The temperature hydration kinetics of *Lens culinaris*

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**KEYWORDS**
Lentil; Rehydration; Kinetics; Temperature; Models

**Abstract** The aim of this study is to evaluate the hydration kinetics of lentil seeds (*Lens culinaris*) in water at different temperatures (25, 32.5, 40, 55, 70 and 80 °C) for assessing the adequacy of models for describing the absorption phenomena during soaking. The diffusion coefficient values were calculated using Fick’s model for spherical and hemispherical geometries and the values were in the range of $10^{-6}$ m²/s. The experimental data were fitted to Peleg, Sigmoidal, Weibull and Exponential models. The models adequacy was determined using regression coefficients ($R^2$), root mean square error (RMSE) and reduced chi-square ($\chi^2$). The Peleg model is the suitable one for predicting the experimental data. Temperature had a positive and significant effect on the water absorption capacities and absorption was an endothermic process.

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1. Introduction

The lentil is an edible pulse. The lentil is a bushy annual plant of the legume family, grown for its lens-shaped seeds. The lentils have the third-highest level of protein (about 30%) after soybeans and hemp (Callaway, 2004). The amino acids essential present in protein are isoleucine and lysine. Lentils also contain dietary fibre, folate, vitamin B₁, and minerals. Red (or pink) lentils contain a lower concentration of fibre than green lentils (11% rather than 31%). The energy provided by the lentil is similar to that of cereals and other pulses. Lentils are an important source of dietary essential minerals, these include macronutrients (K, P, Ca, Mg, Na), micronutrients (Fe, Zn, Cu, Mn) and trace elements (Al, Cr, Ni, Pb, Co, Se, Mo) (Yadav et al., 2007).

The knowledge of the physical properties of lentil seeds is essential for the design of equipment such as for handling, processing and storing of it. The hydration process is, thus, an important unit operation in dried foods, as it describes and defines its properties and using during cooking, extraction, fermenting, germinating and eating. Therefore, it is important to understand the hydration kinetics of different food products, as well as the influence of process conditions (as temperature) on its rate (Oliveira et al., 2013). Abou-Samaha et al. (1985) observed that the soaking in tap water and in saline solution led to increases of the hydration coefficient, weight of seeds, inorganic phosphorus and phosphorus fraction other than phytate phosphorus, solubility of nitrogen and in vitro protein digestibility, and to reduce the cooking time and tannins and improve the seed colour of lentils. Joshi et al. (2010) observed that the same cultivar might have different water uptake
behaviour at the same temperature in function of the seed surface area. They observed that the French-green lentil type was able to imbibe the largest amount of water which can be attributed to its highest seed surface area to volume ration and the highest protein content indicating that at elevated water uptake do not depend on their pore characteristics.

The objectives of this study were to study the temperature dependent water absorption kinetics of lentil seeds (Lens culinaris) and to assess several mathematical models in terms of their adequacy to describe water absorption by chickpea splits.

2. Materials and methods

2.1. Materials

Lentil samples (L. culinaris) were purchased from a local supermarket from the Suceava county, Romania. The lentil samples were cleaned in an air classifier to remove foreign matter. The initial moisture content of lentil was determined using a hot air oven method (Prasad et al., 2010).

2.2. Physical properties

Physical properties (dimensions, mass, bulk density, true density, porosity, geometric mean diameter, sphericity, surface area, porosity, coefficient of static friction) of lentil were determined according to standard methods (Ghadge et al., 2008).

2.3. Water absorption experiments

Soaking experiments were made up at 25, 32.5, 40, 55, 70 and 80 °C. About 20 g of lentil seeds was placed in 600 ml Erlenmeyer flasks which contained 300 ml of distilled water which was already preset to the desired temperatures in a constant temperature water bath (Lauda, Germany). The flasks were covered with aluminium foil to prevent moisture loss during the study. The samples were removed at 10 min interval for up to 3 h. After the desired time, the soaked samples were quickly blotted on paper towels to remove excess moisture adhering on the surface (Vishwakarma et al., 2013), weighed and analysed immediately for moisture content.

2.4. Water kinetics

The hydration kinetics can be described using empirical and theoretical models. For describing the moisture diffusion of different seeds has been used the Fick’s second law of diffusion for a spherical geometry (Prasad et al., 2010).

\[
\frac{\partial M}{\partial t} = \nabla(D \nabla M)
\]  \hspace{1cm} (1)

where \( M \) is moisture content at any given instant \( t \) (kilograms per kilogram, d.b.), \( t \) is time (seconds) and \( D \) represents moisture diffusivity (square metres per second). In 1975, Crank gives some analytical solutions for the Fick’s second law for bodies of regular shape such as sphere, cylinder and slab.

The simplified form of the infinite series diffusion equation (Crank, 1975) was used to model the water absorption process in the seeds:

\[
MR = \frac{M - M_0}{M_S - M_0} = \sum_{i=0}^{\infty} A_i \exp(-D_i^2 t)
\]  \hspace{1cm} (2)

where \( MR \) – moisture ratio (dimensionless), \( M_0 \) – initial moisture content (% dry basis), \( M \) – moisture content at any time of soaking, \( M_S \) – saturation moisture content, \( A_i \) – constant for a given solid shape. The infinite series of the right-hand side of the equation converges rapidly to the first term after a finite soaking period. Thus, equation could be rewritten as follows:

\[
MR = \frac{M - M_0}{M_S - M_0} = A_0 \exp(-D_0^2 t)
\]  \hspace{1cm} (3)

where \( D_0^2 = -k \) is defined as the water absorption rate constant. Nonlinear regression procedure was used to estimate the value of \( k \); subsequently, values of \( D \) and \( A_0 \) were calculated.

Assuming that the lentil is a spherical grain, the diffusion equation can be simplified to the first term of the summation with an error of less than 0.1% (Bello et al., 2004):

\[
MR = \frac{M - M_0}{M_S - M_0} = 6 \frac{\pi^2}{4} e^{-\frac{t}{4D_0}}
\]  \hspace{1cm} (4)

If the lentil is being assumed to be hemispheric, Newman’s solution can be given (Walde et al., 2006) as follows:

\[
MR = \frac{M - M_0}{M_S - M_0} = 1 - 6 \frac{\pi^2}{4} e^{-\frac{t}{4D_0}}
\]  \hspace{1cm} (5)

The values of diffusion coefficient, \( D \), of lentil were fitted to an Arrhenius relationship of the type:

\[
D_e = D_0 \cdot \exp \left( \frac{E_a}{RT} \right)
\]  \hspace{1cm} (6)

where \( D_0 \) – a constant (square metres per second), \( E_a \) – activation energy (kJ/mol), \( R \) - gas constant (8.314 J/mol K), and \( T_0 \) – absolute temperature (K).

2.4.1. Empirical models

The Peleg’s equation (Peleg, 1998) is the most used model to describe the food products hydration phenomena. This equation involves two parameters and describes a continuous change from a first-order (at \( t \to 0 \)) to a zero-order (at \( t \to \infty \)) kinetic. The Peleg’s equation expression is as follows:

\[
M(t) = M_0 + \frac{t}{k_1 + k_2 \cdot t}
\]  \hspace{1cm} (7)

where \( k_1 \) and \( k_2 \) are parameters models.

This model is one of the suitable for hydration data, but it cannot describe an initial lag phase, which is observed during the hydration of some dried grains. Kaptso et al. (2008) proposed another models which describe a sigmoidal behaviour with an initial lag phase followed by a high absorption rate phase and, finally, by a stationary phase, using three parameters: \( \tau \) (that describes the function inflection point, and related the lag phase), \( k \) (the kinetic parameter) and \( M_{eq} \) (the moisture at the equilibrium, that relates the maximum water absorption). The sigmoidal model is described as follows:

\[
M(t) = \frac{M_{eq}}{1 + \exp[-k \cdot (t - \tau)]}
\]  \hspace{1cm} (8)
The temperature hydration kinetics of Lens culinaris

Another model used for hydration phenomena is the Weibull model (Machado et al., 1999):

\[ M_R = \frac{M_S - M_t}{M_S - M_0} = \exp \left( \frac{-t}{\beta} \right) \]  

(9)

where \( \alpha \) is shape parameter (dimensionless) and \( \beta \) is scale parameter (minutes). The Weibull model reduces to the exponential model when \( \alpha = 1 \).

The rate of water uptake is directly proportional to the difference between the saturation moisture content and the moisture content of the bean at any given time (Prasad et al., 2010):

\[ \frac{dM}{dt} = -(M - M_s) \]  

(10)

Integration of the above equation with the initial conditions of \( M = M_s \) at \( t = 0 \) and \( M = M_0 \) at \( t = 0 \) yields to an exponential model as follows:

\[ M_R = \frac{M_S - M_t}{M_S - M_0} = e^{-k_t} \]  

(11)

where \( k \) is the hydration rate constant.

2.5. Statistical analysis

The water absorption data were fitted to all models for the temperature range under study. The nonlinear regression was used for fitting the experimental data to the models. The adequacy of the models was evaluated and compared using the coefficient of determination (\( R^2 \)), root mean square error (RMSE) and reduced chi-square (\( \chi^2 \)):

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(R_{exp,i} - R_{pre,i})^2}{N}} \]  

(12)

\[ \chi^2 = \frac{\sum_{i=1}^{n}(R_{exp,i} - R_{pre,i})^2}{N - n} \]  

(13)

where \( R_{exp,i} \) is the \( i \)-th experimental value, \( R_{pre,i} \) is the \( i \)-th predicted value, \( N \) is the number of observations and \( n \) is the number of constants. The value of RMSE represents the fitting ability of an equation in relation to the number of data points. The smaller the RMSE value, the better the fit of an equation (Doymaz, 2004). The model is considered a good fit when the coefficient of determination (\( R^2 \)) is high and the reduced chi-square (\( \chi^2 \)) is low (Palipane and Driscoll, 1994).

3. Results and discussions

3.1. Physical properties

The physical properties of lentils are presented in Table 1. The lentil length, width, thickness and geometrical mean diameter ranged between 5.550–7.390, 5.29–6.950, 2.190–2.720 and 4.006–5.188 mm respectively. Mohsenin (1986) has highlighted the imperativeness of the axial dimensions in machine design, the comparison of the data with existing work on the other seeds can be sufficient in making symmetrical projection towards process equipment adaptation (Ghadge and Prasad, 2012).

The lentil values for sphericity and aspect ratio 71.139–70.214 and 0.940 and 0.953 help us to conclude that the shape of the lentils can be considered as a sphere (Omobuwajo et al., 2000), however they could slide on their flat surfaces. Knowledge of the tendency to either roll or slide is necessary in the design of hoppers for a milling process. The surface area ranged between 69.239 and 75.561 mm². Surface area is a relevant parameter in determining the shape of a seed, and is an indication of the way seeds will behave on oscillating surfaces during processing. The average split weight was 0.00613–0.00676 g. Weight is an important parameter in the design of grain cleaning systems which employ aerodynamic forces (Oje and Ugbor, 1991). The true density 1.229–1.382 g/cc. The porosity ranged between 44.039 and 48.123%.

The frictional properties examined for the seeds are the angle of repose and the coefficient of static friction. The angle

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Some physical properties of lentil seeds.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties</td>
<td>Unit of measurement</td>
</tr>
<tr>
<td>Length</td>
<td>mm</td>
</tr>
<tr>
<td>Width</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
</tr>
<tr>
<td>Geometric mean dimension</td>
<td>mm</td>
</tr>
<tr>
<td>Surface area</td>
<td>mm²</td>
</tr>
<tr>
<td>Unit mass</td>
<td>G</td>
</tr>
<tr>
<td>True density</td>
<td>g/cc</td>
</tr>
<tr>
<td>Bulk density</td>
<td>g/cc</td>
</tr>
<tr>
<td>Porosity</td>
<td>%</td>
</tr>
<tr>
<td>Sphericity</td>
<td>%</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>%</td>
</tr>
<tr>
<td>Mass of 1000 kernel</td>
<td>g</td>
</tr>
<tr>
<td>Angle of response</td>
<td>Degrees</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td></td>
</tr>
<tr>
<td>Galvanized steel</td>
<td></td>
</tr>
<tr>
<td>Moisture (w.b.)</td>
<td>%</td>
</tr>
</tbody>
</table>

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of repose was 56.489°. This parameter is important in grain processing, particularly in the design of hoppers for milling equipment. The coefficient of static friction was 0.975 on glass, 0.937 on plywood and 0.463 on a galvanized steel sheet. The values for coefficient of static friction are greater than in the case of *Cicer arietinum* splits (Prasad et al., 2010).

### 3.2. Kinetics of water absorption

The water kinetics of lentils and the duration of hydration at temperatures of 25, 32.5, 40, 55, 70 and 80 °C are presented in Fig. 1. The moisture diffusion into lentils takes place because of the moisture gradient between the surface and the centre (Prasad et al., 2010). The temperature influences the rate of water absorption. The splits exhibited an initial high rate of moisture absorption followed by a slower rate of water absorption in the later or relaxation phase. Transition between the primary and the second phases occurred after approximately 40 min of soaking as determined. As expected for a thermally process, as the soak water temperature was increased, the initial slope of the water intake curve increased, and the time taken to achieve the equilibrium moisture content consequently decreased (Fig. 1). The results are in agreement with those reported in the case of chickpea splits (Prasad et al., 2010), rice (Shittu et al., 2012) and guar splits (Vishwakarma et al., 2013).

The moisture at the equilibrium ($M_s$) increased to 40°C, and after these temperatures it decreased (Fig. 1). The same evolution was observed in the case of bambara (Jideani and Mpotokwana, 2009), chickpeas (Gowen et al., 2007) and adzuki beans (Oliveira et al., 2013).

The behaviour of the moisture at the equilibrium was proposed by Gowen et al., 2007 to be a linear decreasing equation. In the case of lentil, the linear equation has the next form:

$$M_s(T) = 1.281 - 0.001 \cdot T$$  \hspace{1cm} (14)

where $T$ is the temperature (°C). The regression coefficients of the Eq. (14) ($R^2 = 0.759$) are smaller than in the case of adzuki beans (Oliveira et al., 2013). The reduction on the $M_s$ was proposed by Abu-Ghannam and McKenna (1997) to be related to the higher extraction of water soluble components of the grain at higher temperatures. Moreover, two other possibilities to explain the $M_s$ behaviour are related to the cell integrity and to the mass transfer phenomenon to the grain. Firstly, it is expected that the higher temperatures damage the cell membranes, resulting in lower water holding capacity. Secondly, as the hydration rate is faster at higher temperatures, the seeds edges quickly absorb water, which, when the external layer is saturated, reduce the mass transfer from the soaking water to the grain surface (Oliveira et al., 2013).

The values of the Eq. (3) parameters for lentil at different soaking temperatures are presented in Table 2. The water absorption constants ($A_i$) for the lentil ranged between 0.961 and 0.996. These values are in the same range with those reported in the case some rice varieties (Shittu et al., 2012).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature</th>
<th>$A_i$</th>
<th>$K$ (min$^{-1}$)</th>
<th>$R^2$</th>
<th>RMSE (%)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lentil</td>
<td>25</td>
<td>0.996</td>
<td>0.019</td>
<td>0.995</td>
<td>1.952</td>
<td>0.00045</td>
</tr>
<tr>
<td></td>
<td>32.5</td>
<td>0.978</td>
<td>0.023</td>
<td>0.994</td>
<td>2.130</td>
<td>0.00054</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.963</td>
<td>0.032</td>
<td>0.992</td>
<td>2.440</td>
<td>0.00071</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>0.961</td>
<td>0.048</td>
<td>0.986</td>
<td>2.990</td>
<td>0.00106</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>0.982</td>
<td>0.087</td>
<td>0.984</td>
<td>2.920</td>
<td>0.00101</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>0.981</td>
<td>0.092</td>
<td>0.977</td>
<td>3.430</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature</th>
<th>Spherical geometry</th>
<th>Hemispherical geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$D_e \cdot 10^{-6}$ (m$^2$/s)</td>
<td>$D_0$</td>
</tr>
<tr>
<td>Lentil</td>
<td>25</td>
<td>2.941</td>
<td>5.02 · 10$^{-2}$</td>
</tr>
<tr>
<td></td>
<td>32.5</td>
<td>4.006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>5.170</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>7.690</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>13.440</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>13.630</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1  Hydration kinetics as function of temperature.
It can be observed that $K$ is increasing with the increasing of the temperature. The rate constant of water absorption ($K$) also increased as the soaking temperature increased from 25 °C to 85 °C due to increased rate of moisture diffusion.

The diffusion coefficients ($D_e$) have been reported for spherical and hemispherical geometries (Eqs. (4) and (5)). The hemispherical diffusion coefficients of lentil seeds are greater than in the case of spherical geometry. However keeping into account the sphericity of lentil the values of diffusion coefficients for spherical geometry would be much correct. This increase in temperature altered the rate of diffusion and thus affected the overall absorption behaviour. A further increase in temperature may damage the structural integrity, promote gelatinization of starch and thus affect the weight gain behaviour of subjects correspondingly.

The Arrhenius equation (Eq.(6)) was used to describe the effect of temperature on the diffusion coefficients of lentil seeds. The activation energy for the spherical geometry was 6 times bigger than the activation energy for the hemispherical geometry. The value of 23.98 kJ/mol is higher than in the case of *C. arietinum* splits (Prasad et al., 2010).

3.2.1. Fitting of model equations

Table 4 presents the results of nonlinear regression analysis of fitting the Peleg, Weibull, Sigmoidal and Exponential models to the experimental data. It is evident that all of the models accurately described the water absorption characteristics of chickpea splits at hydration temperatures from 25 to 85 °C as $R^2$ values were equal to or higher than 96.5%, RMSE values were lower than 8.17 and $\chi^2$ values were lower than 0.001 (Table 4).

In the case of Peleg’s model, the rate constant values, $k_1$, decreased with the increasing of the temperature in a linear way from 0.698 to 0.080 h/% mc (db) (Table 3). The lower $K_1$ at 85 °C reflects the higher initial water absorption rate for lentil seeds. The term $1/k_1$ is termed the initial rate of absorption, thus at a given temperature, as $k_1$ decreases, the amount of water absorbed becomes greater. Several investigators have reported similar results for other seeds and grains (Cunningham et al., 2007).

The relation between the rate of water absorption and the size of lentil seeds is an inverse one, as the larger seed provides a smaller specific surface for moisture transfer (Maskan, 2001). The mean value for the specific surface area of lentil seeds was $71.139 \text{ mm}^2$. In the later stages of the soaking process, the effective diffusion is lower because the rate of absorption slows. The higher initial water absorption rate can be explained by diffusion phenomenon, specifically the greater driving force created by the larger moisture gradient. As hydration proceeds, the water content increases, decreasing the driving force and consequently the sorption velocity. With the decrease in driving force, the soluble solids offer additional resistance to water transfer (Sayar et al., 2001). The capacity constant, $k_3$, of the Peleg’s model showed a significant increase with temperature from 0.654 to 1.025 (Table 4). This is due to a decrease in the water absorption capacity of seeds as temperature increases (Sopade and Obeka, 1990). An inverse relationship exists between $k_3$ and the water absorption capacity of splits. Water absorption capacity depends upon cell wall structure, composition of the seed and the compactness of the cells in the seed (Oliveira et al., 2013).
The kinetic parameter of the sigmoidal model \( (k_3) \) increased exponentially when the soaking temperature was increased (Table 4, Fig. 2), indicating higher water absorption rates. In fact, the water diffusivity through the product is expected to be higher at higher temperatures due to the lower fluid viscosity and higher grain pores. Finally, the parameter \( \tau \), i.e., the time to the hydration curve inflexion point was evaluated. This parameter indirectly relates the lag phase as up to the inflexion point the hydration rate is increasing. The lag phase is a consequence of the seed coat structure, which is resistance to the water flow. The parameter \( \tau \) decreased exponentially when the soaking temperature was increased (Fig. 3), reflecting the same reduction on the lag phase. It is the similar behaviour to those observed for cowpea and bambara (Kaptso et al., 2008) seeds. The \( \tau \) reduction can be related to the explained \( k_3 \) behaviour. As the temperature is increased, the seeds coat hydration is faster, reducing the resistance to the water intake.

From the Weibull shape parameter, \( z \), (Table 4), it can be inferred that at the beginning of the absorption process the kinetics at higher temperatures were faster than at lower ones (Table 4). The shape parameter, \( z \), is a behaviour index that depends upon the process mechanism and the higher its value, the slower the process in the initial phase of absorption (Machado et al., 1999). Thus, the inverse of the parameter was considered an indicator of the initial rate of the hydration process. Table 4 confirms that the rate of absorption was sensitive to temperature. A change in temperature affects the rate of diffusion, thus changing the overall absorption behaviour. This implies that with an increase in temperature from 25 to 85 °C, the rate of absorption in the first phase of process was accelerated by a factor of 1.83.

The Exponential model was fitted to the experimental data and the equations parameters are presented in Table 4. A greater rate of hydration was observed at higher water temperatures. At a higher temperature, a larger proportion of the water is absorbed in the first phase of the process and the product reaches equilibrium in a shorter time of soaking. At lower temperatures, less water is absorbed in the first phase of process and absorption occurs to a greater extent in the second phase (Oliveira et al., 2013).

4. Conclusions

The work presents the influence of time and temperature upon the hydration kinetics of \( L. \) culinaris. The experimental data were subjected to nonlinear regression using Peleg, Sigmoidal, Weibull and Exponential models. The Peleg model predicted better than the others one the evolution of experimental data. The results obtained can be used for product development, food properties and process design.

Conflict of interest

The author declares that there are no conflicts of interest.

References


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