Estimating moisture absorption kinetics of beans during soaking using mathematical models

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Abstract: In this paper, fourteen standard models were used to estimate the moisture ratio of three varieties of bean in Iran (Talash, Sadri and Mahali Khomein). The experiments were carried out using distilled water at three temperatures (5°C, 25°C and 45°C) and three replicates. The standard models of water absorption were fitted to the experimental data. To evaluate the models, three parameters: coefficient of determination (R^2), chi-square (χ^2) and root mean square error (*RMSE*) were used. The appropriate model was chosen based on maximum value of coefficient of determination and minimum value of chi-square and root mean square error. The effective moisture diffusivity coefficient of three varieties in each temperature was estimated by Fick's equation. The results demonstrated that the Weibull model is the most appropriate model for each variety in three experimental temperatures to estimate moisture ratio changes versus time in soaking. Thus, moisture ratio against soaking time was plotted in each case, using Weibull equation. The plotted curves of each variety of bean indicated that moisture ratio decreases with increasing in temperature. Besides that, the effective moisture diffusivity coefficient of three varieties increased in response to raise temperature from 5 - 45°C.

Keywords: water uptake, hydration, moisture ratio, moisture diffusivity, Weibull model

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1 Introduction

Pulses are economical sources of protein, energy, vitamins and minerals. Food legumes decreased incidence of several diseases, such as cancer, cardiovascular diseases, obesity and diabetes (Bhathena and Velasquez, 2002). Legumes contain relatively low quantities of the essential amino acid methionine, compared to whole eggs, dairy products or meat. This means that a smaller proportion of the plant proteins, compared to proteins from eggs or meat, may be used for the synthesis of protein in humans.

Bean (*Phaseolus vulgaris* L.) is an important member of legume group. In the new world, it is one of the main sources of protein and calories in the human nutrition (Graham and Ranalli, 1997). Unlike the chickpea, bean is a summer crop that needs warm climate to grow. Maturity is typically achieved within 55-60 days after planting. Thus, the area under bean is increasing on the planet earth (Hungria et al., 2000).

In Iran, beans have been widely grown as legumes production. High shelf life, the ease of transport, and the added value are attractive to farmers. Three famous varieties of bean are Talash, Sadri and Mahali khomein.

Grains soaking are usually used before dehulling and cooking, understanding water absorption of different seeds during soaking was considered by researchers. Grains in different conditions of soaking have different water absorption rate and water absorption capacity (Sopade et al., 1994). Understanding water absorption in legumes during soaking is important since it affects

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following processing operations and the quality of the final product (Turhan et al., 2002). The water absorption of seed during soaking mainly depends on soaking time and water temperature. Using warm water is a common method to decrease the soaking time, due to higher temperature increases moisture diffusivity leading to higher hydration rate (Kashaninejad et al., 2009).

Relationship between moisture content of seeds in soaking versus time has been expressed by different models (Shafaei and Msoumi, 2014b; Shafaei et al., 2014). Many theoretical and empirical approaches have been employed and occasionally empirical models were preferred because of their relative ease of use (Nussinovitch and Peleg, 1990; Singh and Kulshrestha, 1987). Also these models were used for dehydration of agricultural material (Rafiee et al., 2009). The most popular empirical and semi-empirical models, which have been used to model the water absorption process of agricultural products, are Weibull distribution function (Garcia-Pascual et al., 2006; Machado et al., 1999; Marabi et al., 2003), and exponential model (Gowen et al., 2007; Kashaninejad et al., 2007).

Three mathematical models (Weibull, Peleg and Exponential) for describing the water absorption kinetics of almond kernels were investigated by researchers. The studies on water immersion showed that Peleg and Weibull models were more accurate for describing the water absorption characteristics of almond kernels (Khazaei, 2008a). Water absorption of Tarom variety of rice was modeled by researchers. The results demonstrated that the best equation for predicting the behavior of water uptake was Page model. Also, the water uptake increased with increasing soaking temperature and soaking time. The effective moisture diffusivity coefficient during rice soaking (in range 25 - 70°C) was tested and reported as 5.58×10^{-11} to 3.57×10^{-10} m^2/s (Kashaninejad et al,. 2007). Other researchers reported that the effective moisture diffusivity coefficient varied from 8.376×10^{-12} to 2.22×10^{-12} m^2/s over the temperature range studied during sorghum soaking (Kashiri et al., 2010). Water absorption process during wood soaking in water was studied on three varieties of wood. Two models were considered to describe the kinetics: the Peleg and Khazaei model (based on the viscoelastic properties of materials). The soaking data were fitted to the Fick's model to determine moisture diffusivity coefficient. The calculated moisture diffusivity coefficients for Afra, Ojamlesh, and Roosi wood varieties were reported 1.38×10^{-3}, 3.71×10^{-4}, and 4.88×10^{-4} m^2/s, respectively (Khazaei, 2008b). Shafaei and masoumi (2013a) used the viscoelastic model for modeling water absorption of chickpea seeds during soaking. Also, using artificial neural network to predict water absorption of crop has been reported by many investigators (Kashaninejad et al., 2009; Shafaei and Masoumi, 2013c).

The objectives of the present study were to determine the best model for water absorption of three varieties of bean (Talash, Sadri and Mahali Khomein) to predict moisture ratio changes versus soaking time.

2 Materials and methods

2.1 Sample preparation

Each type of bean was prepared from Legumes seed collection center, agricultural organizations Khomein, Arak, Iran. Before testing, the broken seeds and external materials were removed. Seeds of bean were classified into three groups by size. In order to eliminate the effect of seed size on the soaking trials, medium-size grains were used. The initial moisture content of samples was determined by following ASAE S352.2 DEC97 method (ASAE, 1999).

2.2 Soaking tests

Experiments were conducted in distilled water at 5°C, 25°C and 45°C for different lengths of time. Before each experiment, containers and distilled water were kept at desired temperature for 5 to 12 hours to reach the same temperature.

Ten seeds of each variety were randomly chosen and weighed, then placed in glass beakers containing 200 ml distilled water for each duration,. Amount of water absorption by various seeds were determined 5, 10, 15, 30 and 60 minutes after immersion. The tests followed at intervals of one hour toward gelatinized seeds. After reaching a predetermined soaking time, the samples were drained on a paper and the excess water eliminated with adsorbent paper, and the soaked sample were weighed. A digital chronometer and an electronic weighing balance (AND, Model GF400, Japan) reading to 0.001 gram were used to control soaking duration and measure weight of sample before and after soaking. Tests were done in three replicates. The water absorption capacity was determined by following equation (McWatters et al., 2002):

$$W_a = \frac{W_f - W_i}{W_i} \times 100 \tag{1}$$

where, W_a is water absorption (d. b. %); W_f is weight of seeds after immersion (g) and W_i is weight of seed before immersion (g).

According to Peleg (1988), points were intentionally chosen from recorded data, as extremely small weight gains at the beginning of soaking were not included. Also, data with increasing losses of soluble solids of more than 1% of the initial samples mass were not included. Therefore, at each stage, amount of solid material dissolved in water was controlled by measuring density of distilled water and drained water in each experiment.

2.3 Evaluation of models

In the most studies, water absorption and drying model are achieved based on the moisture ratio (*MR*), due to fewer data dispersion and optimize data (Akpinar et al., 2003).

$$MR = \frac{M_c - M_e}{M_o - M_e} \tag{2}$$

where, MR is moisture ratio at time t; M_o is initial moisture content of seeds that is constant. (d. b. %); M_e is saturated moisture (d. b. %) and M_c is moisture content at time t (d. b. %). The most common water absorption models for seeds, often used by researchers, are shown in Table 1 (Rafiee et al., 2009; Khazaei, 2008a). The parameters of these models for each sample in water absorption during soaking were estimated using Matlab software.

To evaluate the models, three parameters namely coefficient of determination (R^2), Chi-square ($\chi 2$) and root mean square error (*RMSE*) were determined based on Equations (3), (4) and (5), respectively (Garcia-Pascual et al., 2006; Giner and Mascheroni, 2002; Shafaei and Masoumi, 2013b).

$$R^2 = \frac{\sum_{i=1}^{N}(M_{\exp,i} - M_{\exp ave})^2 - \sum_{i=1}^{N}(M_{\exp,i} - M_{pre,i})^2}{\sum_{i=1}^{N}(M_{\exp,i} - M_{\exp ave})^2} \tag{3}$$

$$x^2 = \frac{\sum_{i=1}^{N}(M_{\exp,i} - M_{pre,i})^2}{N - n} \tag{4}$$

$$RMSE = \left[\frac{1}{N}\sum_{I=1}^{N}(M_{pre,i} - M_{\exp,i})^2\right]^{1/2} \tag{5}$$

where, $M_{\exp,i}$ is the ith experimentally observed moisture content (d. b. %); $M_{\mathrm{pre},i}$ the ith predicted moisture content (d. b. %); $M_{\exp\ \mathrm{ave}}$ is average moisture content observed (d. b. %); N is number of data and n is number of constant coefficient of model. Regression index in each temperature were calculated and compared together. The best model was chosen based on maximum value of coefficient of determination and minimum value of chi-square and root mean square error.

2.4 Calculating the effective moisture diffusivity coefficient

Previous studies have been shown that moisture transfer during water absorption of food occurs mainly through the distribution process. Fick's second law can express this distribution using Equation (6) (Doymaz and Pala, 2003):

$$\frac{\partial M}{\partial t} = \nabla^2 (D_{eff} M) \tag{6}$$

where, M is moisture content at time t (d. b. %); D_{eef} is effective moisture diffusivity coefficient (m^2/s). Equation (6) can be rewritten for spherical coordinates as Equation (7):

$$\frac{\partial M}{\partial t} = \left(D_{eff} \left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r} \right) \right) \tag{7}$$

While, r is grains spherical radius. The algebraic solution of Equation (7) can be written as Equation (8):

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D_{eff} n^2 \pi^2}{r^2} t\right) \tag{8}$$

By ignoring higher-order terms that contribute no significant change in the results, the first term of Equation (8) can be written as Equation (9):

$$MR = \frac{6}{\pi^2}\exp(\frac{-D_{eff}\pi^2}{r^2}t) \qquad (9)$$

Logarithm of both sides of Equation (9) can be presented as:

$$Ln(MR) = Ln\left(\frac{6}{\pi^2}\right) - \frac{D_{eff}\pi^2}{r^2}t \qquad (10)$$

A straight line with a slope (*S*) is obtained, by plotting the natural logarithm of the data collected during the soaking test versus time; which is equal to coefficient of (*t*) in Equation (10). The effective diffusion coefficient of moisture can be presented using Equation (11). This method has been used by many researchers (Ozbek and Dadali, 2007; Wang et al., 2007).

$$S = \frac{D_{eff}\pi^2}{r^2} \qquad (11)$$

2.5 Seed Equivalent Radius

The seeds Equivalent radius (*r*) was determined by measuring the average volume of seeds of each variety and using the volume of the equivalent sphere of seeds (Shafaei and Masoumi, 2014b).

2.6 Measuring the seeds volume

In order to determine seeds volume, 50 seeds of each variety were selected randomly. To measure volume of each type of seed, Equation (12) was used (Mohsenin, 1978):

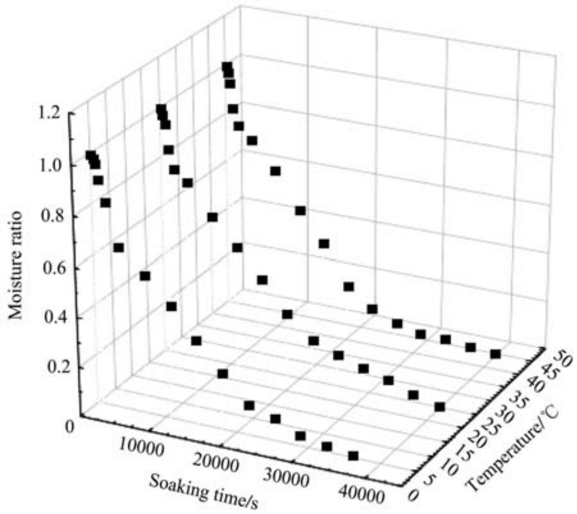
$$V_s = \frac{(W_{pf} - W_p) - (W_{pfs} - W_{ps})}{\rho_f} \qquad (12)$$

Where V_s volume of solid particles or seeds (m^3); W_p is empty weight of pycnometer (g); W_{pf} is weight of filled pycnometer with fluid (g); W_{ps} is weight of pycnometer containing seeds (g); W_{pfs} is weight of pycnometer containing seeds and fluid (g); ρ_f is density of fluid (g/m^3). Ethanol was used as pycnometer fluid because water can penetrate into seeds and is not appropriate as fluid in this study.

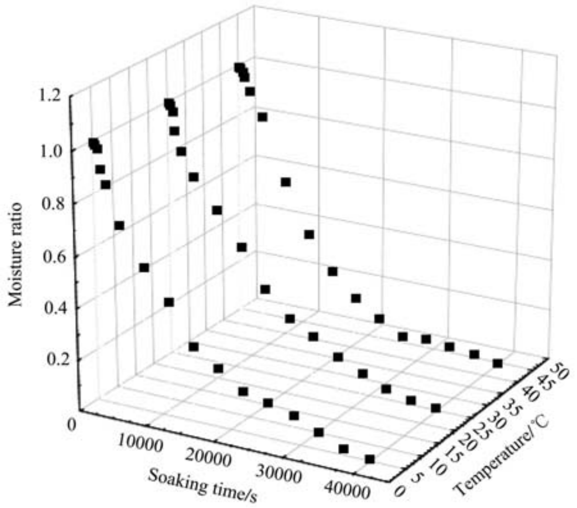
3 Results and discussion

3. 1 Moisture ratio curves

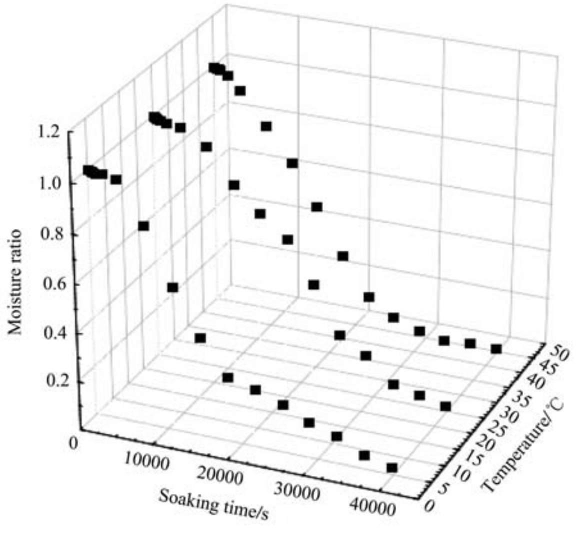
Values of initial moisture content of bean were 7.16%, 7.41% and 7.36% dry basis for Talash, Sadri and Mahali Khomein respectively. They were not significantly difference (P>0.05). The decreasing moisture ratio of samples during soaking time is shown in Figure 1.



a. Talash



b. Sadri



c. Mahali Khomein

Figure 1 Moisture ratio curve of bean type during soaking

Moisture ratio curves show the rate of water absorption increased with increasing temperature, thus with increasing temperature moisture ratio decreased and approached to zero rapidly. In higher water temperature, it required longer time for samples to reach moisture saturation point, due to the increase of propagation velocity of water in seeds. Higher temperatures result to the grain gelatinization which leads to the expansion and softening of grain. Therefore, more pores and cracks opened and finally transmission of water through the seed were increased (Ranjbari et al., 2011). Thus, high temperatures can cause the seeds to soften and expand. The moisture absorption rate increases, if the soaking temperature is closer to gelatinization temperature of seed. Therefore, use of higher temperatures on short time has affected to reach equilibrium moisture in shorter time during soaking. Similar results have been reported for various legumes such as chickpea, cow chickpea, soybean, and chick peanuts (Sopade and Kaimur, 1999; Shafaei and Masoumi, 2014a; Sopade and Obekpa, 1990; Turhan et al, 2002; Pan and Tangratanavalee, 2003).

The results indicated that, water absorption values were significantly different (P<0.05) for different varieties of bean due to the difference in the morphological and physiological difference. Talash variety is the most popular variety of bean which is cultivated in warm and dry areas. Despite Talash, Sadri variety is an improved cultivar which is why it is cultivated in cold climate (Beyzaei et al., 2012) and Mahali Khomein variety is a genetically modified variety based on Kheomin (Markazi- Iran) region.

3.2 Selecting an appropriate model to predict moisture ratio

Fourteen standard models of water absorption were fitted to the experimental data in the present study, and are reported in Table 1. The values of R^2, χ^2 and $RMSE$ corresponding to the models, which described moisture changes during soaking, are listed (Table 2, 3 and 4) in case of varieties of bean. The appropriate model was chosen based on maximum value of coefficient of determination (R^2) and minimum value of chi-square (χ^2) and root mean square error ($RMSE$). The results show that, Weibull model is the most appropriate for three varieties in three experimental temperatures to predict moisture ratio changes versus time in soaking.

Table 1 Regression models was used in modeling of moisture ratio

Model	Equation
Newton	$MR=\exp(-kt)$
Page	$MR=\exp(-kt^n)$
Modified Page	$MR=\exp[-(kt)^n]$
Henderson and Pabis	$MR=a\exp(-kt)$
Modified Henderson and Pabis	$MR=a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$
Logarithmic	$MR=a\exp(-kt)+c$
Binomial	$MR=a\exp(-k_0t)+b\exp(-k_1t)$
Modified Binomial	$MR=a\exp(-kt)+b\exp(-gt)+c$
Binomial exponential	$MR=a\exp(-kt)+\exp(-mt)$
Wang and Sang	$MR=1+at+bt^2$
Diffusion	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$
Midili et al.	$MR=a\exp(-kt^n)+bt$
Werma et al.	$MR=a\exp(-kt)+(1-a)\exp(-gt)$
Weibull	$MR=\exp(-(t/\beta)^\alpha)$

Table 2 Average statistical index of fitted models of soaking at three different water temperatures of Talash variety

Model	R^2	$\chi2\times10^{-2}$	$RMSE$
Newton	0.727	0.108	0.1047
Page	0.942	0.111	0.1054
Modified Page	0.964	0.095	0.0972
Henderson and Pabis	0.961	0.096	0.1000
Modified Henderson and Pabis	0.977	0.105	0.1067
Logarithmic	0.897	0.143	0.1139
Binomial	0.964	0.105	0.1040
Modified Binomial	0.987	0.092	0.1006
Binomial exponential	0.964	0.094	0.0985
Wang and Sang	0.962	0.099	0.0957
Diffusion	0.955	0.106	0.1039
Midili et al.	0.990	0.080	0.0912
Werma et al.	0.958	0.092	0.0927
Weibull	0.995	0.050	0.1299

Table 3 Average statistical index of fitted models of soaking at three different water temperatures of Sadri variety

Model	R^2	$\chi2\times10^{-2}$	$RMSE$
Newton	0.843	0.110	0.1047
Page	0.966	0.111	0.1054
Modified Page	0.952	0.095	0.0972
Henderson and Pabis	0.948	0.096	0.1000
Modified Henderson and Pabis	0.969	0.105	0.1067
Logarithmic	0.983	0.143	0.1139
Binomial	0.962	0.105	0.1040
Modified Binomial	0.987	0.092	0.1006
Binomial exponential	0.954	0.094	0.0985
Wang and Sang	0.983	0.090	0.0957
Diffusion	0.958	0.106	0.1040
Midili et al.	0.935	0.080	0.0912
Werma et al.	0.950	0.092	0.0927
Weibull	0.989	0.050	0.1199

The coefficients of Weibull model of each variety at different temperatures are shown in Table 5. The moisture ratio versus time was plotted for varieties, using

Weibull model in Figure 2. Some researchers reported Binomial model is appropriate model for hydration of chickpea seeds (Shafaei and Masoumi, 2014b).

Table 4 Average statistical index of fitted models of soaking at three different water temperatures of Mahali Khomein variety

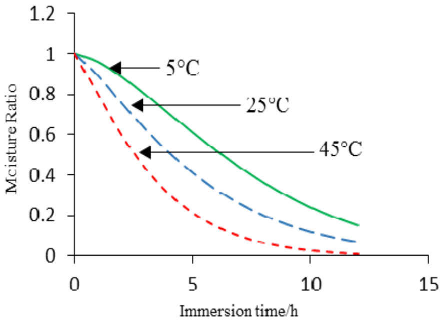
Model	R^2	$\chi 2\times10^{-2}$	*RMSE*
Newton	0.635	0.361	0.1682
Page	0.993	0.101	0.0688
Modified Page	0.985	0.115	0.0741
Henderson and Pabis	0.960	0.126	0.0793
Modified Henderson and Pabis	0.969	0.155	0.0905
Logarithmic	0.985	0.111	0.0738
Binomial	0.961	0.137	0.0776
Modified Binomial	0.992	0.135	0.0845
Binomial exponential	0.960	0.447	0.0818
Wang and Sang	0.975	0.114	0.0769
Diffusion	0.986	0.111	0.0733
Midili et al.	0.992	0.109	0.0723
Werma et al.	0.946	0.142	0.0892
Weibull	0.993	0.101	0.0688

Table 5 The coefficient of Weibull model of each bean variety

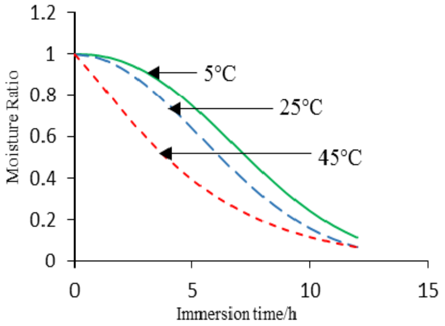
Variety	Temperature/°C	α/hr*%$^{-1}$	β/%$^{-1}$
Talash	5	1.533	7.934
	25	1.259	5.486
	45	1.199	3.486
Sadri	5	2.298	8.589
	25	2.034	7.447
	45	1.094	5.302
Mahali Khomein	5	2.078	11.64
	25	1.885	8.593
	45	1.686	6.531

3.3 Consequence of temperature on effective moisture diffusivity coefficient

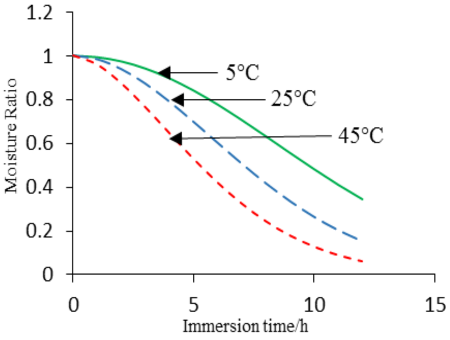
The natural logarithm of the moisture ratio data versus time was plotted during soaking tests of Talash variety and it is shown in Figure 3. The slope of the lines expressed the effective moisture diffusivity coefficient based on Fick's equation. Analogizing line slope indicated that, by increasing water temperature the effective moisture diffusivity coefficient increased that they were significant difference (P<0.05). With increasing water temperature of soaking, seeds lead to higher moisture content in short time. Thus, volume and surface area of seeds increase faster leading to an increase in the effective moisture diffusivity. Similar results were obtained for the other varieties in this study. The effective moisture diffusivity coefficient of seeds in three experiment temperatures was reported in Table 6. Some researchers reported similar results for corn seeds in a soaking process (Kashiri et al., 2010).



a. Talash



b. Sadri



c. Mahali Khomein

Figure 2 Moisture Ratio Weibull model of bean during immersion

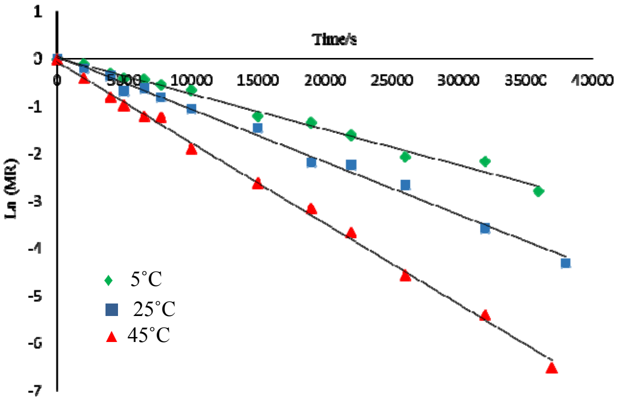


Figure 3 Calculating the effective moisture diffusivity coefficient of Talash variety during soaking

Table 6 Values of effective moisture diffusivity coefficient of bean varieties in soaking

Variety	Temperature/°C	The effective moisture diffusivity coefficient (m^2/s) $\times 10^{-6}$
Talash	5	1.778
	25	3.952
	45	5.141
Sadri	5	1.627
	25	3.651
	45	4.932
Mahali Khomein	5	1.886
	25	3.162
	45	5.354

4 Conclusions

The summary of results obtained in the present experiment indicated that all recommended models by researchers were fitted to bean soaking data are appropriate. The Weibull model was proper for predicting moisture ratio of different types of bean during soaking and could be applied to estimate the moisture content at given soaking time and temperature within the experimental condition considered. The corresponding plotted curves of each variety of bean in three experimental temperatures demonstrated that moisture ratio decreased with increasing temperature; and the effective moisture diffusivity coefficient increased with increasing water temperature according to Fick's equation.

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