and characterize the soaking conditions design food processing equipments and predict water absorption as a function of time and temperature.

Researchers have already demonstrated that increasing the temperature of the soaking medium is an effective way to accelerate water uptake by various foods and hence, to shorten the soaking time [5, 6].

Modelling hydration in grains and legumes during soaking has attracted considerable attention. Soaking is the important unit operation which facilitates for further processing. Hence there is a need to study the hydration characteristics of wheat grain for development of value added products from wheat. Optimizing the water absorption conditions in order to control and predict the process is vital since hydration governs the subsequent operations and quality of the final product [7]. Although the water uptake kinetics has been studied for several cereals

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including wheat [8], rice [7], sorghum [9], amaranth [10] and so on, but information on the water uptake kinetics of different wheat grains grown in South-Eastern Region of Turkey is lacking in the literature. Turkey produced 46% of Durum wheat and 14% of bread wheat in this region in 2013. So, South-Eastern Region of Turkey is an important region for wheat production. The soaking process during tempering has been characterized as a time consuming step and many attempts have been directed towards shortening it. As soaking conditions vary depending upon the particular wheat under study, it is necessary for practical applications to characterize and optimize these conditions. Therefore, water absorption during soaking needs to be predictable as a function of time and temperature. The aims of this study were to determine the effect of time, temperature and wheat variety on the hydration of wheat kernels, to examine the capability of Peleg's model to describe the soaking behaviour of wheat kernels, to calculate the activation energy, and to obtain a general empirical equation describing the water hydration of wheat varieties during soaking process as a function of soaking time, temperature and initial moisture content.

Experimental

Materials

Two Bread wheat (*Triticum aestivum,* local names: Dariyel and Karatopak) and two Durum wheat (*Triticum durum,* local names: BurgosBurgos and Zenit) varieties were used in this study. They were obtained from Southeastern Anatolia Project, International Agricultural Research Institute (Diyarbakır, Turkey). Before conducting the hydration experiment, the samples were manually cleaned to remove foreign materials and broken kernels. In order to obtain kernels of uniform size, they were screened. The initial moisture content of samples was determined by drying about 5 g of samples in an air convection oven at 105±1°C until a constant weight [11] and was found to be 9.99, 10.72, 10.89 and 11.79 (%,d.b.) for BurgosBurgos, Dariyel, Zenit and Karatopak varieties, respectively. The average dimensions (L: length, W: width and T: thickness in mm) of wheat kernels were measured with Mutitoyo No. 505-633, Japan, digital micrometer. The average equivalent diameters ($D_e = (LWT)^{1/3}$) and sphericities ($\phi = (LWT)^{1/3} L^{-1}$) of grains were also calculated [12]. The average equivalent diameters of Dariyel, Karatopak, Zenit and BurgosBurgos wheat varieties were found as 3.86±0.19, 3.94±0.14, 4.13±0.13, 4.21±0.18 (mm), respectively. The sphericities of them in the same order were calculated as to be 0.65±0.03, 0.63±0.02, 0.53±0.02, 0.54±0.01. The hundred kernel weight was measured by tst EN ISI 520 method of analysis and expressed on dry basis (13). The average weight of 1000-kernel (%, d.b.) was 56.00±0.02, 56.50±0.06, 62.00±0.05 and 69.50±0.04 for Karatopak, Dariyel, BurgosBurgos and Zenit, respectively. Nitrogen content was determined by using the Kjeldahl method and was multiplied by a factor of 5.7 to determine protein content expressed on a dry weight basis (14). Protein content of Dariyel, Karatopak, Burgos and Zenit was found to be 12.50±0.08, 12.55±0.05, 13.40±0.06 and 13.60±0.09 % (d.b.), respectively. On the other hand, gluten content was determined by washing according to the Approved methods of the American Association of Cereal Chemists, 38-12.02 (14) and expressed on dry basis. The values were found to be 9.70±0.04, 9.80±0.07, 12.20±0.03, 12.30±0.05 (%, d.b.) for Karatopak, Dariyel, Zenit and BurgosBurgos, respectively [14].

Water Uptake Determination during Soaking

Approximately 10±0.5 g of wheat kernels were placed in 300 ml of deionised water at six different soaking temperatures of 25, 30, 35, 40, 45 and 50 °C. The samples along with the soaking water were placed in a thermostat controller water bath (WiseCircu-WCH-8. Witeg com., 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 360 minutes and soaked samples were withdrawn from the water at different time intervals (30 min). 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 (AS 220/C/2, Radwag-Wagi, Poland) with 0.0001 g accuracy to determine moisture content. There was no correction for lost solids, because the amount of water absorbed was much greater than the amount of solid leached [3]. These operations were conducted at each predetermined time until 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 moisture content of samples in dry basis at any soaking time was calculated by the Eq. 1:

$$M_t = [\frac{(M_o + 1) * W_t}{W_o} - 1] * 100 \quad (1)$$

where W_o is initial weight (g), W_t is weight of sample (g) at any soaking time (t), M_o and M_t are the moisture contents of wheat samples in dry basis initially and at different soaking time, respectively.

Theory of Water Uptake

Among many theoretical, empirical, and semi empirical models, the most important model which has been used to model the hydration process of agricultural products is the Peleg's model [15]. The model is commonly used to describe absorption characteristics of various materials during soaking process [16-19]. Peleg [20] proposed a two-parameter hydration equation and tested its prediction accuracy during water vapour adsorption of milk powder and whole rice, and soaking of whole rice. This equation has since been known as the Peleg's model:

$$M_t = M_o + \frac{t}{K_1 + K_2 * t} \quad (2)$$

where M_t is moisture content at time t in % (d.b.); M_o is initial moisture content in % (d.b.); K_1 is the Peleg rate constant in s %, $(d.b)^{-1}$; K_2 is the Peleg capacity constant in % $(d.b.)^{-1}$.

The rate of absorption or hydration rate (HR, kg water per kg dry solid per min or s) can be obtained from first derivative of the Peleg's equation (2);

$$HR = \frac{dM}{dt} = \pm \frac{K_1}{(K_1 + K_2 * t)^2} = \frac{M_t \pm M_{t+dt}}{dt} \quad (3)$$

where M_{t+dt} is the moisture content (kg water per kg dry solid) at t +dt, and t is the hydration time (min or sec). The Peleg's rate constant K_1 relates to hydration rate at the very beginning (HR_o), i.e., HR at $t=t_o$

$$HR = \left.\frac{dM}{dt}\right|_{t=0} = \pm \frac{1}{K_1} \quad (4)$$

The Peleg capacity constant K_2 relates to maximum (or minimum) attainable moisture content. As $t \rightarrow \infty$, Eq. (2) gives the relation between equilibrium moisture content (M_e) and K_2:

$$\ln(1/K_1) = \ln(K_o) - \frac{E_a}{RT} \text{ or } \frac{1}{K_1} = K_o \exp(\frac{-E_a}{RT}) \quad (5)$$

where, M_e is the moisture content at the equilibrium or saturation moisture content (%, d.b.).

K_1 could be compared to a diffusion coefficient and the Arrhenius equation could be used to describe the temperature dependence of the reciprocal of Peleg's constant K_1 in the following manner:

$$\ln(1/K_1) = \ln(K_o) - \frac{E_a}{RT} \text{ or } \frac{1}{K_1} = K_o \exp(\frac{-E_a}{RT}) \quad (6)$$

where E_a, R, K_o and T are activation energy for the hydration process in $kJ.mol^{-1}$, universal gas constant in $8.314x10^{-3}$ kJ mol^{-1} K^{-1}, frequency factor or pre-exponential constant in % s^{-1}, the soaking temperatures (K), respectively.

When $\ln(1/K_1)$ is plotted against (1/T), a straight line with slope of $-E_a/R$ is obtained from which the activation energy can be calculated and sensitivity of the constant to temperature can be assessed.

Statistical Analysis

The effect of soaking time, temperature and wheat varieties on 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 $P \leq 0.05$ (SPSS Inc., version 16, USA). Non- linear regression analysis was performed on all soaking runs to estimate the parameters associated with considered models from the experimental data using SIGMA PLOT 10 (Jandel Scientific, San Francisco, USA) software. Correlation coefficient (R^2) was one of the main criteria for selecting the best model. In addition to coefficient of correlation, the goodness of fit was determined by root mean square error (RMSE) values.

Results and Discussion

Hydration Rates of Wheat Varieties during Soaking

The changes in the hydration rates (HR) versus hydration time (min) at different temperatures and for different wheat varieties are illustrated in Fig. 1. It is apparent that hydration rate significantly ($P \leq 0.05$) decreased with the soaking time for all wheat varieties. On the other hand, elevation of soaking temperature increased the rate of hydration of wheat varieties (Fig. 1) due to temperature effect of mass transfer and starch gelatinization. When the temperature increased from 25 to 50^{o}C during 30 min soaking, hydration rate (HR) increased from 1.06 to 2.70 (60.74% increase), 1.01 to 3.00 (66.23% increase), 1.34 to 3.68 (63.59% increase) and 1.66 to 4.07 kg water.(kg dry solid.min)$^{-1}$ (59.21% increase) for Zenit, BurgosBurgos, Dariyel and Karatopak wheat varieties, respectively. Similar increase in hydration rates were found in other soaking times.

When comparing the hydration rates of wheat varieties, Karatopak has been the highest and Zenit has been the lowest rate due to size and hardness of kernels (Figs. 1 and 2). Karatopak and Dariyel wheat varieties are shard wheats, are generally used in bread production. On the other hand, Zenit and BurgosBurgos are Durum wheat types and used for pasta, bulgur and semolina production. Also, mean diameters of Dariyel, Karatopak, Zenit and BurgosBurgos have been found as 3.86±0.19, 3.94±0.14, 4.13±0.13 and 4.21±0.18 mm, respectively. The smaller a seed is, the larger is its hydration due to the increased surface area and non-tight protein structure for hydration. Maskan [21] reported similar results. These findings were in the agreement with previous studies for some grains [22-24].

Primary Modelling of Time Dependence of Wheat Hydration

Peleg's model (Eq. 2), for describing the soaking behaviour of wheat kernels, was investigated. The equilibrium moisture content (M_e), Peleg's parameters (K_1, K_2), R^2 and RMSE of different wheat varieties (Zenit, BurgosBurgos, Dariyel and Karatopak) at different soaking temperatures (25, 30, 35, 40, 45 and 50°C) were evaluated by using the non-linear regression analysis (Eq. 2). Fig. 2 represent the variation of experimental and predicted hydration values using the Peleg's model with soaking time for different wheat varieties and temperatures (R^2=0.9805–0.9993).

The Peleg's constant K_1 is related to mass transfer rate and its reciprocal ($1/K_1$) can be linked to a diffusion coefficient [22], the values of K_1 decreased with increasing temperature, this corresponds to an increase in the initial hydration rate and $1/K_1$ values, significantly ($P \leq 0.05$) (Table-1). K_2 values also decreased while M_e values increased with increasing temperature (25-50 °C), significantly ($P \leq 0.05$). The order of magnitude of K_1 values of the present study for all wheat varieties are between 6.28 and 135.29 s. % (d.b.)$^{-1}$ for 25-50 °C temperature range. These values are comparable to those of 28.80-39.60 for chickpea between 25 and 42°C soaking [25], 11.52-147.96 for red kidney beans between 20 and 60 °C soaking [26], 58.79-120.16 for wheat at a temperature range of 20-70 °C [22], 3.42-61.56 for spring chickpea between 20 and 100 °C soaking [27] and 16.32-42.84 for teff grains between 20 and 50 °C soaking [28].

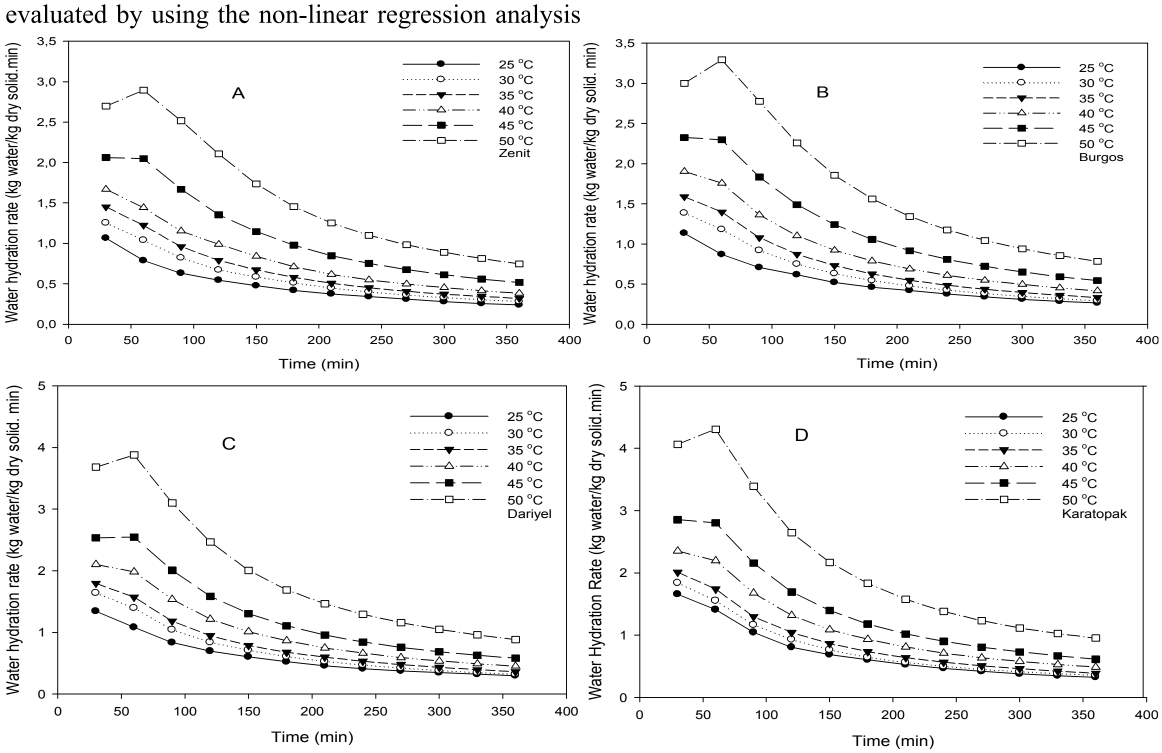

Fig. 1: Change in water hydration rates of Zenit (A), BurgosBurgos (B)), Dariyel (C) and Karatopak (D) wheat veriaties at different temperatures (25, 30, 35, 40, 45 and 50°C) during soaking.

Table-1: Summary of constants fitted in Peleg's equation for wheat veriaties obtained for different temperatures.

Temperature (°C)	Wheat Veriaties	M_e (%, d.b.)	K_1 (s % d.b.$^{-1}$)	$1/K_1$ (s^{-1}% d.b.)	K_2 (% d.b.$^{-1}$)	R^2	RMSE
25	Zenit	52.21 ±0.04^{a,1}	135.29 ±0.38^{f,4}	0.0074 ±0.007^{a,1}	0.0242 ±0.004^{f,4}	0.9965	0.016
	BurgosBurgos	56.94 ±0.07^{a,2}	101.32 ±0.26^{f,3}	0.0099 ±0.009^{a,2}	0.0213 ±0.002^{f,3}	0.9939	0.028
	Dariyel	59.74 ±0.10^{a,3}	70.20 ±0.17^{f,2}	0.0142 ±0.003^{a,3}	0.0202 ±0.004^{f,2}	0.9957	0.022
	Karatopak	60.22 ±0.18^{a,4}	35.30 ±0.16^{f,1}	0.0283 ±0.003^{a,4}	0.0201 ±0.006^{f,1}	0.9927	0.022
30	Zenit	57.19 ±0.08^{b,1}	72.69 ±0.55^{e,4}	0.0138 ±0.002^{b,1}	0.0216 ±0.009^{e,4}	0.9978	0.013
	BurgosBurgos	57.84 ±0.05^{b,2}	46.67 ±0.47^{e,3}	0.0214 ±0.004^{b,2}	0.0209 ±0.001^{e,3}	0.9984	0.010
	Dariyel	61.48 ±0.13^{b,3}	31.75 ±0.22^{e,2}	0.0315 ±0.011^{b,3}	0.0197 ±0.008^{e,2}	0.9983	0.011
	Karatopak	64.77 ±0.34^{b,4}	26.35 ±0.09^{e,1}	0.0380 ±0.008^{b,4}	0.0185 ±0.006^{e,1}	0.9945	0.018
35	Zenit	62.70 ±0.05^{c,1}	49.64 ±0.65^{d,4}	0.0201 ±0.001^{c,1}	0.0193 ±0.007^{d,4}	0.9993	0.007
	BurgosBurgos	64.63 ±0.09^{c,2}	32.71 ±0.33^{d,3}	0.0306 ±0.003^{c,2}	0.0183 ±0.008^{d,3}	0.9988	0.009
	Dariyel	69.20 ±0.21^{c,3}	26.90 ±0.15^{d,2}	0.0372 ±0.005^{c,3}	0.0170 ±0.003^{d,2}	0.9984	0.011
	Karatopak	73.14 ±0.04^{c,4}	21.12 ±0.09^{d,1}	0.0473 ±0.008^{c,4}	0.0163 ±0.008^{d,1}	0.9990	0.009
40	Zenit	76.25 ±0.10^{d,1}	36.86 ±0.72^{c,4}	0.0271 ±0.006^{d,1}	0.0153 ±0.010^{c,4}	0.9950	0.021
	BurgosBurgos	80.91 ±0.11^{d,2}	22.88 ±0.95^{c,3}	0.0437 ±0.005^{d,2}	0.0142 ±0.007^{c,3}	0.9995	0.006
	Dariyel	86.48 ±0.06^{d,3}	18.14 ±0.11^{c,2}	0.0551 ±0.002^{d,3}	0.0132 ±0.003^{c,2}	0.9987	0.011
	Karatopak	92.44 ±0.63^{d,4}	15.13 ±0.04^{c,1}	0.0661 ±0.008^{d,4}	0.0124 ±0.008^{c,1}	0.9992	0.008
45	Zenit	102.63 ±0.12^{e,1}	21.39 ±0.53^{b,4}	0.0468 ±0.003^{e,1}	0.0110 ±0.006^{b,4}	0.9956	0.024
	BurgosBurgos	108.03 ±0.07^{e,2}	17.38 ±0.77^{b,3}	0.0636 ±0.009^{e,2}	0.0102 ±0.010^{b,3}	0.9964	0.025
	Dariyel	111.73 ±0.22^{e,3}	12.96 ±0.02^{b,2}	0.0772 ±0.002^{e,3}	0.0100 ±0.011^{b,2}	0.9962	0.020
	Karatopak	117.05 ±0.18^{e,4}	10.58 ±0.31^{b,1}	0.0945 ±0.001^{e,4}	0.0096 ±0.012^{b,1}	0.9979	0.024
50	Zenit	149.78 ±0.06^{f,1}	12.86 ±0.98^{a,4}	0.0778 ±0.005^{f,1}	0.0072 ±0.013^{a,4}	0.9805	0.051
	BurgosBurgos	157.05 ±0.14^{f,2}	9.96 ±0.36^{a,3}	0.1004 ±0.001^{f,2}	0.0069 ±0.003^{a,3}	0.9827	0.035
	Dariyel	169.45 ±0.25^{f,3}	7.52 ±0.05^{a,2}	0.1330 ±0.005^{f,3}	0.0063 ±0.005^{a,2}	0.9950	0.023
	Karatopak	181.28 ±0.41^{f,4}	6.28 ±0.97^{a,1}	0.1592 ±0.003^{f,4}	0.0060 ±0.007^{a,1}	0.9933	0.026

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{1}^{n}\left[(M_{\exp} - M_{pre})/M_{\exp}\right]^2}$$ n: # of samples, M_{exp}: Experimental moisture content, M_{pre}: Predicted moisture content

$^{a\text{-}f \text{ and } 1\text{-}4}$ Indicate statistical differences between each row at constant temperatures and wheat varieties $\alpha = 0.05$.

When the soaking temperature increased from 25 to 50 °C $1/K_1$ values of Zenit, BurgosBurgos, Dariyel and Karatopak wheat varieties increased from 0.0074 to 0.0778 (90.49 % rise), from 0.0099 to 0.1004 (90.14 % rise), from 0.0142 to 0.1330 (89.32 % rise) and from 0.0283 to 0.1592 (82.22 % rise), respectively. The effect of temperature on soaking can easily be seen as to be about 80-90 % for a 35 °C temperature change. When comparing Zenit with BurgosBurgos, Dariyel and Karatopak wheats at 25 °C soaking temperature, it is clear that % increase in $1/K_1$ was 25.25, 47.89 and 73.85, respectively. BurgosBurgosAlso from Table-1, Fig. 1 and 2, one can seen that Zenit wheat is the least hydrated while Karatopak is the most hydrated one. Then, it can be concluded that Durum wheat types (Zenit and Burgos) are hydrated slower than Bread wheat types (Dariyel and Karatopak).

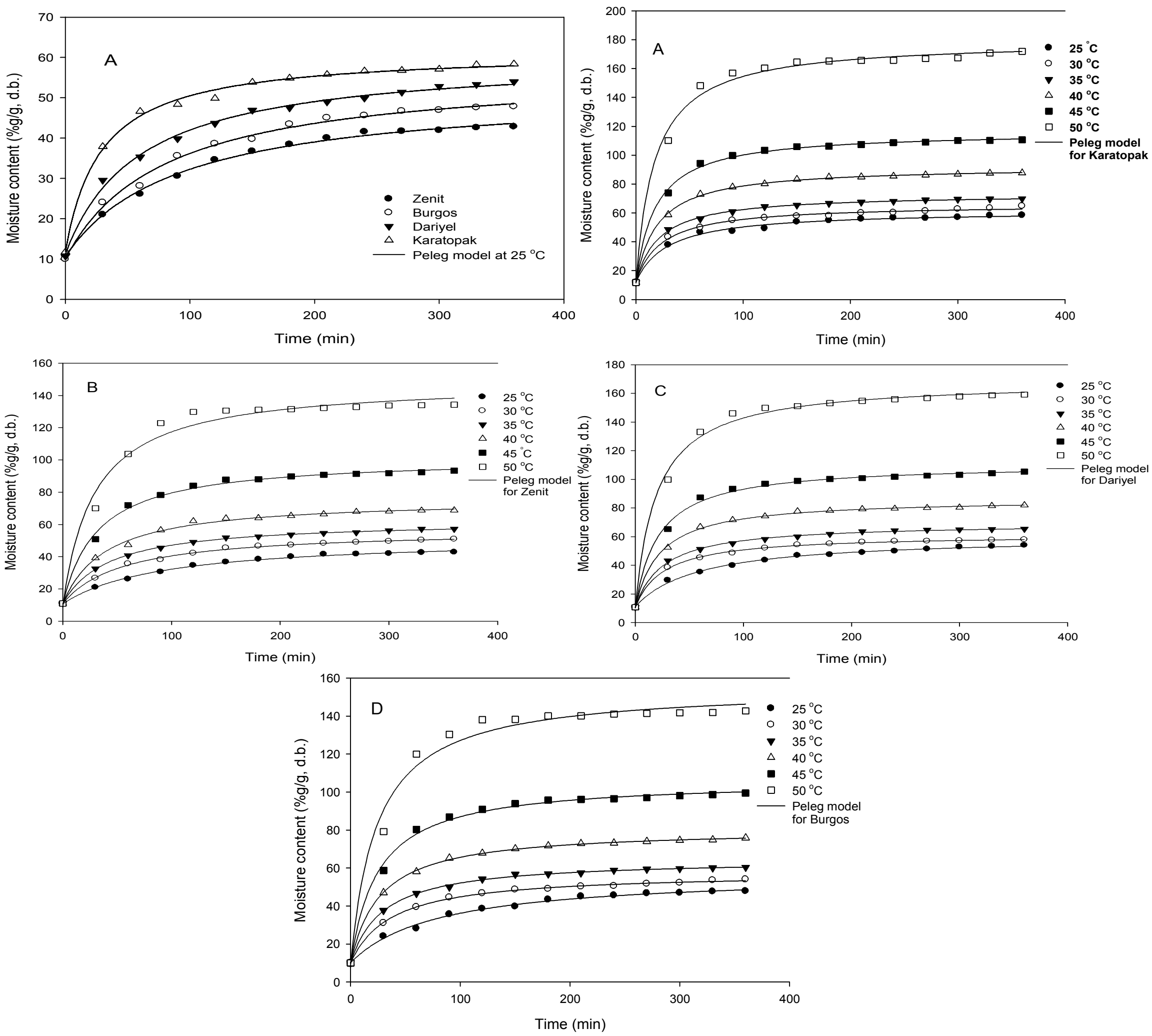

Fig. 2: Means of experimental and predicted moisture contents (%, d.b.) of different (Karatopak(A), Zenit(B), Dariyel(C) and Burgos(D)) wheat varieties at different temperatures (25, 30, 35, 40, 45 and 50°C) BurgosBurgos during soaking.

Similarly, K_2 decreased from 0.0242 to 0.0072 % d.b^{-1} for Zenit, from 0.0213 to 0.0069 % d.b^{-1} for Burgos, from 0.0202 to 0.0063 % (d.b.)$^{-1}$ for Dariyel and from 0.0201 to 0.0060 %. (d.b.)$^{-1}$ for Karatopak wheats as the temperature increased from 25 to 50 °C (Table-1). From the same table, one can conclude that K_2 values of Zenit wheat variety is the highest one while that of Karatopak was found the lowest. This clearly confirms the results that Zenit and Burgos which are Durum wheat types absorbed the least water or hydration rate and the dependence of K_2 on temperature indicated that different equilibrium moisture contents would be obtained for different soaking temperatures. As the soaking temperature increased, the equilibrium moisture content of the wheats increased (Table-1). It may be due to the enhanced plasticity of grain cells at high temperatures during soaking. Therefore, the grain imbibed more water at high temperatures (26).

In the study of Maskan [22] for wheat, K_2 values decreased from 0.0291 to 0.0076 % (d.b.)$^{-1}$ at a temperature range of 20-70 °C. Also, in the another study, K_2 of wheat (*Triticum aestivum*, Local name: Kalyan) decreased from 0.962 to 0.391 %. (d.b.)$^{-1}$, when the soaking temperature increased from 30 to 70 °C [24]. Other researchers have found similar results of K_2 for legumes and cereals [28]. The predicted M_e values, from this model are given in Table-1. Predicted equilibrium moisture contents of Zenit, Burgos, Dariyel and Karatopak wheats increased from 52.21 to 149.78, 56.94 to 157.05, 59.74 to 169.45 and 60.22 to 181.28 (%, d.b.) with increasing soaking temperature (25 to 50 °C), respectively ($P \leq 0.05$) (Table-1). Similar temperature dependence on M_e was found in the literature for rice [29], beans and chickpeas [30], sorghum [9], teff grain [28], amaranth grain [10] and wheat kernel [23].

The goodness of fits was predicted by RMSE and R^2. These values were found to be in the range of 0.006- 0.051 and 0.9805–0.9993 for a temperature range of 25–50 °C and different wheat varieties, respectively (Table-1). Peleg's model was found to be suitable for describing the hydration behavior of wheat kernels.

A General Model to Describe the Water Hydration of Wheat Varieties as a Function of Soaking Time and Temperature

The rate of water transfer in whole cereal and legume grains were found to be changing with temperature. Arrhenius plots of the natural logarithm of Peleg's constan ($1/K_1$) versus the inverse of T (K) for different wheat varieties were superposed in Fig. 3. The activation energies, E_a, are related to the slope of these graphs by linear regression of natural logarithm of $1/K_1$ values versus 1/T, and were found to be 39.94 (R^2=0.9889), 38.03 (R^2=0.9796), 36.25 (R^2=0.9720) and 29.54 kJ mol^{-1} (R^2=0.9668), for Zenit, Burgos, Dariyel and Karatopak, respectively. Higher the activation energy might be due to less the temperature sensitivity. Similar results for activation energy were found by some other researchers. Maskan [22] found the activation energy of wheat during hydration as to be 11.98 kJ mol^{-1}. The activation energies of wheat [23] and rice [31] were found as 34.26 and 34.17 kJ mol^{-1} during hydration, respectively. Similarly, the activation energy of teff grain was found by Sadik *et al*. [28] as 24.59 kJ mol^{-1}. These values of activation energies are comparable with those of present study. On the other hand, higher the activation energy indicates the slow hydration. Activation energy value of Karatopak wheat was the least one and this means that its hydration rate higher than others. It might be because of higher reaction rate during soaking.

The temperature dependence of K_2 can be attributed to the increasing equilibrium moisture content of wheats with temperature (Table-1) as mentioned in previous section. Fig. 3 shows linear relationships between K_2 and temperature with R^2 = 0.9866, 0.9604, 0.9671 and 0.9835 for Zenit, Burgos, Dariyel and Karatopak, respectively.

Using the temperature regression equations for K_1 and K_2 (Fig. 3), a general equation was proposed, based on the Peleg's equation, to model the hydration of different wheat varieties:

$$\text{Zenit } M_t = M_o + \frac{t}{1.72x10^{-5} * \exp(4804.05/T) + (0.13 - 0.000345 * T) * t} \quad (7)$$

$$\text{Burgos } M_t = M_o + \frac{t}{2.47x10^{-5} * \exp(4574.30/T) + (0.12 - 0.000309 * T) * t} \quad (8)$$

$$\text{Dariyel } M_t = M_o + \frac{t}{3.54x10^{-5} * \exp(4359.84/T) + (0.11 - 0.000293 * T) * t} \quad (9)$$

$$\text{Karatopak } M_t = M_o + \frac{t}{3.16x10^{-4} * \exp(3552.81/T) + (0.11 - 0.000289 * T) * t} \quad (10)$$

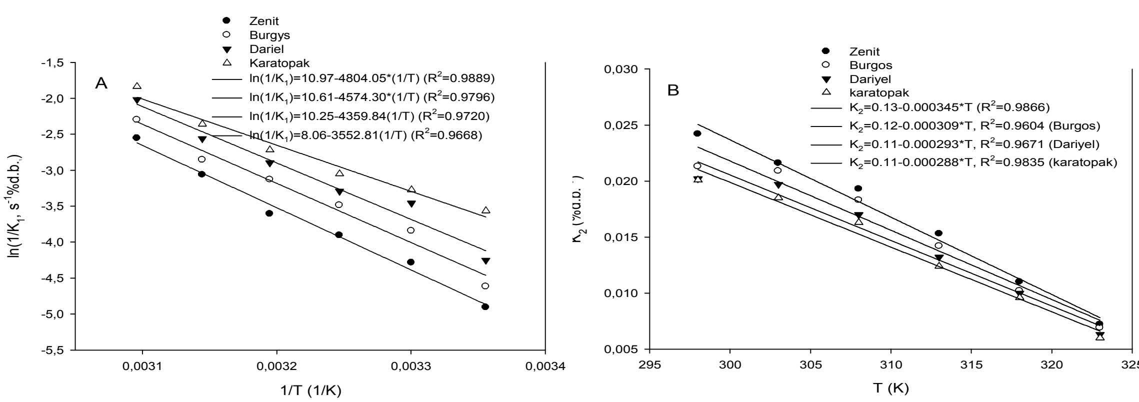

Fig. 3: Arhenius-type relationship between Peleg's constants K_1 and reciprocal absolute temperature (A), K_2 and absolute temperature (B) for different wheat variety.

Equations 7-10 can be used to find the moisture content of wheats during soaking at any time (seconds) and temperature (K) providing that M_o is known. Using these equations can be beneficial to wheat types during processing such as tempering and cooking. For example, at 25 ^{o}C soaking, to reach a moisture content of 40 (%, d.b.), soaking times from Equations 7-10 were calculated as 248, 213, 81 and 50 min for Zenit, Burgos, Dariyel and Karatopak wheat types, respectively.

Conclusions

Hydration rates significantly ($P \leq 0.05$) decreased with the soaking time for all wheat varieties. Increase in temperature resulted to 60.74, 66.23, 63.59 and 59.21% increase in hydration rates for Zenit, Burgos, Dariyel and Karatopak wheat varieties, respectively. Smaller and harder a seed is, the larger is its hydration due to the increased surface area and non-tight protein structure for hydration. Soaking temperature drastically affected the hydration of wheat varieties. Both Peleg's rate and capacity constants, K_1 and K_2 were significantly ($P \leq 0.05$) decreased with increasing temperature from 25 to 50^{o}C for all wheat varieties. The temperature dependence of K_1 and K_2 were adequately described by Arrhenius type relationship. The energies of activation of Zenit, Burgos, Dariyel and Karatopak wheats were found as 39.94, 38.03, 36.25 and 29.54 kJ mol^{-1}, respectively. Peleg's model adequately described the water uptake characteristics of wheats. A general model to describe the water uptake of wheat varieties as a function of soaking time, temperature and initial moisture content was developed. This model could be used by wheat processors to determine the amount of water absorbed during soaking at specific temperature for a known period of time.

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