Diffusion and kinetic modeling of water absorption process during soaking and cooking of chickpea

Parvin Bidkhorí | Vahid Mohammadpour Karizaki

Department of Chemical Engineering, Quchan University of Technology, Quchan, Iran

Correspondence
Vahid Mohammadpour Karizaki, Department of Chemical Engineering, Quchan University of Technology, Quchan, 9477177870, Iran. Email: v.mohammadpour@qiet.ac.ir

Funding information
Quchan University of Technology

Abstract
The chickpea soaking and cooking processes were empirically studied in terms of water absorption. The effective moisture diffusivity ($D_{eff}$) and the convective mass transfer coefficient ($K$) were determined by developing a mathematical model in spherical coordinates. According to the evaluation of mass transfer parameters, the values of $D_{eff}$ and $K$ ranged from $9.1 \times 10^{-12}$ to $1.49 \times 10^{-10}$ m$^2$/s, and $2.02 \times 10^{-10}$ to $7.25 \times 10^{-10}$ m/s, respectively. Also, the kinetic behavior of chickpea during soaking and cooking was successfully modeled by the commonly used predictive models such as Peleg, Page, two-term, and Vega–Lemus. The statistical parameters including the coefficient of determination ($R^2$) and sum of square error (SSE) were applied for comparison of mathematical models. The two-term model was found to be the best predictive equation for describing the soaking behavior of chickpea. In the case of cooking, a proposed model in this study was introduced as the best equation in predicting the moisture content of chickpea against time. The approach that was applied in this work can support the development of diffusion and kinetic modeling in different types of legumes during soaking, cooking, and the other processes related to moisture absorption or removal.

KEYWORDS
chickpea, cooking, modeling, soaking, water absorption

1 | INTRODUCTION

Legumes are economical and rich sources of energy, protein, carbohydrate, vitamins, and minerals. Legume-based foods prevent and reduce the risk of several diseases such as obesity, diabetes, cancer, and cardiovascular infection (Attia et al., 1994; Bhathena & Velasquez, 2002; Shafaei et al., 2016). Depending on the location and culture, the preferences in consumption of the different varieties of legumes vary greatly (Ibarz et al., 2004).

Chickpea (Cicer arietinum L.) is a commonly used legume, the third most in the world after soya and bean (Avola et al., 2012; Costa et al., 2018; Sayar et al., 2001). In particular, it as a staple food crop is widely consumed in tropical and subtropical regions (Alajaji & El-Adawy, 2006; Khattak et al., 2007). Chickpea differs from other type of legumes in its easy digestibility, low content of antinutritional factors, besides better availability of iron (Pramiu et al., 2015). The world’s annual chickpea production is around 15 million tons. The leading producing countries include India, Turkey, Pakistan, Russia Federation, Australia, Myanmar, Ethiopia, and Iran. More than 200,000 tons of chickpea is produced in Iran (Food and Agriculture Organization [FAO], 2021). It is used as the main ingredients of the ethnic and traditional
Iranian legume-based foods such as Shole, Ash, Abgoosht, and Felfafel.

A wide variety of processes and unit operations in food industry deal with the moisture removal or water absorption within the product. For example, moisture removal during drying of food materials (Jayatunga & Amarasinghe, 2019; Karathanos, 1999; Krokida et al., 2003; Togrul & Pehlivan, 2004), osmotic dehydration of fruits and vegetables (Luchese et al., 2015), baking of bakery products (Baik & Marcotte, 2003; Cevoli et al., 2020), frying of foodstuffs (Al Faruq et al., 2019; Krokida et al., 2000; Mojaharul Islam et al., 2019; Yildiz et al., 2007), and storage of fresh materials (Duarte-Molina et al., 2016) have been reported in literature. Also, some researchers studied the water absorption process during rehydration (Maskan, 2001; Moreira et al., 2008), blanching (Gowen et al., 2007), soaking (Sayar et al., 2001; Shafaei et al., 2016; Turhan et al., 2002; Yildirim et al., 2011), and cooking (Ibarz et al., 2004; Karizaki, 2016).

Soaking and cooking are the oldest and the best known technique for making legumes edible. They confer particular sensorial properties to the product, such as consistence, taste, and color as appreciated by consumers (Avola et al., 2012). Before being consumed in human diet, legumes are usually soaked and cooked for improving the protein quality by inactivation or destruction of the unstable antinutritional factors (Yildirim et al., 2011). Several studies have been published about the soaking and cooking of chickpea in the recent years. For example, Jood et al. (1988) investigated the effects of various domestic treatments including soaking, ordinary cooking, pressure cooking, and sprouting on the contents and digestibility of carbohydrates of important cultivars of chickpea. The soaking and cooking allow the water molecules to penetrate the chickpea coat. As the process proceeds, the moisture travels through the solid and towards the center of the chickpea (Gowen et al., 2007). Water uptake in the chickpea is the main change during soaking and cooking process. This change facilitates the softening of dry legume after which it can be easily eaten (Costa et al., 2018; Gowen et al., 2007).

Understanding the dynamics of water absorption in legumes and predicting the mass transfer rate during soaking and cooking are of particular importance because they affect the quality of final product (Yildirim et al., 2011). In the other word, the study of diffusion phenomenon creates the efficient, safe, and economical results through design, control, and optimization of the process (Karizaki, 2016; Sayar et al., 2001). The water absorption process is a phenomenon that can be described by different mathematical models based on concepts of physical or chemical kinetics. Also, it can be explained by analytic expressions derived and simplified from Fick’s second law of diffusion (Pramiu et al., 2015).

To the best of our knowledge, there is little information on water uptake modeling in chickpea during soaking and cooking. The starch gelatinization, solid loss, and texture changes have been successfully described in the available mathematical models. The aim of the study of water absorption during soaking and cooking process of chickpea in the present work is twofold: (i) to develop a diffusion model in spherical coordinates for determination of effective moisture diffusivity and convective mass transfer coefficient and (ii) to find the best predictive kinetic models for describing the chickpea behavior in the process. The experimental data were analyzed for validation of kinetic modeling.

2 | MATERIALS AND METHODS

2.1 | Materials

Dry chickpea (C. arietinum L.) was purchased from a local market in Quchan, Iran. Chickpea seeds were hand selected for removing the cracked, broken, and damaged seeds and foreign materials. The grains with 12 mm in diameter were screened out for using in the work (Sayar et al., 2001; Turhan et al., 2002). Initial moisture content of grains was determined by drying 6 g chickpea at 90°C till constant weight. Samples were stored in sealed bags at 25°C in a dark place prior to processing (Gowen et al., 2007).

2.2 | Methods

Six grams of chickpea seeds were placed into a beaker containing 180-ml tap water in each experiment. The water absorption process in seeds was studied at a seed/water ratio of 1:30 (w/w). The required data for modeling of the process were obtained in two different modes: (1) soaking: the soaking process of chickpea seeds were conducted at room temperature. The moisture contents of samples were calculated after 1.5 h and at every 1.5-h time interval up to 12 h. Then, the time interval was increased to 2 h up to 24 h. (2) Cooking: boiling tap water was used for cooking of chickpea seeds. The samples were analyzed by determination of moisture content after 10 min and at every 10-min time interval up to 150 min. Afterwards, the time interval was changed to 30 min up to 300 min. Moisture content of the chickpea seeds at each time step was determined based on increasing seed mass at corresponding times in all two modes. For this purpose, each sample was removed from the beaker, superficially dried by paper towel, and subsequently weighed.

3 | MODELING OF WATER ABSORPTION PROCESS

3.1 | Diffusion modeling

The continuity equation is employed as the origin of diffusion modeling in this work. Determination of mass transfer parameters during soaking and cooking of chickpea is the main goal of mathematical model development. The general form of the partial differential equation in spherical coordinates for component w can be written as (Bird et al., 1960; Mosavian & Karizaki, 2012):

\[
\frac{\partial w}{\partial t} = D \frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( D \frac{\partial w}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 w}{\partial \theta^2} + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( D \frac{\partial w}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 w}{\partial \phi^2}
\]
\[
\frac{\partial C_w}{\partial t} = \frac{u_r}{r} \frac{\partial C_w}{\partial r} + \frac{u_\theta}{r} \sin \theta \frac{\partial C_w}{\partial \theta} + \frac{u_\varphi}{r} \sin^2 \theta \frac{\partial C_w}{\partial \varphi^2} = D_{eff} \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial C_w}{\partial r} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial C_w}{\partial \theta} \right) + \frac{1}{r^2 \sin^4 \theta} \frac{\partial^2 C_w}{\partial \varphi^4} \right] + R_w
\]

(1)

where \( w \) is symbol of water and \( C_w \) is water concentration or moisture content at any point any time. The system velocities in three directions of \( r, \theta, \) and \( \varphi \) are \( u_r, u_\theta, \) and \( u_\varphi, \) respectively. \( R_w \) is rate of water generation, and \( D_{eff} \) is effective moisture diffusivity. Equation 1 can be simplified under the following assumptions (Crank, 1975):

i. The moisture distribution within the chickpea seed during soaking and cooking is uniform. This assumption describes that the values of moisture content do not vary with positions within the spherical chickpea.

ii. The moisture content gradients in two directions of \( \theta- \) and \( \varphi- \)axes are negligible. Therefore, a radial one-dimensional diffusion model is obtained.

iii. The water production or consumption by chemical reaction during process and also the system velocities in three directions of \( r, \theta, \) and \( \varphi \) are zero.

iv. The effective moisture diffusivity and mass transfer coefficients are constant.

v. The chickpea seed is considered as a homogenous sphere, and its radial changes during process are immaterial.

After applying the presented hypothesis on the continuity equation, the following simple form is obtained.

\[
\frac{\partial C_w}{\partial t} = D_{eff} \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial C_w}{\partial r} \right) \right]
\]

(2)

Equation 2 gives the concentration of water as a function of location and time for a spherical piece. One initial condition and two boundary conditions are necessary for solving the Fick’s second law (i.e., Equation 2) as given at Equations 3 to 5.

Initial condition:

\[
C_w(r, 0) = C_0
\]

(3)

First boundary condition:

\[
C_w(0, t) \text{ finite}
\]

(4)

Second boundary condition:

\[
-D_{eff} \frac{\partial C_w(R, t)}{\partial t} = K (C_w(R, t) - C_m)
\]

(5)

where \( C_0 \) is initial moisture content of chickpea seed and \( C_m \) is moisture content of soaking or cooking medium. The values of \( C_0 \) and \( C_m \) on dry basis (d.b) in this study were 0.177 kg/kg solid and 30 kg/kg solid, respectively. \( R \) (m) is the spherical chickpea seed radius, and \( K \) (m/s) is convective mass transfer coefficient. The solution of Equation 2 for chickpea seed as a homogenous sphere by separation of variable method can be obtained as (Crank, 1975; Kreyszig, 1999):

\[
C_w(r, t) = C_\infty + \sum_{n=1}^{\infty} \left[ 
C_0 - C_\infty \right] \times \frac{\sin(R_\beta \sin \beta r)}{2 \sin^2 \beta R_\beta} \times \frac{\sin(R_\beta \sin \beta t)}{r} \times e^{-D_{eff} \beta^2 t}
\]

\[
\beta_n \text{ is known as the root of the characteristic equation in spherical pieces. It is determined by solving the following nonlinear relation:}
\]

\[
\beta_n \cos(R \beta_n) = \frac{1}{R} \frac{K}{D_{eff}}
\]

(7)

Crank (1975) showed that enough accurate results can be provided by using the first term of Equation 6 for small piece radius (the greater value of \( \frac{R^3}{D_{eff}} \) the more acceptable result). Therefore, Equation 6 can be written in a simple form:

\[
\frac{C_w(r, t) - C_\infty}{C_0 - C_\infty} = \left( \frac{\sin(R \beta_1 \sin \beta r)}{2 \sin^2 \beta R_{\beta_1}} \times \frac{\sin(R \beta_1 \sin \beta t)}{r} \times e^{-D_{eff} \beta_1^2 t} \right)
\]

\[
\left( \frac{C_w(r, t) - C_\infty}{C_0 - C_\infty} \right) = \delta \times e^{-D_{eff} \beta_1^2 t}
\]

\[
\delta = \frac{(\sin(R \beta_1) - R \beta_1 \cos(R \beta_1))^2}{(R \beta_1)^3 (R \beta_1 - \sin(R \beta_1) \cos(R \beta_1))}
\]

(11)

A nonlinear relation of the average moisture content versus time is obtained in Equation 10. It can be converted to a linear equation by taking the natural logarithm of its both sides:

\[
\ln \left( \frac{C_{ave}(t) - C_m}{C_0 - C_m} \right) = \ln \delta - D_{eff} \beta_1^2 t
\]

(12)

After plotting the \( \ln \left( \frac{C_{ave}(t) - C_m}{C_0 - C_m} \right) \) against time, the slope and intercept of the obtained linear graph are equated to \( -D_{eff} \beta_1^2 \) and \( \ln \delta, \)
respectively. The effective moisture diffusivity and convective mass transfer parameter in water absorption process during soaking and cooking of chickpea can be determined in three following steps:

i. Calculation of the root of characteristic equation (\(\lambda_i\)) from Equation 11.
ii. Determination of effective moisture diffusivity (\(D_{\text{eff}}\)) from the slope of \(\ln \left( \frac{C(t)}{C_0} \right) - t\) plot.
iii. Determination of convective mass transfer parameter (\(K\)) from the Equation 7.

A computer program based on the model was developed and implemented in MATLAB software to find the mass transfer parameters.

## 3.2 | Kinetic modeling

Kinetic modeling is a useful way for better understanding the progress of unit operations and processes. A wide variety of mathematical models were provided by investigators to express the frying, drying, baking, cooking, or soaking kinetics of food materials. The most commonly used of kinetic models such as Peleg, Page, two-term, Vega–Lemus, rational, and quadratic were considered in this study (Table 1).

These models were applied for predicting the moisture content as a function of time. The experimental data in the work were used for evaluation of mathematical models given in Table 1. This table shows the model’s name and the mathematical formula of the predictive equations. The best predictive models for describing the soaking and cooking kinetics of chickpea were determined using linear and nonlinear regression analysis. The coefficient of determination \(R^2\) and the sum of square error (SSE) were considered for specifying the mathematical models that provide the best fit on dataset. These statistical parameters were calculated using the following equations:

\[
R^2 = 1 - \frac{\sum_{i=1}^{N}(M_{\text{exp}} - M_{\text{pre}})^2}{\sum_{i=1}^{N}(M_{\text{exp}} - \bar{M})^2}
\]

(13)

\[
\text{SSE} = \sum_{i=1}^{N}(M_{\text{exp}} - M_{\text{pre}})^2
\]

(14)

where \(M_{\text{exp}}\) is the \(i\)th moisture content observed experimentally. \(M_{\text{pre}}\) is also the \(i\)th predicted moisture content. \(N\) and \(\bar{M}\) are number of observations and mean of observed data, respectively. The value close to one for \(R^2\) indicates an almost perfect relationship between data and mathematical model. Also, a SSE value closer to zero implies a better fit. The curve fitting toolbox of MATLAB software was used for regression analysis in this study.

### 4 | RESULTS AND DISCUSSION

#### 4.1 | Determination of \(D_{\text{eff}}\) and \(K\)

The experimental data of soaking and cooking process of chickpea were converted to \(\ln \left( \frac{C(t)}{C_0} \right) - t\) graph for determination of effective moisture diffusivity and mass transfer coefficient.

Figure 1 shows the values of moisture concentration ratio as a function of time during soaking of chickpea. The employed approach in this work is based on using a constant value for mass transfer coefficients. Fick’s second law is written as Equation 1 in this situation. Therefore, a simple analytical solution can be obtained for finding the values of \(D_{\text{eff}}\) and \(K\). The solution leads to creation of a linear relation between dimensionless moisture content ratio and time of the process (Equation 12).

However, Figure 1 shows a clear nonlinear change in the slope of plotted data. Consequently, the fitting of just one linear equation on the whole data of Figure 1 is not an acceptable trend for finding effective diffusivity. Therefore, dividing the experimental data into two

| No. | Model’s name | Predictive equation | Reference(s) |
|-----|--------------|---------------------|--------------|
| 1   | Two-term     | \(M = ae^{-bt} + ce^{-dt}\) | (Henderson, 1974) |
| 2   | Quadratic    | \(M = at^2 + bt + c\) | (Karizaki, 2016) |
| 3   | Qubic        | \(M = at^2 + bt + c\) | (Karizaki, 2016) |
| 4   | Page         | \(M = e^{-at}\) | (Bi et al., 2015; Simal et al., 2005) |
| 5   | Rational     | \(M = (at + b)/(t + c)\) | (Karizaki, 2016) |
| 6   | Vega–Lemus   | \(M = (a + bt)^2\) | (Vega-Gálvez et al., 2009) |
| 7   | Peleg*       | \(M = M_0 + t/(a + bt)\) | (Peleg, 1988) |
| 8   | Monomial     | \(M = at^b\) | (Karizaki, 2016) |
| 9   | Proposed model | \(M = (at^2 + bt + c)/(t + d)\) | This study |
| 10  | Midilli and Kucuk | \(M = ae^{-bt} + dt\) | (Midilli et al., 2002) |

*\(M_0\) is the initial moisture of the sample.
parts (i.e., the beginning and the end of process) is a proper way for determination of mass transfer parameters during the initial and the final periods of the soaking process.

It is noteworthy that another approach for determination of mass transfer parameters during water absorption processes has been proposed by investigators. It uses a variable equation of $D_{eff}$ as a function of temperature, time, moisture content, or combination of these parameters. Simplifying the Fick’s law of diffusion with the variable diffusivity results in obtaining a relatively complex equation. Usually, numerical modeling is employed for solving the problem in this situation. For example, Dutta et al. (2020) determined variable diffusivity coefficient in rice soaking process using a numerical model.

When the soaking process starts, the driving force of water absorption is at the highest value. After beginning of the soaking process, the rate of water absorption continuously decreased due to filling of water molecules into free capillary, porous, and intercellular spaces (Abu-Ghanam & McKenna, 1997; Sayar et al., 2001). Also, increasing the extraction of soluble ingredients of solid chickpea in the opposite direction to the water transport creates additional resistance to the water movement. More leaching of solid matter from grains at the end of soaking process has been introduced as a negative factor during water absorption (Shafaei et al., 2016). Similar reports have been published for other foodstuffs such as sorghum, pasta, milled rice, chick peanuts, and barley seeds (Cunningham et al., 2007; Pan & Tangratanavalee, 2003; Shafaei et al., 2016).

The driving force of water absorption is decreased over time and reached to minimum after 24 h. Due to the differences in the values of driving force during the soaking, two straight lines were fitted on experimental data at the beginning and the end of the process. The greater the slope of the straight line, the higher the value of effective moisture diffusivity and mass transfer coefficient. A linear relationship between the dimensionless moisture concentration ratio and the time of the process has been reported in the other studies related to water absorption or removal in food materials (Mosavian & Karizaki, 2012; Yildiz et al., 2007). The moisture concentration ratio against time for cooking process of chickpea is also shown in Figure 2. Following a similar line of reasoning, two straight lines were considered for fitting on the data at the beginning and the end of the cooking process. The obtained values of mass transfer parameters including $D_{eff}$ and $K$ for soaking and cooking process of chickpea were presented in Figure 3.

The effective moisture diffusivity ranged from $0.91 \times 10^{-12}$ to $1.44 \times 10^{-10}$ m$^2$/s, and $1.2 \times 10^{-11}$ to $1.49 \times 10^{-10}$ m$^2$/s in soaking and cooking process of chickpea, respectively. The magnitude of the convective mass transfer coefficient for soaking was between $2.02 \times 10^{-10}$ and $2.53 \times 10^{-9}$ m/s, whereas the range of $[1.78 - 7.25] \times 10^{-9}$ m/s was obtained for cooking process. Figure 3 shows that $D_{eff}$ and $K$ were considerably decreased at the end of water absorption processes. The findings of this work show that the calculated values of effective moisture diffusivity and convective mass transfer coefficient are consistent with data reported by other investigators (Costa et al., 2018; Pramiu et al., 2015; Sayar et al., 2001).

For example, Sayar et al. (2001) determined the magnitude of $D_{eff}$ in the range of $[10^{-10} - 10^{-9}]$ m$^2$/s for soaking process of chickpea. The authors conducted the experiments of soaking in higher range of temperatures [20–100]°C. Thus, a comparison of results indicates the lower values of effective moisture diffusivity in our study are reasonable. Several researchers have confirmed that the increasing temperature during food processes leads to increase the effective moisture diffusivity (Mosavian & Karizaki, 2012, Yildiz et al., 2007).

Also, the range of $[10^{-11} - 10^{-10}]$ m$^2$/s for effective moisture diffusivity coefficients during cooking is in reasonable agreement with the data published in the literature. For example, the value about $10^{-10}$ m$^2$/s for $D_{eff}$ is presented by Briffaz et al. (2014) during cooking of rice.

4.2 Description of the kinetic behavior of chickpea

The moisture content data during soaking and cooking process of chickpea were fitted to the mathematical models. Figure 4 shows the curve fitting results of all predictive models on the experimental data.
of chickpea soaking. As expected, an ascending trend was observed in the moisture content of samples against time of the process. The curve fitting results of 10 mathematical models on the experimental data during cooking process are also shown in Figure 5. The moisture content of cooked chickpea has been increasingly changed during the cooking.

Table 2 shows the calculated constants of all predictive models for soaking and cooking process. These equations are known as the commonly used of predictive models for considering the behavior of water absorption or removal in food processes (Karizaki, 2016; Vega et al., 2007).

The calculated constants were resulted from an optimization procedure that is performed by curve fitting toolbox of MATLAB software. The optimized data were achieved based on the minimization of the mean standard deviation between empirical and predicted values of moisture content in the water absorption processes.

The statistical parameters including the coefficient of determination \(R^2\) and the SSE were used as the criteria to identify the best mathematical models describing the soaking and cooking behavior of chickpea. The higher values of \(R^2\) and the lower values of SSE show the better goodness of fit.

In the other words, the best model predicting the soaking or cooking characteristics of chickpea was selected as the one with the least SSE and the highest coefficient of determination. The \(R^2\) and SSE values of all predictive models are also presented in Table 2 for soaking and cooking process.

According to the obtained results of 10 predictive models, the two-term model in this study gave best prediction during soaking process. The coefficient of determination that is denoted \(R^2\) was the highest value for two-term model during soaking of chickpea (Table 2). Also, the minimum value of 0.01678 as SSE was found in the fitting of this model for the soaking process. The two-term model...
was firstly developed by Glenn (1978) through a semi-empirical approach for kinetic modeling of grain drying systems. This model consists of two terms of infinite series of negative exponentials obtained from a general solution to the Fick’s diffusion equation (Kashaninejad et al., 2007).

Many researchers have confirmed that the two-term model creates good fits to describe the drying behavior of foods and agricultural products (de Medeiros et al., 2016; Sacilik et al., 2006; Vijayan et al., 2016). In addition, the behavior of moisture loss against time in soaking and cooking processes are acceptably predicted by the two-term model in the literature (Karizaki, 2016; Maneesh Kumar et al., 2018).

As well as the two-term model, the proposed model in this study showed a very good prediction of data in all experiments. This model in mathematics is a fractional equation that has a linear term and quadratic term as numerator and denominator, respectively. The main feature of this model is the flexibility that makes it possible to predict the required data accurately. However, not much research has been performed for the using of these types of fractional equations in the analysis of sorption behavior in food processes. Thus, it is proposed to
investigate the sorption behavior of other food materials and processes with the new model presented in this work.

As it is shown in Table 2, the best predictive models in the case of cooking process are the proposed model in this study, two-term, rational, and Peleg equation. Similar to two-term model, Peleg model is also used to describe sorption processes in food and agriculture products. The Peleg model is one of the most popular models that has been applied for kinetic modeling of soaking and cooking processes (Shafaei et al., 2016).

Due to the type of Peleg equation, the researchers have proposed this mathematical model for prediction of short time experimental data (Djendoubi et al., 2009; Shafaei et al., 2016). This is why the Peleg model had a better prediction of moisture content-time data for cooking rather than the soaking process.

Validation of the four best models in this work was made by comparing the obtained values of predicted moisture content with the experimental data during the soaking process of chickpea (Figure 6). The predicted values and experimental data laid around the straight line in the figure. Also, Figure 7 shows the similar comparison for the cooking process. As one can see from these two figures, the two-term model and the proposed model in this study showed the best prediction of the soaking and cooking behavior of chickpea, respectively.

| No. | Model’s name       | Number of constants | Calculated constants                                                                 | Statistical parameters | Calculation \( R^2 \) | SSE | \( \text{Statistical parameters} \) | Calculation \( R^2 \) | SSE |
|-----|--------------------|---------------------|--------------------------------------------------------------------------------------|-------------------------|-------------------------|-----|-------------------------|-------------------------|-----|
| 1   | Two-term           | 4                   | \( a = 1.087 \) \( b = 9 \times 10^{-6} \) \( c = -0.9524 \) \( d = 0.0041 \) | 0.01678 \( R^2 = 0.9847 \) | 0.9966                  |     | \( a = 0.6341 \) \( b = 0.0011 \) \( c = -0.4479 \) \( d = -0.02121 \) | 0.002463 \( R^2 = 0.9966 \) |     |
| 2   | Proposed model     | 4                   | \( a = -0.0002 \) \( b = 1.71 \) \( c = 51.64 \) \( d = 373.9 \) | 0.02131 \( R^2 = 0.9807 \) |     | \( a = 0.0005 \) \( b = 0.8598 \) \( c = 9.484 \) \( d = 54.02 \) | 0.001381 \( R^2 = 0.9981 \) |     |
| 3   | Qubic              | 4                   | \( a = 1 \times 10^{-9} \) \( b = -3 \times 10^{-6} \) \( c = 0.0028 \) \( d = 0.174 \) | 0.02256 \( R^2 = 0.9796 \) |     | \( a = 4.7 \times 10^{-6} \) \( b = -2.9 \times 10^{-6} \) \( c = 0.0069 \) \( d = 0.221 \) | 0.007786 \( R^2 = 0.9894 \) |     |
| 4   | Rational           | 3                   | \( a = 1.256 \) \( b = 26.43 \) \( c = 205.6 \) | 0.03489 \( R^2 = 0.9684 \) |     | \( a = 1.072 \) \( b = 16.9 \) \( c = 88.29 \) | 0.002753 \( R^2 = 0.9962 \) |     |
| 5   | Peleg              | 3                   | \( a = 208.5 \) \( b = 0.9195 \) \( M_0 = 0.177 \text{kg/kg solid} \) | 0.03764 \( R^2 = 0.9659 \) |     | \( a = 93.3 \) \( b = 1.134 \) \( M_0 = 0.177 \text{kg/kg solid} \) | 0.003077 \( R^2 = 0.9958 \) |     |
| 6   | Page               | 2                   | \( a = 5022 \) \( b = -1.848 \) | 0.08061 \( R^2 = 0.927 \) |     | \( a = 6.49 \) \( b = -0.6079 \) | 0.056 \( R^2 = 0.9237 \) |     |
| 7   | Quadratic          | 3                   | \( a = -8.137 \times 10^{-7} \) \( b = 0.00165 \) \( c = 0.2962 \) | 0.09741 \( R^2 = 0.9118 \) |     | \( a = -9.2 \times 10^{-6} \) \( b = 0.0046 \) \( c = 0.2675 \) | 0.02228 \( R^2 = 0.9696 \) |     |
| 8   | Monomial           | 2                   | \( a = 0.1725 \) \( b = 0.2627 \) | 0.1322 \( R^2 = 0.8802 \) |     | \( a = 0.1487 \) \( b = 0.3175 \) \( M_0 = 0.177 \text{kg/kg solid} \) | 0.03544 \( R^2 = 0.9517 \) |     |
| 9   | Midilli and Kucuk   | 4                   | \( a = 0.6555 \) \( b = 9.659 \) \( c = -3.909 \) \( d = 0.0003795 \) | 0.256 \( R^2 = 0.7682 \) |     | \( a = 0.4164 \) \( b = 0.3801 \) \( c = -6.887 \) \( d = 0.001864 \) \( M_0 = 0.177 \text{kg/kg solid} \) | 0.03222 \( R^2 = 0.9561 \) |     |
| 10  | Vega–Lemus         | 2                   | \( a = 0.7703 \) \( b = 0.000241 \) | 0.4519 \( R^2 = 0.5907 \) |     | \( a = 0.6448 \) \( b = 0.00118 \) \( M_0 = 0.177 \text{kg/kg solid} \) | 0.1502 \( R^2 = 0.7953 \) |     |
CONCLUSION

In this study, the water absorption process of chickpea during soaking and cooking was considered using diffusion and kinetic modeling. The methodology in diffusion modeling for determination of effective moisture diffusivity and convective mass transfer coefficients was based on the using time-dependent moisture content values. The obtained results were comparable with those reported in the literature. This study also predicted the kinetic behavior of chickpea during soaking and cooking by various mathematical models.

Of the 10 considered models, the two-term model showed the best results for soaking process according to the statistical parameters. A rational proposed model in this study was also found to be the best predictive relation in the case of cooking.

In addition, the proposed model and two-term model showed very good results in prediction of experimental data for soaking and cooking process, respectively. Although the newly proposed model was able to predict the experimental data acceptably, preferring this model to the other previously established models such as two-term and Peleg model requires more investigations by researchers.

The proposed approach of diffusion and kinetic modeling in this work is significant for use not only in the soaking and cooking process of chickpea but also in design, control, and optimization of other unit operations related to moisture absorption or removal.

ACKNOWLEDGEMENT

Financial support of this study from Quchan University of Technology is gratefully acknowledged.

CONFLICT OF INTEREST

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Vahid Mohammadpour Karizaki https://orcid.org/0000-0002-8681-5520

REFERENCES

Abu-Ghannam, N., & McKenna, B. (1997). The application of Peleg's equation to model water absorption during the soaking of red kidney beans (Phaseolus vulgaris L.). *Journal of Food Engineering*, 32(4), 391–401. https://doi.org/10.1016/S0260-8774(97)00034-4

Al Faruq, A., Zhang, M., & Adhikari, B. (2019). A novel vacuum frying technology of apple slices combined with ultrasound and microwave. *Ultrasonics Sonochemistry*, 52, 522–529. https://doi.org/10.1016/j.ultsonch.2018.12.033

Alajaji, S. A., & El-Adawy, T. A. (2006). Nutritional composition of chickpea (Cicer arietinum L.) as affected by microwave cooking and other traditional cooking methods. *Journal of Food Composition and Analysis*, 19(8), 806–812. https://doi.org/10.1016/j.jfca.2006.03.015

Attia, R. S., Shehata, A. M. E. T., Aman, M. E., & Hamza, M. A. (1994). Effect of cooking and decortication on the physical properties, the chemical composition and the nutritive value of chickpea (Cicer arietinum L.). *Food Chemistry*, 50(2), 125–131. https://doi.org/10.1016/0308-8146(94)90108-2

Avola, G., Patané, C., & Barbagallo, R. N. (2012). Effect of water cooking on proximate composition of grain in three Sicilian chickpeas (Cicer arietinum L.). *LWT - Food Science and Technology*, 49(2), 217–220. https://doi.org/10.1016/j.lwt.2012.07.004

Baik, O.-D., & Marcotte, M. (2003). Modeling the moisture diffusivity in a baking cake. *Journal of Food Engineering*, 56(1), 27–36. https://doi.org/10.1016/S0260-8774(02)00144-9

Bhathena, S. J., & Velasquez, M. T. (2002). Beneficial role of dietary phytoestrogens in obesity and diabetes. *The Journal of Clinical Nutrition*, 76(1), 191–201.
Jood, S., Chauhan, B. M., & Kapoor, A. C. (1988). Contents and digestibility processing and cooking. Food Chemistry, 30(2), 113–127. https://doi.org/10.1016/0308-8146(88)90149-5

Karathanos, V. T. (1999). Determination of water content of dried fruits by drying kinetics. Journal of Food Engineering, 39(4), 337–344. https://doi.org/10.1016/S0260-8774(98)00132-0

Karizaki, V. M. (2016). Kinetic modeling and determination of mass transfer parameters during cooking of rice. Innovative Food Science & Emerging Technologies, 38, 131–138. https://doi.org/10.1016/j.ifset.2016.09.017

Kashaninejad, M., Mortazavi, A., Safekordi, A., & Tabil, L. G. (2007). Thin-layer drying characteristics and modeling of pistachio nuts. Journal of Food Engineering, 78(1), 98–108. https://doi.org/10.1016/j.jfoodeng.2005.09.007

Khattak, A. B., Zeb, A., Khan, M., Bibi, N., & Khattak, M. S. (2007). Influence of germination techniques on sprout yield, biosynthesis of ascorbic acid and cooking ability, in chickpea (Cicer arietinum L.). Food Chemistry, 103(1), 115–120. https://doi.org/10.1016/j.foodchem.2006.08.003

Kreyszig, E. (1999). Advanced engineering mathematics. New York: John Wiley & Sons, Inc.

Krokida, M. K., Karathanos, V. T., Maroulis, Z. B., & Marinou-Kouris, D. (2003). Drying kinetics of some vegetables. Journal of Food Engineering, 59(4), 391–403. https://doi.org/10.1016/S0260-8774(02)00498-3

Krokida, M. K., Oreopoulou, V., & Maroulis, Z. B. (2000). Water loss and oil uptake as a function of frying time. Journal of Food Engineering, 44(1), 39–46. https://doi.org/10.1016/S0260-8774(99)00163-6

Luchese, C. L., Gurak, P. D., & Markatz, L. D. F. (2015). Osmotic dehydration of physalis (Physalis peruviana L.). Evaluation of water loss and sucrose incorporation and the quantification of carotenoids. LWT - Food Science and Technology, 63(2), 1128–1136. https://doi.org/10.1016/j.lwt.2015.04.060

Maneesh Kumar, M., Prasad, K., Sarat Chandra, T., & Deb Nath, S. (2018). Evaluation of physical properties and hydration kinetics of red lentil (Lens culinaris) at different processed levels and soaking temperatures. Journal of the Saudi Society of Agricultural Sciences, 17(3), 330–338. https://doi.org/10.1016/j.jssas.2016.07.004

Maskan, M. (2001). Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. Journal of Food Engineering, 48(2), 177–182. https://doi.org/10.1016/S0260-8774(00)00155-2

Midilli, A., Kucuk, H., & Yapar, Z. (2002). A new model for single-layer drying. Drying Technology, 20(7), 1503–1513. https://doi.org/10.1081/DRT-12005864

Mohajari Islam, M., Zhang, M., Bhandari, B., & Guo, Z. (2019). A hybrid vacuum frying process assisted by ultrasound and microwave to enhance the kinetics of moisture loss and quality of fried edamame. Food and Bioproducts Processing, 118, 326–335. https://doi.org/10.1016/j.fbp.2019.10.004

Moreira, R., Cheno, F., Chaguri, L., & Fernandes, C. (2008). Water absorption, texture, and color kinetics of air-dried chestnuts during rehydration. Journal of Food Engineering, 86(4), 584–594. https://doi.org/10.1016/j.jfoodeng.2007.11.012

Mosavian, M. T. H., & Karizaki, V. M. (2012). Determination of mass transfer parameters during deep fat frying of rice crackers. Rice Science, 19(1), 64–69. https://doi.org/10.1016/S1672-6308(12)60022-5

Pan, Z., & Tangratanavee, W. (2003). Characteristics of soybeans as affected by soaking conditions. LWT - Food Science and Technology, 36(1), 143–151. https://doi.org/10.1016/S0023-6438(02)00202-5

Peleg, M. (1988). An empirical model for the description of moisture sorption curves. Journal of Food Science, 53(4), 1216–1217. https://doi.org/10.1111/j.1365-2621.1988.tb13565.x

Pramuk, P. V., Rizzi, R. L., do Prado, N. V., Coelho, S. R. M., & Bassinello, P. Z. (2015). Numerical modeling of chickpea (Cicer arietinum) hydration: The effects of temperature and low pressure.
Sacilik, K., Elicin, A. K., & Unal, G. (2006). Drying kinetics of Üryani plum in a convective hot-air dryer. *Journal of Food Engineering*, 76(3), 362–368. https://doi.org/10.1016/j.jfoodeng.2005.05.031

Sayar, S., Turhan, M., & Gunasekaran, S. (2001). Analysis of chickpea soaking by simultaneous water transfer and water-starch reaction. *Journal of Food Engineering*, 50(2), 91–98. https://doi.org/10.1016/S0260-8774(00)00196-5

Shafaei, S. M., Masoumi, A. A., & Roshan, H. (2016). Analysis of water absorption of bean and chickpea during soaking using Peleg model. *Journal of the Saudi Society of Agricultural Sciences*, 15(2), 135–144. https://doi.org/10.1016/j.jsasas.2014.08.003

Simal, S., Femenia, A., Garau, M. C., & Rosselló, C. (2005). Use of exponential, Page’s and diffusional models to simulate the drying kinetics of kiwi fruit. *Journal of Food Engineering*, 66(3), 323–328. https://doi.org/10.1016/j.jfoodeng.2004.03.025

Togrul, I. T., & Pehlivan, D. (2004). Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. *Journal of Food Engineering*, 65(3), 413–425. https://doi.org/10.1016/j.jfoodeng.2004.02.001

Turhan, M., Sayar, S., & Gunasekaran, S. (2002). Application of Peleg model to study water absorption in chickpea during soaking. *Journal of Food Engineering*, 53(2), 153–159. https://doi.org/10.1016/S0260-8774(01)00152-2

Vega-Gálvez, A., Andrés, A., Gonzalez, E., Notte-Cuello, E., Chacana, M., & Lemus-Mondaca, R. (2009). Mathematical modelling on the drying process of yellow squat lobster (Cervimunida jhoni) fishery waste for animal feed. *Animal Feed Science and Technology*, 151(3), 268–279. https://doi.org/10.1016/j.anifeedsci.2009.01.003

Vijayan, S., Arjunan, T. V., & Kumar, A. (2016). Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. *Innovative Food Science & Emerging Technologies*, 36, 59–67. https://doi.org/10.1016/j.ifset.2016.05.014

Yıldırım, A., Öner, M. D., & Bayram, M. (2011). Fitting Fick’s model to analyze water diffusion into chickpeas during soaking with ultrasound treatment. *Journal of Food Engineering*, 104(1), 134–142. https://doi.org/10.1016/j.jfoodeng.2010.12.005

Yıldız, A., Koray Palazoğlu, T., & Erdogdu, F. (2007). Determination of heat and mass transfer parameters during frying of potato slices. *Journal of Food Engineering*, 79(1), 11–17. https://doi.org/10.1016/j.jfoodeng.2006.01.021

How to cite this article: Bidkhori, P., & Mohammadpour Karizaki, V. (2022). Diffusion and kinetic modeling of water absorption process during soaking and cooking of chickpea. *Legume Science*, 4(1), e116. https://doi.org/10.1002/leg3.116