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Water absorption of black chickpea using a finite difference method

Nesa Dibagar[1,2*], Stefan Jan Kowalski[2], Reza Amiri Chayjan[1]

[1] Bu-Ali Sina University, Faculty of Agriculture, Department of Biosystems Engineering, 6517833131, Hamedan, Iran
[2] Poznan University of Technology, Institute of Technology and Chemical Engineering, Department of Process Engineering, Berdychowo 4, 60-965 Poznan, Poland

Evaluation of moisture absorption in foodstuffs such as black chickpea is an important stage for skinning and cropping practices. Water uptake process of black chickpea was discussed through normal soaking in four temperature levels of 20, 35, 50 and 65 °C for 18 hours, and then the hydration kinetics was predicted by Peleg's model and finite difference strategy. Model results showed that with increasing soaking temperature from 20 to 65 °C, Peleg's rate and Peleg's capacity constant reduced from 13.368×10^{-2} to 5.664×10^{-2} and 9.231×10^{-3} to 9.138×10^{-3}, respectively. Based on key results, a rise in the medium temperature caused an increase in the diffusion coefficient from 5.24×10^{-10} m^2/s to 4.36×10^{-9} m^2/s, as well. Modelling of moisture absorption of black chickpea was also performed employing finite difference strategy. Comparing the experimental results with those obtained from the analytical solution of the theoretical models revealed a good agreement between predicted and experimental data. Peleg's model and finite difference technique revealed their predictive function the best at the temperature of 65 °C.

Keywords: water absorption, black chickpea, finite difference method, Peleg's model

1. INTRODUCTION

Chickpea is categorised among adaptable and trustworthy foodstuffs dominating the food sector due to its adaptable and reliable source of protein. It is one of the most consumed legumes in the world, originally allocated to the some tropical and subtropical countries of the Middle East (Singh, 2010) containing minerals, vitamins, fibre, carbohydrates, and high energetic values. Besides better availability of iron, it differs from other legumes due to its low content of anti-nutritional substances and high digestibility (Pramiu et al., 2015; Yildirim et al., 2012). There are two categories for peas based on the size including Kabuli or coarse (Macroperma) and Deci or granular peas (Microperma). The Kabuli type has thin, white seed coat while Desi type has a small thick, coloured seed coat and both of them can be consumed fresh or baked, and must be hydrated in both cases (Ghribi et al., 2015; Shafaei and Masoumi, 2014).

Black chickpea is from the Deci or local classification; its seeds are used as cotyledon after splitting process (Copeland and McDonald, 2012). Different factors such as the original amount of moisture content, variety of the seeds, soaking duration, and temperature and acidity level of the soaking medium determine the amount of water absorbed by seeds during soaking (Montanuci et al., 2015). On the other hand, the agricultural-based kernels consist of three major parts, namely, seed coat, endosperm, and embryo, which

* Corresponding author, e-mail: n.dibaga93@gmail.com

cause the kernel to be non-uniform (Shafaei et al., 2016). Therefore, many researchers focus to understand the water absorption characteristics of different seeds during soaking since soaking of grains is practically important, which affects the following processing operations such as dehulling, cooking, and subsequently product final quality. Different soaking conditions yield in different water absorption rate and capacity constants of grains, as well (Singh, 2010; Shafaei and Masoumi, 2014).

Water absorption is a phenomenon that can be explained with models based on the concepts of chemical kinetics, as developed by Peleg (1988), and by analytic expressions derived from the Fick's second law of diffusion (Shafaei and Masoumi, 2013b and 2013c).

Due to the relative ease of use, many theoretical approaches can be employed to express the relationship between moisture content of seeds in soaking and time. Thus, from a processing and engineering point of view, modelling of soaking process helps to know how one can predict the soaking time under given conditions, how fast the absorption of water can be accomplished, and how it will be influenced by processing variables. Hence, quantitative data on the effect of processing variables are necessary for practical applications to optimise and characterise the soaking conditions, design food processing equipment, and predict water absorption as a function of time and temperature (Montanuci et al., 2015).

Modelling provides a variety of engineering and scientific tasks to study about fundamental physical processes that occur during thermal process for design, optimisation, and analysis of laboratory and field experiments (Kowalski and Pawłowski, 2010). Most of the applied models are based on the Fick's second law of moisture diffusion to describe the soaking process (Galvez et al., 2009). Among the recommended empirical equations, Peleg's model is easier and intuitive, applied for a wide range of foodstuffs and legumes. Another equation, which is commonly used to model chemical, enzymatic or microbiological changes in the food engineering, is Weibull's equation, which is very simple and flexible for parameter estimation. Numerical methods are usually simpler and more usable than analytical ones in solving engineering problems, even in cases when there is no possibility to use analytical techniques to solve engineering problems (Kowalski and Mierzwa, 2013). Applying numerical methods is prevalent to model foodstuffs and solving partial differential equations. In this way, the numerical modelling methodologies such as finite element method (FEM) and finite difference method (FDM) offer an alternative tool for conventional approaches to analyse various processes (Kowalski and Perré, 2007; Kashiri et al., 2010).

Some researchers applied the viscoelastic model to discuss water uptake characteristics of beans during immersion and they found that the model has enough ability to predict the moisture content of seeds during soaking (Shafaei and Masoumi, 2013a). Viscoelastic model can be also utilised for drying progress, which can lead to negative values of constant coefficient.

In several studies, crops behaviour, moisture ratio and diffusion coefficient were evaluated and measured during soaking process. Prasad et al. (2010) have conducted a detailed study on the temperature dependency of hydration kinetics in chickpea. A comparison between the theoretical and developed models of Peleg, Weibull and exponential with experimental data highlighted an excellent closeness between experimental data and Peleg's hydration model. In another study, moisture absorption kinetics of pea was evaluated using Peleg's model and finite difference technique. Results indicated that when temperature increased the moisture diffusion coefficient of pea increased, as well (Sabapathy, 2005). Kashiri et al. (2010) investigated the moisture absorption kinetics of sorghum using Peleg's model. It was argued that a decrease in the Peleg's rate and capacity constant occurred with increase in the soaking temperature (Kashiri et al., 2010). Moisture diffusion coefficient of some crops, such as lentils, beans, and peas was evaluated in another study and reported within the ranges of 3.53×10^{-10} to 1.33×10^{-9}, 4.35×10^{-11} to 3.79×10^{-9} and 9.71×10^{-11} to 5.98×10^{-10} m^2/s, respectively (Gurtas et al., 2001). Moisture absorption models during soaking have attracted considerable attention in other products such as oak (Moreira et al., 2008), tomato (Cunningham et al., 2008), aloe vera (Galvez et al., 2009), nut (Ranjbari et al., 2010), mushroom cap (Segovia et al., 2010) and chickpea (Turhan et al., 2008).

As far as we know, there is no information about the behaviour of black chickpea during soaking; therefore, the aim of this work is to deepen on the study of the uptake kinetics to evaluate the effect of temperature on the black chickpea moisture absorption ratio during soaking process and process modelling using empirical model (Peleg's model) and finite difference method (FDM).

2. MATERIALS AND METHODS

2.1. Sample preparation

Iranian cultivar of black chickpea was selected and provided from legume seed collection center, Hamedan, Iran, to ensure genetic purity. To avoid moisture exchange with the surroundings and mold development, all samples were put in airtight double-layer bags and kept in the refrigerator at 4 ± 0.5 °C for later analysis. Before experiments, the seeds were manually cleaned and separated from impurities, broken and damaged seeds. To determine the physical properties of chickpea, samples of approximately 100 g were selected randomly. For each grain, three basic dimensions (length, width and thickness) were measured using a digital caliper (General Ultratech EDF-6, USA) with a precision of 0.01 mm. The geometric mean diameter (GMD) and sphericity (φ) were calculated using the following equations (Mohsenin, 1987):

$$GMD = (abc)^{\frac{1}{3}} \tag{1}$$

$$\varphi = \frac{GMD}{a} \tag{2}$$

The initial moisture content of black chickpea grains was determined in four replicates using standard method of oven drying by heating 10 g of the sample in the oven at 130 °C for 24 hours (Shafaei and Masoumi, 2013a), based on the following equation (Pramiu et al., 2015):

$$MC = \frac{M - M_e}{M_e} \times 100 \tag{3}$$

2.2. Determination of water absorption

The container and distilled water were kept in the desired temperature for a few hours to reach the studied temperature before each experiment. Afterwards, to determine the water absorption kinetics of black chickpea, 10 g of samples was weighted in a container with the volume of 250 ml filling with 150 ml of distilled water. The water container was placed inside the temperature controller device. Soaking process continued in four temperature levels of 20, 35, 50 and 65 °C up to 18 hours. During experiments, relative humidity and temperature of ambient air were recorded by a hygrometer with an accuracy of 3% for reading the air relative humidity and 0.1 °C for reading the temperature (Lutron TM-903, Taiwan). Figure 1 shows the time evolution of the ambient air temperature and relative humidity during experiments.

During the soaking at each temperature, the samples were periodically released out of the water after 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 14 and 18 hours (Alvarez et al., 2019; Miano et al., 2018), and the excess moisture of seeds was dried using a paper towel, then they were weighed using a digital balance (0.01 g, Max 1000 g; model 2354, Sartorius, Germany) within 10 s and placed again into the water to continue the hydration process (Gurtas et al., 2001; Kashiri et al., 2010). An LCD Digital Stopwatch (23011 Supelco) with an accuracy of 0.01 s was applied to record soaking duration. Soaking process continued until two consecutive readings were made with no significant mass gain, indicating achievement of the equilibrium moisture content. For each time interval, moisture content was calculated using the difference between

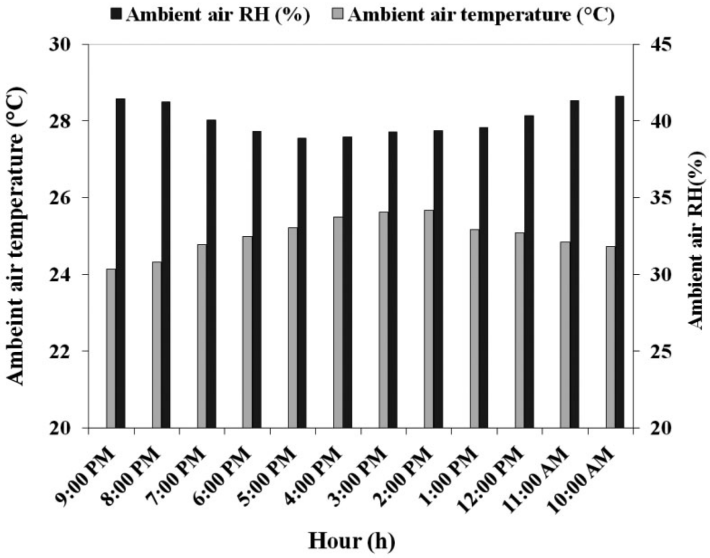

Fig. 1. Time evolution of ambient air temperature and relative humidity

weights of samples just before and after soaking (weight of absorbed water). All tests were performed in triplicate to reduce the error.

Two equations are proposed to study water absorption in food products and investigate their accuracy in predicting water uptake. Peleg's model is given by an empirical equation, which is widely used to simulate crop soaking process (Kashiri et al., 2010; Peleg, 1988). The basic form of Peleg's model is shown by Eq. (4), and can be also written in form of Eq. (5).

$$M_t = M_0 \pm \frac{t}{K_1 + K_2 t} \tag{4}$$

$$\frac{t}{M_t - M_0} = K_1 + K_2 t \tag{5}$$

In Eq. (4), sign (+) is applied for moisture absorption process while sign (−) in the case of moisture desorption. Water absorption rate of the product is dependent upon the Peleg's rate constant expressed by the following equation:

$$R_0 = \left.\frac{dM}{dt}\right|_{t\to 0} = \frac{1}{K_1} \tag{6}$$

Peleg's capacity constant is associated with maximum moisture is available for the sample, which is explained by the following equation for an infinite time:

$$\left.M\right|_{t\to\infty} = M_e = M_0 \pm \left(\frac{1}{K_2}\right) \tag{7}$$

The Fick's second law evaluates the moisture diffusion coefficients of spherical and symmetry products in one-dimensional cases as follow (Gurtas et al., 2001):

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{n^2 Dt}{R^2}\right] \tag{8}$$

Since the average sphericity of black chickpea was 83.55%, Eq. (8) was used to evaluate the moisture diffusion coefficient of this product. The following equation was employed to calculate the moisture ratio (Gurtas et al., 2001).

$$MR = \frac{M - M_e}{M_o - M_e} \tag{9}$$

Finite difference strategy was applied to solve mathematical equations in MATLAB 2010 software. Several parameters such as soaking time, initial moisture content of the samples, soaking temperature, and product geometry could affect the final moisture content of the product (Pramiu et al., 2015). Finding the optimal point and combination of these parameters is possible using repeated experiments by computer models and confirmed by experimental data (Kowalski, 2012; Kowalski and Mierzwa, 2013).

In this study, the modelling assumptions were as follows:

1. Black chickpea is considered to be a sphere with respect to its physical properties.
2. One dimensional moisture transfer occurs in radial direction and in unstable conditions.
3. Initial moisture distribution is assumed uniform.
4. Black chickpeas were assumed homogeneous.
5. Slope of the sample moisture content was considered time-dependent.

According to these assumptions, a mathematical model of chickpea moisture transfer was studied.

2.3. Initial and boundary conditions

General solution of the equation proposed for moisture diffusion coefficient of different initial and boundary conditions can be investigated. If moisture transfer is considered radial, moisture diffusion equation for a constant diffusion coefficient is defined in a spherical system as follows (Crank, 1975):

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial R^2} + \frac{2}{R}\frac{\partial M}{\partial R}\right) \tag{10}$$

Boundary conditions for the centre of grain ($R = 0$) and for the surface ($R = R_0$) are defined as a one-dimensional system. The initial distribution of the moisture content is assumed uniform and equal. Initial and boundary conditions for moisture transfer were considered as follow:

$$M(R, 0) = M_0 \tag{11}$$

$$\left.\frac{\partial M}{\partial t}\right|_{R=0} = 0 \tag{12}$$

Convective mass transfer was supposed to be insignificant and negligible, since there is no external force to improve the soaking process. Surface moisture content of the samples was considered in instantaneous equilibrium with the environment (Huang and Mittal, 1995; Williams and Mittal, 1999; Sabapathy, 2005).

$$M_{R=R_0} = M_e \tag{13}$$

2.4. Dimensionless relations

Moisture ratio (MR) expressed by Eq. (9) can be replaced by a dimensionless parameter of moisture concentration (M), and a radial length (ψ) can be used to make the following relations dimensionless as follow:

$$MR = M \tag{14}$$

$$\psi = \frac{r}{R} \tag{15}$$

Mass transfer equation when using the dimensionless parameters is now expressed as follows:

$$\frac{\partial M}{\partial t} = \frac{D}{R^2}\left(\frac{\partial^2 M}{\partial \psi^2} + \frac{2}{\psi}\frac{\partial M}{\partial \psi}\right) \tag{16}$$

$$M(\psi, 0) = 1 \tag{17}$$

$$\left.\frac{\partial M}{\partial \psi}\right|_{\psi=0} = 0 \tag{18}$$

2.5. Finite difference equations for black chickpea

In order to apply the finite difference technique one-dimensionally, the sphere geometry of black chickpea consisted of ten concentric layers with the same thicknesses for moisture modelling during soaking. A total of 11 nodes were considered, the first node was specified on the centre of sphere, the 11$^{\text{th}}$ considered on the surface, and others were between them. Each node was studied as the representative of the self-layer. Differential equations, which were solved automatically by the software, are listed below:

Using the boundary conditions for zero node (in the geometric centre):

$$\frac{dM_0}{dt} = 300\frac{D}{R^2}(M_1 - M_0) \tag{19}$$

For nodes 1 to 9 using the central difference method:

$$\left.\frac{dM_i}{dt}\right|_{i=1-9} = \frac{D}{R^2}\left(\frac{2}{\psi_i}\frac{M_{i+1} - M_{i-1}}{2\Delta\psi} + \frac{M_{i+1} - 2M_i + M_{i-1}}{(\Delta\psi)^2}\right) \tag{20}$$

$$\left.\frac{dM_i}{dt}\right|_{i=1-9} = \frac{100D}{R^2}\left(\frac{2i+1}{2i-1}M_{i+1} - 2M_i + \frac{2i-3}{2i-1}M_{i-1}\right) \tag{21}$$

The following equations were obtained for each node:

$$\begin{aligned}
\frac{dM_1}{dt} &= \frac{100D}{R^2}(3M_2 - 2M_1)\\
\frac{dM_2}{dt} &= \frac{100D}{R^2}\left(\frac{5}{3}M_3 - 2M_2 + \frac{1}{3}M_1\right)\\
\frac{dM_3}{dt} &= \frac{100D}{R^2}\left(\frac{7}{5}M_4 - 2M_3 + \frac{3}{5}M_2\right)\\
\frac{dM_4}{dt} &= \frac{100D}{R^2}\left(\frac{9}{7}M_5 - 2M_4 + \frac{5}{7}M_3\right)\\
\frac{dM_5}{dt} &= \frac{100D}{R^2}\left(\frac{11}{9}M_6 - 2M_5 + \frac{7}{9}M_4\right)\\
\frac{dM_6}{dt} &= \frac{100D}{R^2}\left(\frac{13}{11}M_7 - 2M_6 + \frac{9}{11}M_5\right)\\
\frac{dM_7}{dt} &= \frac{100D}{R^2}\left(\frac{15}{13}M_8 - 2M_7 + \frac{11}{13}M_6\right)\\
\frac{dM_8}{dt} &= \frac{100D}{R^2}\left(\frac{17}{15}M_9 - 2M_8 + \frac{13}{15}M_7\right)\\
\frac{dM_9}{dt} &= \frac{100D}{R^2}\left(\frac{19}{17}M_{10} - 2M_9 + \frac{15}{17}M_8\right)
\end{aligned} \tag{22}$$

For node 10, close to the surface:

$$\frac{dM_{10}}{dt} = \frac{400D}{R^2}\left(\frac{40}{57}M_s - M_{10} + \frac{17}{57}M_9\right) \tag{23}$$

For node 11, which is located on the surface, the sample surface conditions were considered.

3. RESULTS AND DISCUSSION

As the structure and composition of the chickpea grains is a key factor to determine the physicochemical properties after processing, some dominant physical principles of black chickpea are given in Table 1. Length, width, thickness, and sphericity of the seeds were measured within the ranges of 5.97–9.82 mm, 5.12–7.45 mm, 5.06–6.87 mm, and 74.25–89.65%, respectively. The average seed diameter was calculated 8 mm based on Eq. (1) with initial moisture content of 7.52%. The chickpea mean value for sphericity was 83.55%, which helped to conclude that the shape of the chickpea seed could be considered to be a sphere.

Table 1. Dominant physical properties of black chickpea

Parameters	Dimension	Min	Max	Mean	CV%
Length	mm	5.97	9.82	8.01	6.70
Width	mm	5.12	7.45	6.26	3.69
Thickness	mm	5.06	6.87	6.08	3.98
Sphericity	(%)	74.25	89.65	83.55	3.67

Figure 2 demonstrates the rehydration dynamic of black chickpea as a function of medium (water) temperature. Each value was reported as a mean value of three replications in the relevant soaking time. The moisture diffusion into samples occurred due to the moisture difference between the seed centre and surface layers (Prasad et al., 2010). Rehydration process begins by rapid water transfer to the product surface. Afterwards, the water spreads slowly into the sample and diffuses within the solid and the solid dissolves in the water. Eventually, the solute conveys to the solution (Montanuci et al., 2015). The solid loss is attributed to the phenomenon of solute transmission to the solution. In Fig. 2, all curves show typical rehydration behaviour with a high water absorption rate mainly at the beginning of the soaking process. The possibility of rapid initial water uptake was due to the filling of cavities (intercellular spaces). As water absorption progressed, the soaking rate began to decline because of the filled intercellular spaces with water. Absorption rate reduced at the end of hydration until equilibrium was reached after 18 h of processing. The downward concave shape (DCS) behaviour in Fig. 2 presents a high hydration rate from

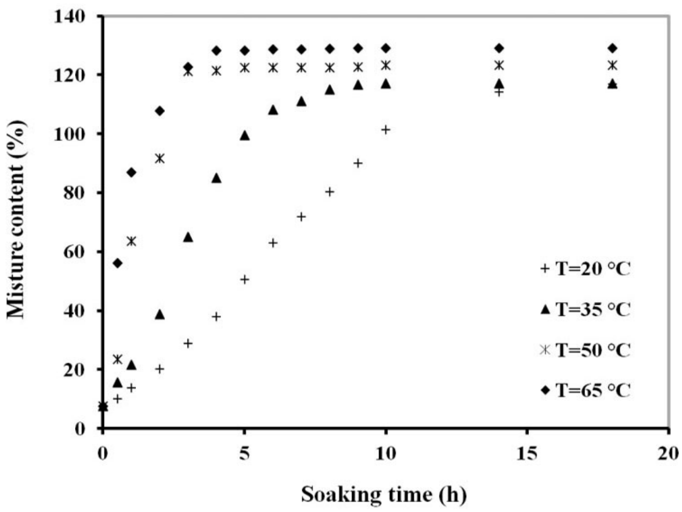

Fig. 2. Hydration of the black chickpea grains at different temperatures between 20 and 65 °C

the beginning of the process due to the water activity difference between the kernels and the soaking water. This rate reduces until reaching the equilibrium moisture content (Miano and Augusto, 2015). Approximately, 5 h was the transition time that lasted from the primary and the second phases (relaxation phase) of chickpea soaking process for all soaking temperatures. Similar DCS trend was reported for hydration of common beans (Miano et al., 2018) and Botswana bambara (Alvarez et al., 2019). The soaking process ceased when the grains attained the saturation moisture content (Bayram et al., 2004). In soaking process, saturation moisture content is the same as equilibrium moisture content due to the slow diffusion of water into the seeds until the seeds eventually reach a constant level of moisture content throughout the period of seed immersion (Pramiu et al., 2015). Figure 2 and Table 2 report the saturation moisture content of black chickpea, which was increased by rise in the soaking medium temperature. Resio et al. (2006) and Sopade and Obekpa (1990) observed similar behaviour in soybeans.

Table 2. Diffusion coefficient, Peleg's constants, and equilibrium moisture content of black chickpea at different temperatures

T	Diffusion coefficient [m^2/s]	$K_1 \times 10^{-2}$ [h/%]	$K_2 \times 10^{-3}$ [1/%]	M_e [% d.b]
20	5.24E−10	13.368	9.138	116.95
35	1.63E−09	7.863	9.126	117.1
50	3.45E−09	6.167	8.642	123.23
65	4.36E−09	5.664	8.231	129.01

Temperature of the rehydration medium had a severe effect on the water absorption of samples. The higher the medium temperature, the higher the water absorption velocity. It emphasises the temperature dependency characteristic of the hydration process in a positive way. The hydration rate theoretically increases with an increase in soaking temperature. This increment is attributed to the changes in the grain diffusion resistance. Higher soaking temperatures are known to expand and soften grains (Geankopolis, 1983). Numerous researchers have found that rising the immersion medium temperature is a good practical way to accelerate the water absorption of various seeds, shortening the immersion time (Maskan, 2002; Montanuci et al., 2015). During up taking process, the moisture content of the grains can be directly depending upon two soaking variables of time and temperature. As the hydration time is increased, the amount of water absorbed also increases (Montanuci et al., 2015).

The change of grain moisture ratio versus time during uptake process from medium temperature of 20 to 65 °C is shown in Fig. 3. It is obvious that as the process proceeded, the amount of moisture ratio reduced until it reached zero, meaning that time passage caused the water to fill the small capillary spaces of the specimens. Moisture absorption stopped as soon as the samples reached the equilibrium moisture content. When the moisture ratio was zero, the samples were completely soaked in the water and there was no excessive moisture exchange between water and samples (relaxation phase). These results were consistent with results reported for peas (Sabapathy, 2005) and pasta (Cunningham et al., 2007). Figs. 2 and 3 reveal that change in temperature influences the grain diffusion rate, such that the overall absorption behaviour of grains in higher soaking temperatures shows a slight change.

Values of the moisture diffusion coefficient of the samples were calculated using the Fick's second law (Eq. (8)); and the obtained values are provided in Table 2. The values of the diffusion coefficient were within the range of 4.36×10^{-9} to 5.24×10^{-10} m^2/s, which is in the similar orders argued by researchers for different products. In another study, diffusivity values of 1.922×10^{-9} to 3.237×10^{-9} m^2/s were reported for

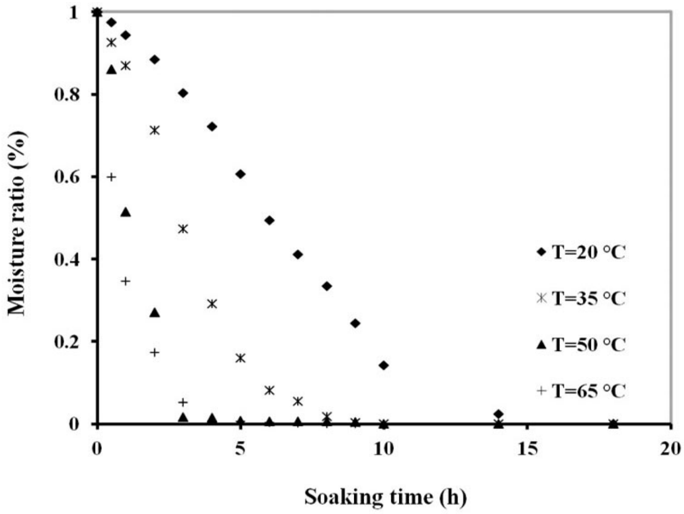

Fig. 3. Moisture ratio of black chickpea grains during soaking at different medium temperatures

chickpeas subjected to the rehydration process at temperatures from 40 to 60 °C (Prasad et al., 2010). For amaranth grains, diffusivity was found within the range of 0.27×10^{-11} to 3.70×10^{-11} m^2/s at temperatures from 30 to 90 °C (Resio etal., 2006). Khazaei and Mohammadi (2009) stated that at temperatures from 27 to 60 °C, the diffusivity values of sesame grains differed from 4.16×10^{-11} to 6.979×10^{-11} m^2/s. Table 2 reveals that moisture diffusion coefficient of chickpea grains increased with a rise in the soaking temperature. Increase in the water temperature could soften sample surface layers and cause volumetric expansion, which in turn accelerates water transfer and increases water diffusion as a result. This means, external mass fluxes at high medium temperatures are higher and the water uptake is more excessive due to lowering the boundary layer of the grains. Similar trend was reported for peas (Sabapathy, 2005), lentil and bean (Gurtas et al., 2001), and tomato (Cunningham et al., 2008).

In Fig. 4, ln (D) is plotted against time. The key results indicated that a direct relationship could be observed between ln (D) and time, which has a similar trend reported for sorghum (Kashiri et al., 2010). Parameter of $\dfrac{t}{M_t - M_0}$ is also plotted versus time in Fig. 5, with which Peleg's constants can be obtained. Peleg's rate constant (K_1) and Peleg capacity constant (K_2) were computed at different soaking temperatures and the

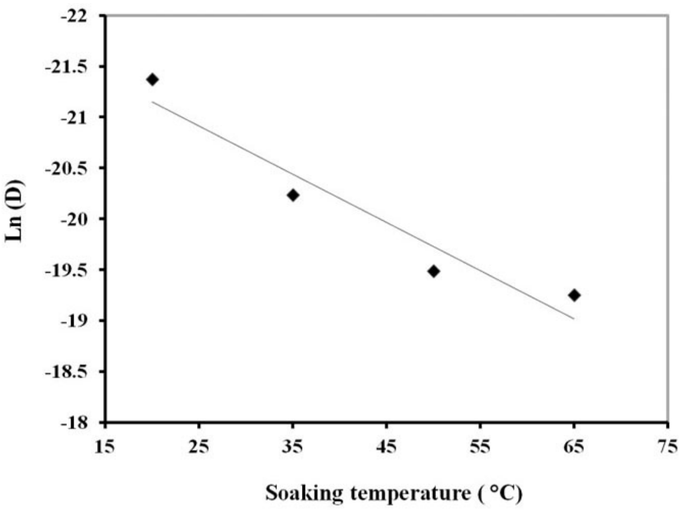

Fig. 4. Diffusion coefficient of black chickpea at soaking temperatures between 20 and 65 °C

results are shown in Table 2. The values of constant K_1 and the constant K_2 were obtained in the ranges of 5.664×10^{-2} to 13.368×10^{-2} and 8.231×10^{-3} to 9.138×10^{-3}, respectively. As can be seen, Peleg's rate constant is inversely related to the soaking temperature.

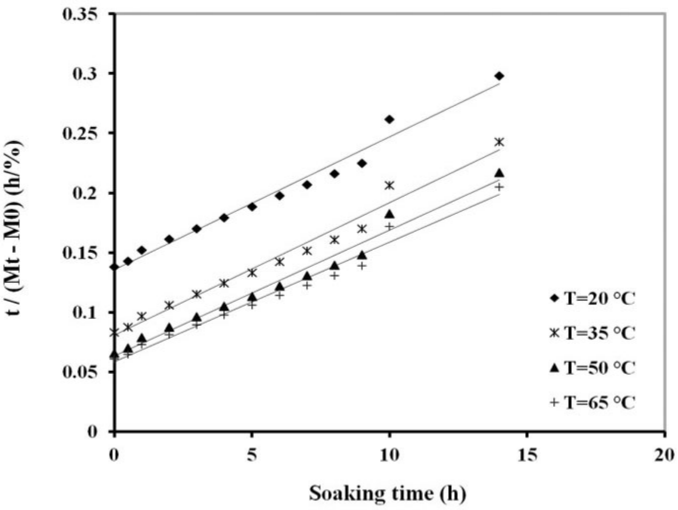

Fig. 5. Fitting of experimental water absorption data of black chickpea to the Peleg's model

Based on key results reported in Table 2, the Peleg's rate constant (k_1) is reversely related to the medium temperature and a decrement observed in k_1 when temperature increased from 20 to 65 °C. This is justified in such a way that increase in water temperature causes grain gelatinisation and subsequently the expansion and softening of grain. Therefore, by opening more pores and cracks inside the solid matrix water transfer through the seed increases (Ranjbari et al., 2011). The Peleg's capacity constant (k_2), related to the maximum water absorption capacity, was also decreased with rising temperature (Fig. 6) in turn caused increment in the equilibrium moisture content, which is confirmed by the experimental data. This is due to the higher water absorption rates in greater medium temperatures. Regarding the higher grain pores and lower fluid viscosity at higher soaking temperatures, the acceleration of water diffusion through the product is more probable. Cell wall structure, composition of the seed and the compactness of the cells in the seed are considered as key factors, which significantly affect the water absorption capacity of grains (Shafaei et al., 2014). Similar results have been reported for sorghum (Kashiri et al., 2010), pasta (Cunningham et al., 2007), and oak (Moreira et al., 2008).

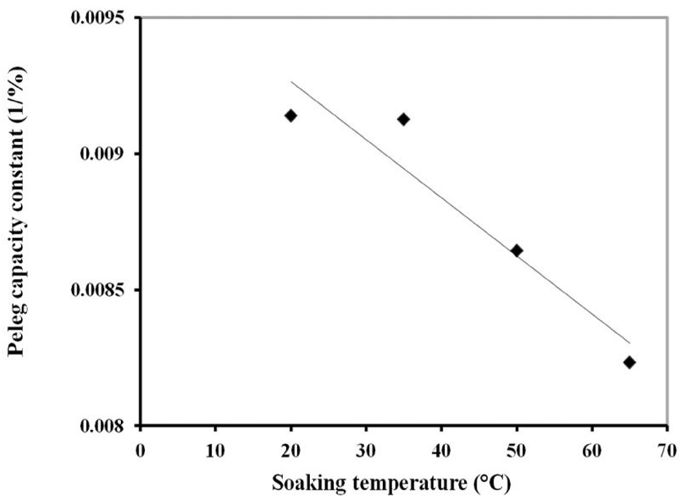

Fig. 6. Effect of medium temperature on Peleg's capacity constant of black chickpea

Moisture content of black chickpea obtained by experiments was fitted to Peleg's and finite difference models in Figs. 7 to 10 for soaking temperatures of 20, 35, 50 and 65 °C, respectively. A significant closeness is observed between experimental and predicted data in all soaking temperatures supporting the appropriateness of the two models for the representation of the water uptake of black chickpea during soaking at medium temperatures between 20 and 65 °C.

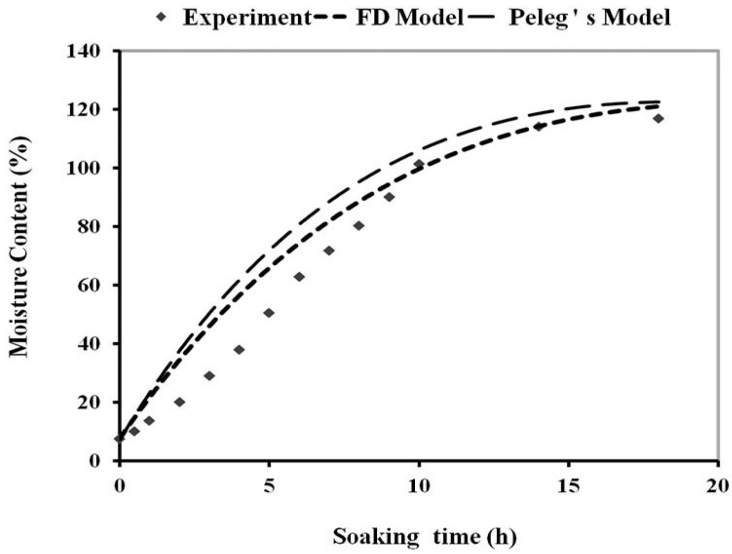

Fig. 7. Comparison of experimental and predicted moisture content of black chickpea obtained in soaking temperature of 20 °C

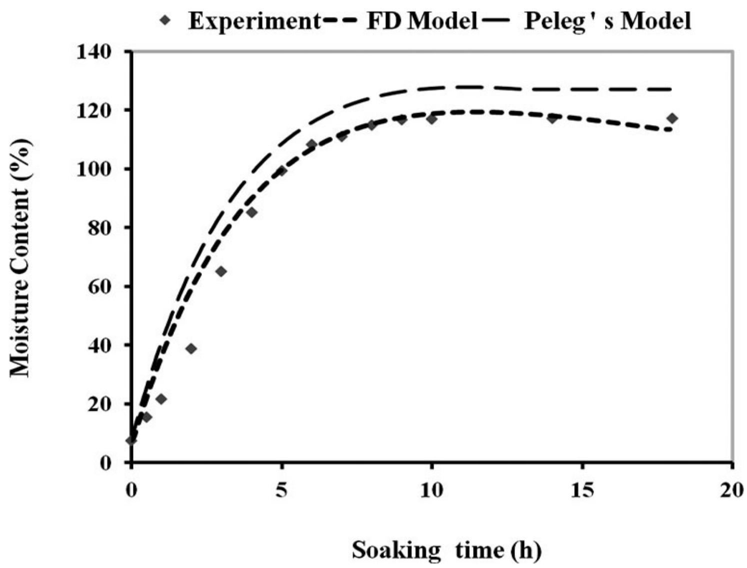

Fig. 8. Comparison of experimental and predicted moisture contents of black chickpea obtained in soaking temperature of 35 °C

Based on Table 3, the highest correlation coefficient of 0.9978 was obtained between experimental and the predicted values at the temperature of 65 °C, which was established by fitting the experimental data to the finite difference model, and the lowest correlation coefficient (0.9398) belonged to the temperature of 50 °C presented by the Peleg's model. This reflects high accuracy of the applied models to predict the amount of black chickpea moisture absorption during soaking within the study range of medium temperature.

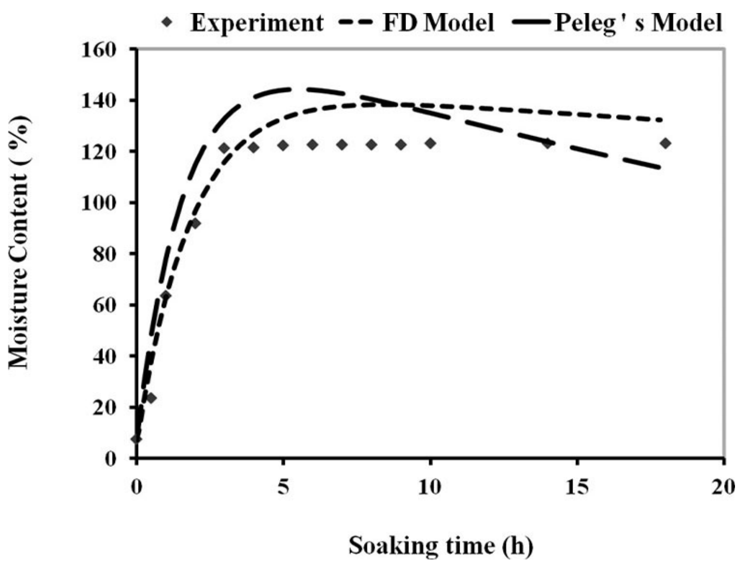

Fig. 9. Comparison of experimental and predicted moisture contents of black chickpea obtained in soaking temperature of 50 °C

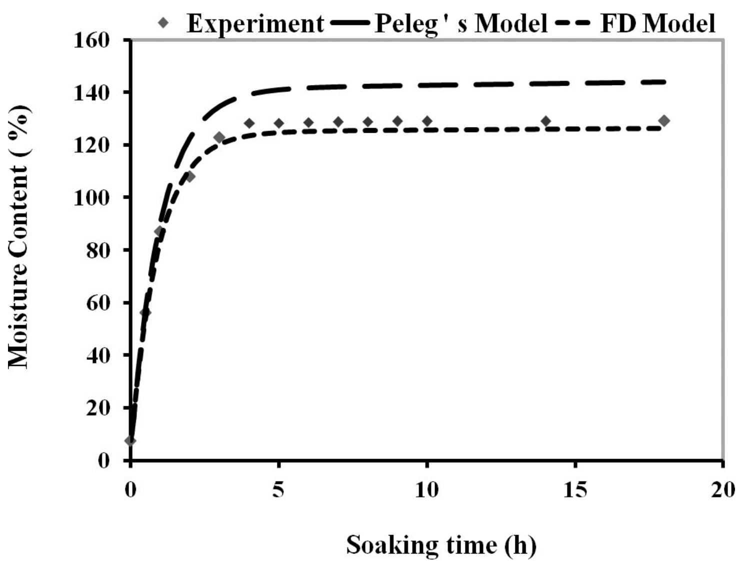

Fig. 10. Comparison of experimental and predicted moisture contents of black chickpea obtained in soaking temperature of 65 °C

Table 3. Correlation coefficient between experimental and predicted results by FDM and Peleg Model

T [°C]	R^2	
	FDM	Peleg
20	0.9732	0.9611
35	0.9800	0.977
50	0.9765	0.9398
65	0.9978	0.9973

4. CONCLUSIONS

In this research water absorption of black chickpea during soaking process was evaluated and simulated with Peleg model and finite difference strategy. Peleg's equation and finite difference model successfully represented the water absorption behaviour of black chickpea during soaking process at different temperatures. Moisture content of samples was well predicted by the Peleg's equation and FDM at given soaking times and temperatures within the experimental conditions. The Peleg's constants K_1 and K_2 were a function of medium temperature for black chickpea product and decreased with increase in the soaking temperature while sample diffusivity increased with a rise in temperature. This study revealed the possibility of estimating water absorption characteristics of black chickpea, which can help to optimise its soaking conditions.

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SYMBOLS

a	length, mm
b	width, mm
c	thickness, mm
D	moisture diffusion coefficient, m^2/s
GMD	geometric mean diameter, mm
K_1	Peleg's rate constant, h/% m.c (d.b)
K_2	Peleg's capacity constant, 1/% m.c (d.b)
M	moisture concentration
MC	moisture content (dry basis), %
M_0	initial moisture content, %
M_t	moisture content as a function of time, %
M_e	equilibrium moisture content, %
MR	moisture ratio
R	sample radius, m
r	radial distance, m
t	hydration time, h
φ	sphericity, %
ψ	radial length

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