Applying Peleg's equation to modelling the kinetics of solid hydration and migration during soybean soaking

Aplicación de la ecuación de Peleg para modelar la cinética de hidratación y de migración de sólidos durante el remojo de soya

M. C. Quicazán[1], L. A. Caicedo[2], M. Cuenca[3]

ABSTRACT

Legume soaking is an important practice in food processing; the characteristics of beverages and tofu mainly depend on this operation regarding soybeans. Peleg's equation has been used in this work to describe the kinetics of water absorption and solid loss during soaking at 20°C, 40°C and 80°C. The moisture content of grain and solids in the remaining water was measured for 10 hours. Variance analysis and principal components analysis showed high fitting of kinetics to Peleg's equation for predicting both transference phenomena. This work found that the value of k_1 (rate) depended on temperature according to a polynomial function while k_2 (capacity) did not, meaning that the value of equilibrium moisture content was independent of soaking temperature. k_1 had the minimum value for the migration of solids to soaking water at 40°C; this was related to lost solids' high speed and the microbial degradation of carbohydrates; the values obtained for k_2, showed that it was possible to lose total soluble solids at 20°C, while further migration of insoluble compounds occurred at 80°C

Keywords: Soybean, hydration, Peleg's equation, solid migration.

RESUMEN

El remojo de leguminosas tiene gran importancia en los procesos de elaboración de alimentos, a partir de ellas. En la soya las características de las bebidas y el tofu dependen fundamentalmente de esta etapa. En este trabajo se utilizó la ecuación de Peleg para describir la cinética de absorción de agua y de pérdida de sólidos durante el remojo de semillas de soya a 20, 40 y 80 °C. Se efectuaron mediciones, durante diez horas, de la humedad del grano y del contenido de sólidos en el agua remanente. Mediante análisis de varianza y de componentes principales se comprobó un alto grado de ajuste de la ecuación de Peleg para predecir los dos fenómenos de transferencia. Sobre la hidratación se encontró que el valor de k_1, constante de velocidad, depende de la temperatura y obedece a una función polinómica de esta, mientras que k_2, constante de capacidad, es independiente de la temperatura, lo cual implica que el valor de la humedad de equilibrio es independiente de la temperatura de remojo. Para la pérdida de sólidos se encuentra que a 40 °C se presenta el valor mínimo de k_1, lo cual tiene que ver con la alta velocidad de emigración de sólidos y está relacionado con la disponibilidad de carbohidratos para la degradación microbiana; para k_2, los valores obtenidos indican que a 20 °C es posible perder el total de sólidos solubles, mientras que a 80 °C se produce adicionalmente migración de compuestos no solubles.

Palabras clave: soya, hidratación, ecuación de Peleg, migración de sólidos.

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Introduction

Although the basic principles of hydration are unique, their study has been emphasised in non-food substances(Karoglou *et al.*, 2005). What happens in one food material is very different from another. Soaking common beans has aready been evaluated(Abu-Ghannam & McKenna, 1997a), as has wheat (Roman-Gutierrez *et al.*, 2002), mushroom dehydration and rehydration (Garcia-Pascual *et al.*, 2005) and effects on seed texture(Bayram *et al.*, 2003). Many studies have examined the transformation occurring in seeds and soaking water composition as time elapses(Bayram *et al.*, 2004; Nashed *et al.*, 2003). Soybeans have an atypical composition; their fat and protein content are high but in practice they are the only legume lacking starch content; their carbohydrates are essentially insoluble dietary fiber and oligosaccharides. Soybeans are now appreciated for their bioactive compound content whose functionality and concentration are affected during soaking (Góes-Favoni *et al.*, 2010; Vijayakumari *et al.*, 2007; Wardhani *et al.*, 2008).

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Peleg's model

Studies have been focused on understanding the principles governing hydration and dehydration for more than fifty years now(Becker 1960), trying to apply Fick's law to understand the phenomenon. Such studies have been extended to seeds like maize and other seeds (Fan *et al*., 1965; Turhan *et al*., 2002). Some models consider that the diffusion coefficient is independent of temperature and that transfer surface resistance is negligible (Abu-Ghannam, & McKenna, 1997b). Three seed hydration models, (Peleg, 1988; Pilosof *et al*., 1985), involving non-exponential equations, have parameters that can be interpreted in practical hydration kinetics. The equivalence of the three models has been demonstrated, having identical predictive ability for wheat starch, some seeds and some types of protein (Sopade, *et al*., 2007), and their applicability for dehydration and extension to the Arrhenius model (Harrynanan & Sankat, 2008). Peleg's model is more used and is represented in equation (1), which can be rearranged to obtain equation (2):

$$M = M_0 + \frac{t}{k_1 + k_2 t} \tag{1}$$

$$\frac{t}{M - M_0} = k_1 + k_2 t \tag{2}$$

where:

M: % grain moisture content, dry basis
t: soaking time
k_1: Peleg's rate constant (time^{-1}. %$^{-1}$ w.b.)
k_2: Peleg's capacity constant (%$^{-1}$ w.b.)

The first constant is inversely related to the speed at which water absorption by the seed occurs, while the second constant is related to its ability to absorb water. If time goes to infinity, equation (3) shows the expression for equilibrium moisture content, dry basis (M_e):

$$M_e = M_0 + \frac{1}{k_2} \tag{3}$$

According to equation (2), a plot of t / (M-M0) against time gives a straight line, where k1 is the intercept on the ordinate and k2 is the slope of the line. The rate of hydration (W) is given by equation (4):

$$W = \frac{dM}{dt} = \frac{k_1}{(k_1 + k_2 t)^2} \tag{4}$$

In evaluating W at the beginning of the process (W_0), t → 0, W = W_0, expression (5) shows W_0 (the initial rate of hydration), as the reciprocal of k_1:

$$W_0 = \left.\frac{dM(t)}{dt}\right|_{t\to 0} = \frac{1}{k_1} \tag{5}$$

Some studies have been related to soybeans for modelling hydration and its relationship with texture (Pan & Tangratanavalee, 2003) but solid behaviour has not been studied. This paper attempts to evaluate and model the effect of temperature on hydration rate and total solids' leaching during soybean soaking, focused on understanding the resulting implications when preparing beverages.

Materials and methods

Soybeans

A Colombian variety of soybean, Soyica P-33 (non-GM) a crop from the Valle del Cauca department in Colombia, was used for the experiments. Proximate composition was determined according to AOAC methods (AOAC International, 1998): moisture method (925.10), ash by gravimetric method using incineration (942.05), protein by the Kjeldahl method (960.52), crude fibre (962.09) and crude fat by Soxlhet method (945.39).

Soybean soaking

A completely randomised block design was used, involving three treatments using 20°C, 40°C and 80°C soaking temperature. 10 steel containers were taken for each test containing 100g of soybean and 300 of water at the test temperature; one container was taken each hour, over a 10-hour period. The variables measured were grain weight, the weight of the remaining liquid and its solid content (dry matter content by gravimetric method using oven drying at 103°C forced air until constant weight, according to AOAC method 952.10, 1998).

Statistical analysis

Principal component analysis (PCA) was used for variance behaviour. Variance was analysed (ANOVA) (α=0.05) to determine the effect of time and temperature on response variables. Differences in mean values were evaluated using a Tukey test (95% reliability). Matlab R 2009b management software was used for analysing this information.

Results and discussion

Table 1 presents the results obtained for the soybeans' proximate composition, expressed on a wet and dry basis.

Table 1: Proximate composition and carbohydrates regarding the soybeans used here

Component	Content % w.b.	Standard deviation	Content % d. b.
Moisture	9.10	0.14	10.02
Protein	36.20	0.33	39.82
Fat	21.88	0.10	24.07
Ash	4.49	0.05	4.94
Crude fibre	4.58	0.29	5.04
Total solids	90.90	0.74	100.00

Water absorption

Figure 1 gives the mean values of the results obtained for hydration. The analysis of variance (α=0.05) had significant differences regarding the results for both the effect of time and temperature; higher degrees of hydration occurred at 40°C. The rate of water absorption decreased as time elapsed for all temperatures tested.

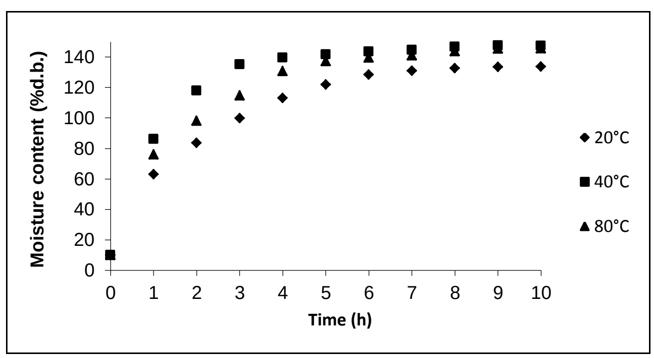

Figure 1. Soybean moisture content (dry basis) compared to hydration time at three temperatures

Maximum water uptake occurred after 8 hours at 40°C when it reached 147% moisture; this value was greater than that reported by other authors (Pan & Tangratanavalee, 2003) (140%) and (Chopra & Prasad, 1994) (129%). The soybeans in the present study absorbed more water and faster at 40°C than at 20°C. However, at 80°C the proportion of water absorbed and the rate of hydration was lower than the rate at 40°C. This result did not agree with that reported by other authors for wheat starch (Sopade & Okonmah, 1993); this might have been due to special aspects regarding soybeans' chemical composition as protein content was quite high and starch was virtually zero. Figure 2 gives the PCA results, taken every hour; samples were compared to the first component and showed the overall hydration kinetic profile, having a typical saturation form. 98.9% variance was explained by the first main component and the first four hours had the greatest variance.

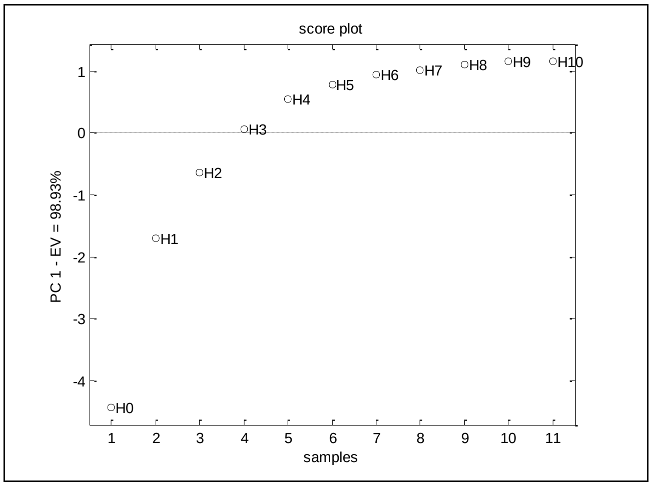

Figure 2. PC1 time: soybean moisture content during hydration at the three test temperatures, obtained by PCA.

According to Peleg's model, initial seed moisture (M_o) has an effect on hydration kinetics. In real terms, some studies recommended harvesting soybeans having 13% and 15% moisture content when plant foliage has begun to dry out; seeds should then be dehydrated at 60°C to reach 9% to 10% moisture content (equivalent to 10% and 11%, dry basis). If moisture content is above 15%, then seeds deteriorate very quickly whereas if moisture content is less than 13% when soybeans are harvested, then seed pods tend to open, facilitating grain contamination. If the seeds' moisture content is too low (below 10% on harvesting) the soybeans tend to crack and therefore the quality indexes and price drop (Iowa State University, Univerity Extension, 2008). Peleg's model would thus only apply to initial moisture values between 10% and 11% in the case of soybeans, thereby providing practical versatility. Figure 3 shows the actual results which could be predicted by applying Peleg's model.

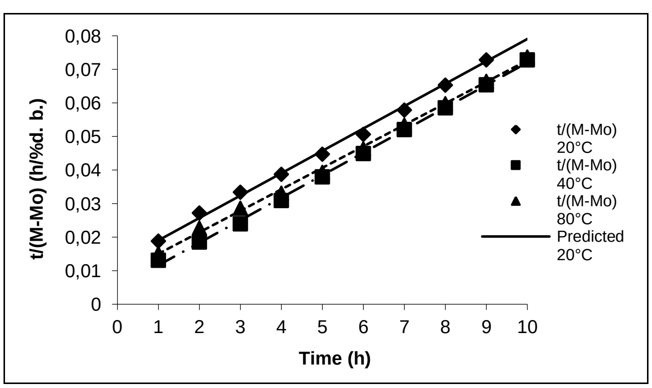

Figure 3: Applying Peleg's model to soybean hydration at different temperatures

Table 2 shows the parameters found for this model and the correlation coefficient for each temperature tested. It was found that, regardless of temperature, the value of k_2 was the same, implying that equilibrium moisture content (M_e) was the same. This fact was consistent with that found for cereals (Sopade *et al.*, 1992) and beans (Abu-Ghannam & McKenna, 1997a).

Table 2: The Peleg model's parameters for soybean hydration at three temperatures

Temperature	Parameter					
	M_o	k_1	k_2	W_o	M_e	R^2
20°C	10.02	0.0124	0.0067	80.64	159	0.9966
40°C	10.02	0.0049	0.0067	204.08	159	0.9986
80°C	10.02	0.0086	0.0064	116.27	166	0.9979

The k_1 values had a special pattern; k_1 was less at 40°C than at 20°C. This implied higher initial hydration rate at 40°C. The k_1 value was intermediate at 80°C. These values matched, respectively, the 40°C and 80°C values found for beans (Abu-Ghannam, N. McKenna, 1997b). By contrast, there was no agreement with the results for soybeans found by other authors (Pan & Tangratanavalee, 2003) as k_1 dropped when temperature increased. Wheat (Maskan, 2002), amaranth grain (Calzetta-Resio, Aguerre, & Suarez, 2006) and *Botswana bambara* (Jideaniand & Mpotokwan, 2009) have been shown to have a pattern showing increased hydration rate as temperature increases. This could be explained by the effect of high temperatures on soy proteins (contrary to the behaviour of starch); these nutrients become denatured or coagulated, thereby losing hydration capacity. The dependence of k1 on T (absolute temperature) was explained by equation (6), a polynomial function having a high correlation coefficient (R^2=1) and differed from the correlations found for soybeans by other authors: k_1=-0.0001T +0.0081(Pan & Tangratanavalee, 2003):

$$k_1 = -0.000008T^2 - 0.0051\,T + 0.8376 \qquad (6)$$

Regarding the value of k_2, no difference was found regarding hydration temperature. The numerical value of k_2 coincided with that found in other work (Abu-Ghannam & McKenna, 1997b) (k_2 = 0.0067) for non-blanched beans and equilibrium moisture value therefore coincided. This behaviour was also different from the results reported by other authors in terms of k_2 decreasing with temperature, for soybeans (Pan & Tangratanavalee, 2003), chickpeas (Turhan *et al.*, 2002), amaranth (Calzetta- Resio *et al.*, 2006), beans and groundnuts (Sopade & Kaimur, 1999) and wheat (Maskan, 2002). On the contrary, it has been found for some African nuts that k_2 has increased with temperatures ranging from 25°C to 75°C (Jideaniand & Mpotokwan, 2009). Such discrepancies may indicate that, depending on seed type and chemical composition, there may be different equilibrium moisture depending on temperature; however, the soybean discrepancies may have been related to differences in the expression of moisture and corrections for the loss of solids.

Migration of solids

Figure 4 displays the results for solid loss compared to time at the temperatures tested here. According to variance analysis, both time and temperature had an effect on solid migration. However, this pattern was different to that found for hydration. Data was taken for more than 8 hours at 20°C, but a reduction in solid content values for hydration fluid was noticed after three hours soaking at 40°C; this agreed with that reported in other studies (Pan & Tangratanavalee, 2003) and was caused by sugar fermentation at this temperature, which is very suitable for mesophilic and thermophilic microorganism growth.

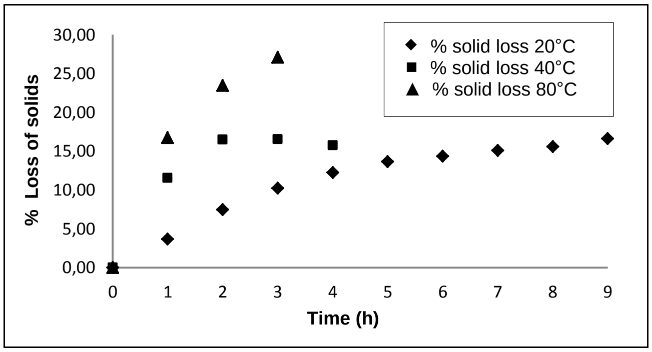

Figure 4. Loss of soybean solids compared to hydration time at the three temperatures tested here

Solid migration rate increased with temperature. The pattern during the last hours was only important at 80°C; a virtually complete extraction of soluble solids could be performed at this temperature with an effect on other compounds. Overall kinetic behaviour was scanned by evaluating the PCA results for the first 4 hours (Figure 5). The variance was mostly explained by the first principal component (PC1) (95.53% total variance); the greatest variance occurred during the first hour of hydration for the temperatures tested here.

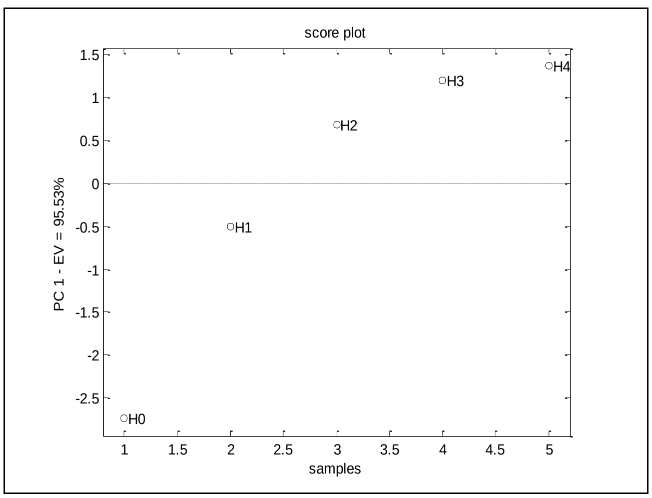

Figure 5. PC1 time resulted in the loss of solids from the soybean during hydration at the three test temperatures (PCA)

Peleg's equation can also be used for evaluating solid migration from seed to liquid during soaking, but in the opposite direction to hydration, by analysing the phenomenon occurring in the seed as a stripping of these components with time (t) and taking the initial amount of solids in soybeans (Mo) as the basis for expressing the percentage of this loss (M), and taking changes in the soaking liquid due to hydration into account. Figure 6 shows the actual and expected results from applying the model.

Table 3 shows the model's parameters and the correlation coefficient for each temperature. The value of k_1 at 20°C was greater than at 40°C, whereas such value was intermediate at 80°C. The behaviour of the inverse of this constant, defined as the initial specific rate of solid loss, was similar to that of hydration; it was observed that the initial rate at 40°C was the highest and that the value was different than that expected at 80°C. Chemical changes in seed cuticle and cotyledon are probably important at this temperature, thereby preventing solid departure. By contrast, 40°C leads to these components' easy hydration and promotes solute migration into the soaking water.

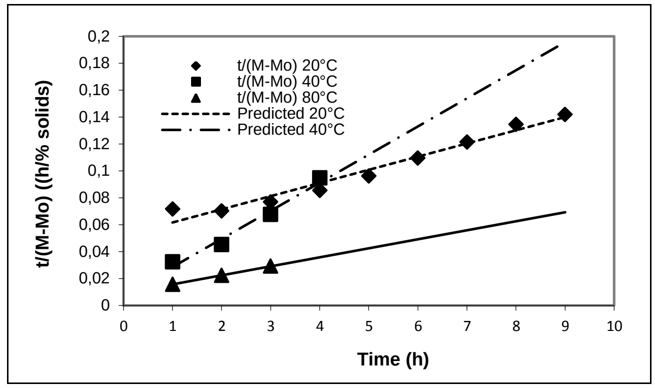

Figure 6. Applying Peleg's model to carbohydrate migration to water during soybean soaking

Table 3: Peleg's model parameters regarding soybean solid migration during soaking

Temperature	Parameter					
	M_o	k_1	k_2	W_o	M_e	R^2
20°C	100.0	0.0518	0.0098	19.30	102	0.9666
40°C	100.0	0.0075	0.0209	133.33	48	0.9771
80°C	100.0	0.0089	0.0067	112.36	149	1

Me values greater than 100%, for 40°C and 80°C, reflected grain components' outflow facility. In accordance with other studies (Bayram *et al*., 2004), the effect of temperature on grain was actually softening, thereby leading to easy migration of solids (not necessarily initially counted as being water-soluble) outward from the seed in addition to soluble carbohydrates, leaving minerals, polysaccharides present in the fibre and pigments. This has been observed in other seeds by other researchers (Vijayakumari *et al*., 2007, 1998). A polynomial function (equation 7) between absolute temperature and k1 would thus be given by:

$$k_1 = 0.00004\, T^2 - 0.025\, T + 4.1436 \qquad (6)$$

Conclusions

The kinetics of hydration and solid loss during soybean soaking had a pattern which adjusted appropriately to Peleg's equation, despite significant differences concerning structure and composition regarding previously-studied seeds. The equilibrium moisture content reached during soaking was independent of temperature (a most important aspect) while solid loss did depend on temperature.

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