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MODELLING OF WATER ABSORPTION IN CHICKPEA (*Cicer arietinum* L) SEEDS GROWN IN MEXICO´S NORTHWEST

MODELADO DE LA ABSORCIÓN DE AGUA EN SEMILLAS DE GARBANZO (*Cicer arietinum* L) COSECHADAS EN EL NOROESTE DE MÉXICO

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Abstract Chickpea is a legume with good nutritional value and commercial importance in Mexico's Northwest. The storage of chickpea can develop a hardening phenomenon known as hard-to-cook (HTC), which negatively increases technological parameters such as cooking time (CT) and decrease its nutritional and sensory attributes. The aim of this work was to study the rehydration parameters of 18 chickpea genotypes grown in 4 planting locations of Mexico's Northwest: Culiacan, Los Mochis, Hermosillo and Cd. Obregon, by using a new development of Peleg's model and to evaluate the effect of genotype, planting location and its interaction on rehydration kinetic parameters. Results showed that low water absorption capacity (WAC) and high CT ($p < 0.05$) were associated to HTC chickpea seeds. Also, experimental data of fresh and HTC chickpea had a good fit to Peleg´s model ($R^2 = 0.955 - 0.995$) and allowed to predict rehydration kinetic parameters (maximum water absorption capacity $(\mathrm{WAC})_{max}$, water absorption constant (K), maximum velocity of water absorption (V_{max}) and time to reach the half of maximum WAC ($t_{1/2W}$)). The interaction: genotype/planting location affected ($p < 0.05$) the rehydration parameters. This study can be useful to select the adequate chickpea genotype, according to planting location, thus obtaining appropriate conditions for processing.

Keywords:chickpea, genotype, Peleg's model, rehydration, water absorption capacity.

Resumen

El garbanzo es una leguminosa con alto valor nutricional y comercial en la región Noroeste de México. El almacenamiento del garbanzo ocasiona un fenómeno de endurecimiento conocido como hard-to-cook (HTC), el cual afecta negativamente parámetros tecnológicos como el tiempo de cocción (CT) y disminuye sus atributos nutricionales y sensoriales. El objetivo de este trabajo fue estudiar los parámetros cinéticos de rehidratación de 18 genotipos de garbanzo cosechados en 4 localidades del Noroeste mexicano: Culiacán, Los Mochis, Hermosillo y Cd. Obregón, a través de un nuevo desarrollo matemático del modelo de Peleg. Los resultados mostraron bajos valores de capacidad de absorción de agua (WAC) y altos CT ($p < 0.05$) para las semillas de garbanzo HTC. Además, el ajuste al modelo de Peleg propuesto ($R^2 = 0.955 - 0.995$) permitió realizar predicciones de: máxima capacidad de absorción de agua $(\mathrm{WAC})_{max}$, constante de absorción de agua (K), máxima velocidad de absorción de agua (V_{max}) y tiempo para alcanzar la mitad de WAC ($t_{1/2W}$). La interacción genotipo/localidad afectó significativamente ($p < 0.05$) dichos parámetros. La aplicación de este estudio radica en la selección adecuada del genotipo de garbanzo con base en la localidad de cultivo, y de esta manera, obtener condiciones adecuadas para el procesamiento.

Palabras clave: garbanzo, genotipo, modelo de Peleg, rehidratación, capacidad de absorción de agua.

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1 Introduction

Chickpea (*Cicer arietinum* L) is a legume with commercial importance on Mexico's Northwest, being Sinaloa, Sonora and Baja California Sur the main producer states of this country (SIAP, 2016). Also, chickpea is a good source of energy and protein (18-25%) and has an important content of vitamins such as niacin, thiamine, ascorbic acid; minerals as calcium, iron, copper, zinc, phosphorus, potassium and magnesium; also, chickpea is rich in unsaturated fatty acids (oleic and linoleic acid). Chickpea contains a wide range of phenolic compounds, which could be considered as bioactive compounds due to their antioxidant capacity (Garzón-Tiznado *et al*., 2013).

Acceptability properties of grain legumes include a wide variety of attributes, such as grain size, shape, colour, and appearance, storage stability, soaking and cooking properties and, quality and flavour of the final product (Olguín-Arteaga *et al*., 2015). Among these properties, soaking (water absorption capacity) and cooking time (CT) are two important factors which influence the consumer perception about the grain quality (Garzón-Tiznado *et al*., 2012).

On the other hand, when chickpea is stored at high temperature and high relative humidity (25 °C, ≥65% relative humidity), the grain tends to develop a hardening phenomenon, known as hard-to-cook (HTC). HTC phenomenon causes an increase in CT and a decrease in nutritional quality and sensory attributes of leguminous (Reyes-Moreno and Paredes-López, 1993; Reyes-Moreno *et al*., 2000, 2001). Most of the changes that occurred as a consequence of HTC have been associated with changes at microstructural level which can be studied through microscopy (Reyes-Moreno and Paredes-López, 1993). These microstructural changes can be evaluated by means of physicochemical properties such as water absorption kinetics (Hernández-Nava *et al*., 2011).

Also, water absorption has been evaluated as a quality parameter in bean flours produced by extrusion process (Rodríguez-Miranda *et al*., 2014). However, several works analyzed the water absorption process in foods by means of mathematical models of rehydration kinetics, in which empirical equations have been developed in order to explain changes during rehydration process by fitting experimental data as a function of time (Mercier *et al*., 2015; Parthasarathi and Anandharamakrishnan, 2014). There have been developed models in order to study water absorption process such as Fick's law solutions, Peleg's empirical model and Weibull's probabilistic model which are the most used in literature (Zura-Bravo *et al*., 2013; Vengaiah *et al*., 2012; Noshad *et al*., 2012). It has been demonstrated that these models properly simulate the process and described the mechanisms and variables during rehydration (García-Pascual, 2006). Among the studied models, Peleg's model is one of the more used due to the calculation of parameters can be employed for process optimization (Bilbao-Sáinz *et al*., 2005).

So that Peleg's model is based on two constants: velocity (K_1) and capacity (K_2). K_1 refers to sorption velocity from the beginning of rehydration; and K_2 defines the maximum (or minimum) water content that the material can reach (Turhan *et al*., 2002). Recently, Peleg's model has been used to describe the behaviour of water absorption in agricultural commodities (Taghipour *et al*., 2016; Yogendrarajah *et al*., 2015; Paquet-Durand *et al*., 2015). Therefore, it is important to study water absorption kinetics in chickpea seeds due to the further application in agricultural fields, selecting the correct planting genotype and obtaining products with better technological properties such as reduced CT.

Therefore, the aims of this research were to study the rehydration kinetics in chickpea seeds grown on four Mexican localities (Culiacan, Los Mochis, Cd. Obregon and Hermosillo) using a Peleg's model modification; and to evaluate genotypes, planting location and, the interaction of genotype/planting location effects on rehydration parameters calculated by Peleg's model.

2 Materials and methods

2.1 Material

Eighteen chickpea (*Cicer arietinum* L) seeds genotypes (Hoga 08, Hoga 011, Hoga 012, Hoga 021, Hoga 340-2, Hoga 447-6, Hoga 490-2, Hoga 508, Hoga 509, Hoga 607, Hoga 674, Hoga T-180, Hoga L-10, Hoga Pro-23, Costa 04, Bco-Sin-92, Suprema 03 and Jamu 96), which were grown in four planting locations of Mexico's Northwest: Culiacan, Los Mochis, Hermosillo and Cd. Obregon, were used for this work. The seeds were provided by Instituto Nacional de Investigaciones Forestales, Agricolas y Pecuarias (INIFAP), Culiacan Experimental Station, Sinaloa. After harvest, the material was manually cleaned, and stored at 4 °C until used.

2.2 Hardening procedure

Fresh chickpea seeds were hardened using the methodology reported by Reyes-Moreno *et al.* (1994) with modifications. Fifty five grains of each sample were placed in covered plastic containers, which previously were perforated on their surface. The containers were placed inside bigger containers which had distilled water at the bottom (100% relative humidity). Then, the containers were hermetically closed and placed at 37±1 °C during 8 days, removing from the oven each 48 h in order to check and ventilate samples. Once concluded the period of time, the samples were stored at 4 °C until used.

2.3 Determination of seed coat percentage

Reyes-Moreno *et al.*'s (2000) methodology was used to determine the seed coat percentage, in which 25 chickpeas of each genotype were employed. Chickpeas were soaked into three volumes of distilled water at room temperature during 4 days. Then, the material was drained and the excess of humidity was removed with an absorbent tissue. The hull was manually removed to separate coat and cotyledons. Next, those anatomical parts were dried at 60 °C during 48 h, and were placed into desiccators. Seed coat percentage was calculated using the following equation:

$$\text{Seed coat percentage} = \frac{DSC}{DC + DSC} \times 100 \qquad (1)$$

where: DSC is the weight of dried seed coat and DC is the weight of dried cotyledons.

2.4 Cooking time (CT)

A modified Mattson bean cooker (Reyes-Moreno *et al.*, 2001), manually operated was used to test 25 chickpea seeds of each genotype. Equipment consisted on a frame with three plates, each perforated with 25 holes, in which 25 stainless steel plungers (weight 75±0.5 g, point diameter 2 mm) were placed into each orifice on the top of every chickpea seeds, which were laid in the bottom plate. The Mattson equipment was placed into a container with boiling water. When chickpea seeds were softened by cooking, the plungers pass through the seeds. Cooking time (CT) was defined as the average time of three replications, when 15 (60%) plungers dropped and penetrated individual seeds. According to Paredes-López *et al.*, (1991), 60% of penetrated seeds corresponded to acceptable cooking.

2.5 Water absorption capacity (WAC)

This parameter was determined in fresh and hardened chickpea seeds following the methodology reported by Reyes-Moreno *et al.* (2001). Samples (25 whole seeds) were soaked into four volumes of distilled water at 25±2 °C. The test was carried out during 24 h. After first 8 h, water was drained and the weight of the seeds was recorded at 1 h intervals and the rest of time, the weight of the seeds was measured each 2 h. The water absorption capacity was calculated as follow (Heiras-Palazuelos *et al.*, 2013):

$$WAC(\%) = \frac{MSW - DMW}{DMW} \times 100 \qquad (2)$$

where WAC is water absorption capacity of sample, MSW is the weight of soaked material and DMW is the weight of dry material.

2.6 Water absorption model

Water absorption kinetics of chickpea seeds was studied by using Peleg's model (Peleg, 1988):

$$M_t - M_0 = \frac{t}{K_1 + K_2 t} \qquad (3)$$

Where M_t is the water content at a certain time, M_o is the initial water content, t is time; and, K_1 and K_2 are Peleg's model constants.

2.7 Prediction of rehydration kinetics parameters

The rehydration parameters such as maximum water absorption capacity ($(\text{WAC})_{max}$), water absorption constant (K), time to reach half of maximum water absorption capacity ($t_{1/2W}$) and maximum velocity of water absorption (V_{max}) were predicted by means of Peleg's model, adjusting experimental data of chickpea seeds water absorption.

This work proposes a mathematical procedure to obtain the rehydration kinetics parameters, which is described in next sub-sections.

2.6.1 Calculation of maximum water absorption capacity $(WAC)_{max}$ and water absorption constant (K)

The increment in weight from Peleg's model (Eq. (3)) was used as:

$$M_t - M_0 = WAC \qquad (4)$$

thus:

$$WAC = \frac{t}{K_1 + K_2 t} \qquad (5)$$

Then, Eq. (5) was divided by K_2 as follows:

$$WAC = \frac{\frac{1}{K_2}t}{\frac{K_1}{K_2} + \frac{K_2}{K_2}t} \tag{6}$$

if:

$$\frac{K_1}{K_2} = K \tag{7}$$

$$\frac{1}{K_2} = (WAC)_{max} \tag{8}$$

Where (WAC)$_{max}$ is the maximum water absorption capacity and K is Peleg's model constant.

Thus solving Eq. (6):

$$WAC = \frac{(WAC)_{max}}{K+t}t \tag{9}$$

Then, Eq. (9) was transformed in its reciprocal, obtaining a linear equation as:

$$\frac{1}{WAC} = \frac{K}{(WAC)_{max}}\left(\frac{1}{t}\right) + \frac{1}{(WAC)_{max}} \tag{10}$$

Eq. (10) was in the form: $y = mx + b$, where y is the dependent variable, x is the independent variable, m is the slope of the line and b is the intercept of the line with y axis.

Consequently:

$$y = \frac{1}{WAC} \tag{11}$$

$$x = \frac{1}{t} \tag{12}$$

$$m = \frac{K}{(WAC)_{max}} \tag{13}$$

$$b = \frac{1}{(WAC)_{max}} \tag{14}$$

Finally, a linear regression of x, y data of Eq. (10) was computed to obtain (WAC)$_{max}$ and K.

2.6.2 Determination of time to reach half of maximum water absorption capacity ($t_{1/2W}$)

The time to reach the half of maximum water absorption capacity ($t_{1/2W}$) was defined when:

$$WAC = \frac{1}{2}(WAC)_{max} \tag{15}$$

thus, Eq. (9) was transformed as:

$$\frac{1}{2}(WAC)_{max} = \frac{(WAC)_{max}t_{1/2W}}{K + t_{1/2W}} \tag{16}$$

Then:

$$t_{1/2W} = K \tag{17}$$

2.6.3 Calculation of maximum velocity of water absorption (V_{max})

The procedure to obtain the maximum velocity of water absorption (V_{max}) is presented next.

From the first derivative of Eq. (9):

$$\frac{d(WAC)}{dt} = \frac{(WAC)_{max}}{K+t}dt \tag{18}$$

$$\frac{d(WAC)}{dt} = \frac{(WAC)_{max}K}{(K+t)^2} \tag{19}$$

From the assumption: $K \gg t$, $t \rightarrow 0$ and, Eq. (19) was transformed as follows:

$$\frac{d(WAC)}{dt} = \frac{(WAC)_{max}}{K} \tag{20}$$

and:

$$\frac{d(WAC)}{dt} = V_{max} \tag{21}$$

Therefore:

$$V_{max} = \frac{(WAC)_{max}}{K} \tag{22}$$

2.8 Statistical analysis

Two-way (factors: genotype and planting location) analysis of variance (ANOVA) was performed to evaluate the significance of the response variables. Also, the mean comparison was carried out by Duncan´s multiple range test with significance level of 95%.

Finally, a dendrogram (Camelo-Méndez *et al.*, 2013) was constructed for the interaction genotype/planting location and was based on the similarity percentage of K values obtained with Peleg's model. Groups were classified in 12 clusters.

3 Results and discussion

Results showed that genotype and planting location affected significantly ($p < 0.05$) the rehydration parameters of WAC and CT (data not shown). Also, the interaction genotype/planting location had a significant ($p < 0.05$) influence on WAC, CT, (WAC)$_{max}$, K and V_{max} values of 18 chickpea genotypes in four planting locations of Mexico's Northwest: Culiacan, Los Mochis, Cd. Obregon and Hermosillo.

3.1 Water absorption capacity (WAC) and cooking time (CT)

Fresh chickpea seeds showed WAC values in a range from 99.53 to 126.04%. Genotypes with the lowest and highest ($p < 0.05$) WAC were Hoga 012 Culiacan and Suprema 03 Cd. Obregon, respectively.

The hardening phenomenon caused a decrease on WAC in all chickpea seeds. WAC values of HTC chickpea seeds varied from 64.79 to 103%; Hoga 021 Hermosillo and Hoga 011 Cd. Obregon genotypes showed the lowest and highest ($p < 0.05$) WAC, respectively.

In Reyes-Moreno *et al.*'s (1993) review, the hard-to-cook (HTC) phenomenon was revised in common bean. They reported that the mechanisms of water penetration into intact hardened stored beans and into fresh beans did not substantially differ. Within 2 to 4 h, water enters into the seed at the hilum, and water moves to the periphery of the cotyledon via the spongy parenquima cells of the seed coat and into the space between the cotyledons. After 8 h of soaking, water penetration increases uniformly from the periphery to the centre of the seed as soaking time progresses, and no concentration gradients occurs across the cotyledon. After 14 h of soaking, water penetrates the entire cotyledon. Also, in this review, it was reported that water transport across the hilum is slower than the rate of diffusion through the seeds; therefore, the hilum is the rate-limiting barrier in the water imbibition process. These authors reported that when common beans are stored at high temperatures and high humidity, the amount of water absorbed during soaking of bean grains decrease with the storage time. They also suggested that, besides the limiting role that hilum may play, changes of biochemical and/or physicochemical nature occurs in cotyledons of aged seeds, as a result of giving a lower uptake capacity. Several hypotheses were proposed in this review to explain the cause of bean hardening: lipid oxidation and/or polymerization, formation of insoluble pectates, lignification of middle lamella, and multiple mechanisms. All the changes that occurred during the HTC phenomenon by the proposed mechanisms have a significant effect on the water absorption in hardened grains. The lipid oxidation and/or polymerization produce changes in water permeability in hardened grains. The formation of insoluble pectates, which is due to phytate chelated Ca and Mg ions, prevented formation of calcium and magnesium cross-linkages between the pectate molecules of the middle lamellar tissue; the resultant Ca and Mg pectates do not dissolve readily restricting cell separation and thus producing decrease in the water absorption. The lignification of middle lamella, which occur due to the oxidation and polymerization of polyphenolic compounds mediated by cell wall bound peroxidase in cotyledons, is one of the factors that restricts the absorption of water in hardened grains. In addition, grains with harder seed coats absorb less water during soaking due to a possible lignification-type reaction involving phenol polymerization which induces hardening in the seed coat. These authors concluded that the mechanisms involved in the HTC have not been elucidated satisfactorily, and that a better knowledge of cotyledon and seed coat microstructure may lead to a better understanding of the causes of seed hardness.

Therefore, the mechanisms involved in water absorption of legume grains and changes carried out during the HTC phenomenon are complex and still unintelligible. So that, the explanation of the differences between fresh and HTC chickpea seeds for each variety as a response to the planting location based on chemical and morphological changes, is also complex. It is necessary to carry out further studies on the chemical composition, physical and physicochemical properties, related to morphology of chickpea grains for the different varieties, planted in different localities; as well as, the changes that occur in these properties during the HTC phenomenon, and relate them to the changes in the water absorption properties of these materials.

On the other hand, CT of fresh chickpea seeds were in a range from 141.5 to 240.5 min, in which the highest and lowest ($p < 0.05$) CT corresponded to Hoga 490-2 Hermosillo and Suprema 03 Cd. Obregon, respectively.

Previous reports of chickpea seeds found that mainly the soil type produced a high CT and genotype factor had a slight influence on this parameter (Iliadis *et al.*, 1991). On the other hand, Wassimi *et al.* (1978) and Bhatty *et al.* (1984) attributed these differences mainly to genotype, observing that soil fertility had a low effect on CT.

Also, it has been reported that the seed coat percentage of chickpea affected its rehydration parameters (Reyes-Moreno *et al.*, 2000). Therefore, a linear correlation with those variables was performed. Significant correlations ($p < 0.05$) were found for seed coat percentage and WAC for fresh and HTC, and K for fresh and HTC chickpea seeds in which was obtained the following correlation coefficients (r): 0.457, 0.487, -0.257 and -0.260, respectively. Consequently, this confirmed the existence of genotypes with different CT. Erskine, Williams & Nakkoul (1985) reported that cooking times on lentils (*Lentils culinaris* L) showed high genotype dependence. In this study, genotype Hoga 490 had the highest CT ($p < 0.05$) with 217.1 min.

However, the unfavourable effect that was observed on CT as a consequence of some planting locations, for example a higher CT ($p < 0.05$) of chickpea seeds grown in Hermosillo and Culiacan (191.64 and 192.36 min, respectively), can be minimised with the use of genotypes with low CT. Iliadis (2003) reported that both factors, genotype and soil type, had an influence on the CT of lentils (*Lentils culinaris* Mendikus), in which the most significant factor was genotype.

Furthermore, Reyes-Moreno *et al.* (1993) reported that, in general, bean cookability and/or texture of the cooked products are influenced by a number of factors, including variety, growing location, moisture content of stored bean, chemical composition, and pretreatment by soaking in water or salt solutions. These factors may modify cookability in beans by altering physical and chemical relationships of cellular and intercellular constituents (e.g., changes in morphology, the content of minerals, protein and organic phosphorus compounds, and enzymatic activity), which may ultimately influence the rate of hydration, hydrogen bond disruption, and other phenomena associated with the process of cooking. In addition, the size and shape of beans, surface area, seed thickness, rate of starch gelatinization, and the nature and amounts of nonstarch constituents that act as a physical barrier to the swelling of starch granules, may influence the rate of water uptake during the cooking of dry beans. Also, they reported that thickness of the palisade layer and the lignin and cellulose content of the seed coat and possible cotyledon cell walls are important determiners of cooking quality.

In general, HTC phenomenon caused an increase in CT for all chickpea seeds. CT values of HTC chickpea seeds varied from 138.5 to 269.5 min; the lowest and highest ($p < 0.05$) CT corresponded to genotypes Jamu 96 Los Mochis and Hoga 340-2 Cd. Obregon, respectively.

Also, in literature, it has been widely reported that storage of common beans under the adverse conditions of high temperature and high humidity renders them susceptible to a hardening phenomenon characterized by extended cooking times for cotyledon softening. A possible interpretation of the HTC phenomenon mechanisms can be that both enzymatic and nonenzymatic reactions are concurrently or sequentially participating in events that lead to increased toughness in both the cotyledon and seed coat in stored legumes (Reyes-Moreno *et al.*, 1993). These effects also appear in a similar way in the absorption of water during the process of cooking. Reducing water absorption during cooking significantly increases the cooking time of grains that suffered from the HTC phenomenon. Another factor that affects the cookability of grains, which suffered HTC phenomenon, is the inhibition of cell separation due to the changes in the cell wall/middle lamella complex. The middle lamella in HTC grains remains intact in spite of cooking and, hence, it prevents cell separation. It has been suggested that the failure of middle lamella to breakdown during cooking may be correlated to the decrease in solubility of pectic substances and divalent cation content due to hardening phenomenon (Reyes-Moreno *et al.*, 1993).

3.2 *Effect of genotype and planting location on rehydration parameters of fresh and HTC chickpea seeds obtained by Peleg's model*

From Eq. (5), K_1 and K_2 were calculated, which lowest values of these constants indicated a higher water absorption rate and maximum WAC in the linear and asymptotic part of the kinetics. This behaviour can be observed in Figs. (1)-(3). In general, WAC varied with genotype and planting location when fitted to Peleg's model. As an example, a comparison was carried out among planting locations on WAC kinetics for fresh Costa 04 genotype (Fig. 1). The time to reach the half of WAC, measured by constant K, varied depending of planting location. Culiacan presented lower time (1.18 h) in comparison to Los Mochis, Hermosillo and Cd. Obregon with values of 1.80, 2.23 and 2.41 h, respectively. Also, for Costa 04 chickpea genotype, Culiacan and Hermosillo location had the lowest [10.6×10^{-3} h (% adsorbed water)$^{-1}$] and highest [17.8×10^{-3} h (% adsorbed water)$^{-1}$] values of K_1, respectively; whilst Hermosillo and Culiacan location had the lowest [7.4×10^{-3} (% adsorbed water)$^{-1}$] and highest [9×10^{-3} (% adsorbed water)$^{-1}$] values of K_2, respectively.

On the other hand, the genotype effect on WAC kinetics was observed for fresh Costa 04 and fresh Hoga 509 grown in Culiacan, as a representative example due to both genotypes had the lowest and

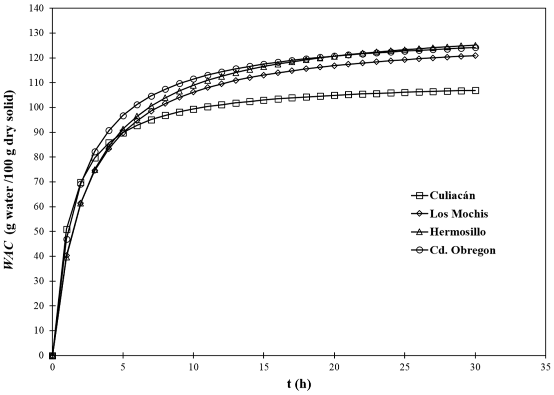

Fig. 1. Effect of planting location on water absorption capacity (WAC) kinetics of fresh Costa 04 chickpea genotype. Curves correspond to data fitted to Peleg's model.

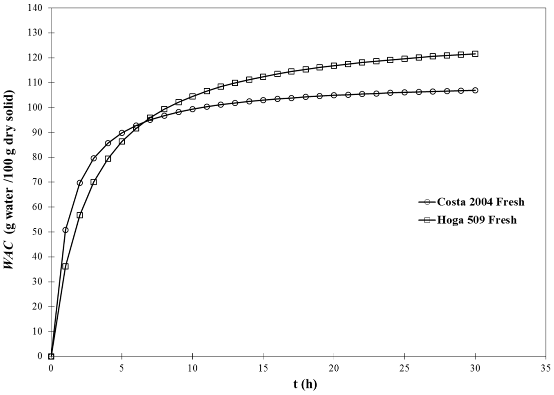

Fig. 2. Effect of genotype on water absorption capacity (WAC) kinetics of fresh Costa 04 chickpea genotype. Curves correspond to data fitted to Peleg´s model.

highest K values, respectively (Fig. 2). Hoga 509 absorbed higher water content after 30 h in comparison to Costa 04, which indicated that Hoga 509 required longer time to absorb the half of WAC. Also, the effect on K_1 and K_2 of chickpea genotype grown in the same planting location (Culiacan) was analysed (Fig. 2). Costa 04 genotype showed the lowest K_1 [10.6×10^{-3}h (% adsorbed water)$^{-1}$] value and Hoga 509 genotype had the lowest K_2 [7.5×10^{-3} (% adsorbed water)$^{-1}$].

Fig. 3 shows the effect of the hardening process on WAC kinetics, taking as example the same genotype: Hoga 509 grown in Culiacan. Fresh chickpea absorbed higher water content after 30 h in comparison to HTC chickpea. However, HTC Hoga 509 required lower time to reach the half WAC, which meant that the absorption water rate was faster than fresh Hoga 509.

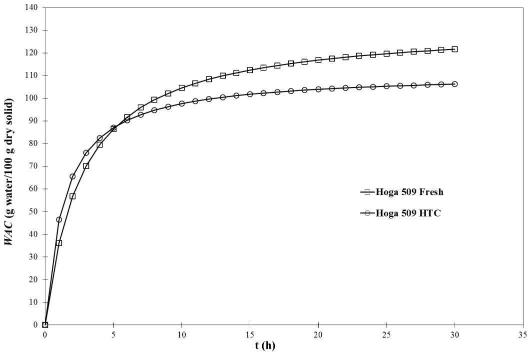

Fig. 3. Effect of hardening on water absorption capacity (WAC) kinetics of Hoga 509 chickpea genotype. Curves correspond to data fitted to Peleg's model.

It is worthy to mention that this result was not consistent for the rest of the genotypes, since WAC kinetics depends on the location and genotype. Furthermore, the effect of hardening phenomenon on Peleg's constants was observed for Hoga 509 chickpea genotype grown in Culiacan planting location, indicating that HTC chickpea seed quickly absorbed the water at the initial phase; however, fresh chickpea seed showed a higher maximum WAC value at the end of the soaking process.

Lower K_1 values in genotypes and planting locations can be explained due to differences in morphology and physiology of the evaluated genotypes, i.e., genotypes with thick hull will need longer times to reach the water saturation compared with thin hull genotypes. This statement agreed with Paquet-Duran *et al.*'s work (2015) that evaluated Peleg's constants in bran, endosperm and whole grain of wheat, and found that bran reached the water saturation faster than the endosperm, which required a longer time during the soaking process. However, the water content at the end of soaking is higher in endosperm than bran.

On the other hand, Shafei *et al.* (2016) used Peleg's model to evaluate K_1 and K_2 in 3 chickpea genotypes: Kabuli, Chico and Desi, which were harvested under same conditions and planting location; water adsorption had no statistically difference between genotypes concluding that morphological and physiological properties were similar among genotypes analysed. In general, Shafei *et al.* (2016) found that the water absorption rate was faster at the beginning and slow at the end of soaking process.

The main advantage of Peleg's model was to save time by the prediction of sorption kinetics of foods including the equilibrium water content and using short-time experimental data, considering that the range of selected data on sorption curves affects K_1 and K_2 values and hence affects the model's fit (Turhan *et al*., 2002).

3.3 *Effect of the interaction of genotype/planting location on rehydration parameters of fresh and HTC chickpea seeds obtained by Peleg's model*

Peleg's model of water absorption predicted the variability of rehydration kinetic parameters of fresh and HTC chickpea genotypes, grown on four planting locations from Mexico's Northwest. Good fittings resulted for the applied modified model obtaining high coefficients of determination (R^2), which values ranged from 0.955 to 0.995 for each genotype/planting location interaction.

The interaction of genotype/planting location affected significantly ($p < 0.05$), the values of rehydration kinetic parameters: $(WAC)_{max}$, K and V_{max} of fresh and HTC chickpea seeds by using Peleg's model (Table 1 and 2).

Fresh chickpea seeds of planting locations Culiacan and Cd. Obregon genotypes showed the lowest and highest ($p < 0.05$) value of $(WAC)_{max}$, respectively (Table 1). On the other hand, a decrease in $(WAC)_{max}$ was observed for HTC chickpea seeds, in which the planting locations of Los Mochis and Cd. Obregon exhibited the lowest and highest ($p < 0.05$) values, respectively (Table 1).

Table 2 shows the results obtained for K and V_{max} of fresh and HTC chickpea seeds, in which the planting locations of Los Mochis and Culiacan presented the lowest and highest ($p < 0.05$) values of K of fresh chickpea seeds, respectively. Also, K values decreased for HTC chickpea seeds, indicating that Culiacan and Los Mochis had the lowest and the highest ($p < 0.05$) values, respectively (Table 2).

Furthermore, the effect of genotype on the results of V_{max} in fresh chickpea seeds in different planting locations was significant ($p < 0.05$). The lowest and highest ($p < 0.05$) values of V_{max} were observed for Culiacan and Hermosillo planting locations, respectively. However, accelerated store (HTC) caused a decrease on V_{max} values for all chickpea seeds, in which Los Mochis and Cd. Obregon had the lowest and highest ($p < 0.05$) values, respectively (Table 2).

On the other hand, K parameter represents an indicator of chickpea's cooking time due to its relation with $t_{1/2W}$ and is an important factor to consider for technological purposes. Therefore, K values were used in order to obtain a classification according to chickpea genotype and planting location, by using a dendrogram which showed the effect of these two factors in K (Fig. 4). The following genotypes did not show dependence on planting location: Hoga 490, Hoga 447, Hoga 674, Hoga 340, Hoga 607, Hoga 012, Hoga 021, Jamu 96, Hoga T-180 and Bco-Sin-92, due to their K value had a higher similarity among them. Also, it can be observed (Fig. 4) that genotypes which were dependent of the planting location were: Hoga 08, Suprema 03, Hoga Pro-23, Hoga 508, Costa 04, Hoga 011 and Hoga 509, and presented K values with lower similarity among them. Also, the planting locations that did not show a dependence on the genotype were Culiacan and Cd. Obregon in which most of the genotypes were found in the same group. Oppositely, Hermosillo was the planting location that showed more dependence on the genotype according to K values. K values were related to the time in which chickpea reach the half of $(WAC)_{max}$. Therefore, the groups showed in the dendrogram can be used to select the adequate genotype for technological purposes such as cooking, according to the planting location. Finally, Hoga 011 Hermosillo, Hoga 011 Cd. Obregon, Costa 04 Culiacan, Costa 04 Los Mochis and Hoga 021 Los Mochis were the chickpea seeds that showed lower similarity with the rest of the genotypes and planting locations. The differences found on the interaction between genotype and planting location of chickpeas can be related to variances according to particular features of each genotype grain such as changes in microstructure, anatomical structures (seed coat, thickness, seed volume, hilum size), chemical composition (humidity, protein, lipids, minerals, fiber, starch, pectic substances, phytates, polyphenols, other), and arrangements of chemical micro and macro components. Also, Estrada-Girón *et al.* (2014) reported differences in rheological, microstructural and thermal properties of dough when using a hybrid variety of maize, thus explaining changes in technological applications derived from a gene modification.

Table 1. Maximum water absorption capacity $(WAC)_{max}$ (g water/100 g dry solid) of the interaction of chickpea genotype/planting location of fresh and hard-to-cook (HTC) chickpea seeds, obtained by Peleg's model.

	Culiacán		**Los Mochis**		**Hermosillo**		**Cd. Obregón**	
Genotype/location	**Fresh**	**HTC**	**Fresh**	**HTC**	**Fresh**	**HTC**	**Fresh**	**HTC**
	$(WAC)_{max}$	$(WAC)_{max}$	$(WAC)_{max}$	$(WAC)_{max}$	$(WAC)_{max}$	$(WAC)_{max}$	$(WAC)_{max}$	$(WAC)_{max}$
Hoga 08	123.48^{abc}	100.51^{efg}	138.1^{ab}	100.51^{efg}	138.1^{a}	111.12^{abc}	137.01^{abcd}	115.61^{f}
Hoga 011	119.06^{abc}	99.5^{fg}	128.83^{ab}	99.5^{fg}	128.83^{ab}	108.31^{ab}	126.60^{bcde}	132.46^{a}
Hoga 012	115.61^{bc}	96.67^{g}	133.16^{ab}	96.67^{h}	133.16^{ab}	100^{abc}	125.83^{bcde}	115^{f}
Hoga 021	112.36^{c}	97.12^{g}	132.46^{ab}	97.12^{i}	132.46^{ab}	92.26^{e}	123.76^{cde}	$117. 06^{ef}$
Hoga 340-2	115.61^{bc}	109.9^{bcd}	136.99^{ab}	109.9^{cde}	136.99^{ab}	118.35^{abc}	126.58^{bcde}	114.29^{fg}
Hoga 447-6	122.74^{abc}	107.53^{cde}	132.5^{ab}	107.53^{bc}	132.5^{ab}	122.81^{bcd}	129.89^{abcde}	118.35^{def}
Hoga 490-2	116.34^{bc}	115.08^{b}	137.94^{ab}	115.08^{a}	137.94^{ab}	129.96^{abcd}	132.46^{abcde}	114.29^{fg}
Hoga 508	125.83^{abc}	111.76^{bcd}	142.86^{ab}	111.76^{efg}	142.86^{a}	112.36^{abc}	144.93^{a}	106.22^{h}
Hoga 509	132.46^{ab}	111.17^{bcd}	143.95^{a}	111.17^{cde}	143.95^{a}	118.35^{bcd}	140.84^{abc}	126.58^{abc}
Hoga 607	116.96^{bc}	105.27^{def}	142.86^{ab}	105.27^{def}	142.86^{b}	113.64^{bcd}	122.81^{de}	107.54^{gh}
Hoga 674	118.35^{abc}	114.29^{bc}	132.46^{ab}	114.29^{bc}	132.46^{ab}	121.95^{a}	135.13^{abcde}	125.18^{bcd}
Hoga T-180	119.12^{abc}	116.29^{ab}	127.44^{ab}	116.29^{abc}	127.44^{b}	124.23^{e}	119.20^{e}	114.38^{fg}
Hoga L-10	117.65^{abc}	122.02^{a}	125.83^{b}	122.02^{ab}	125.83^{ab}	128.21^{ab}	132.59^{abcde}	120.76^{cdef}
Hoga Pro-23	120.48^{abc}	98.05^{fg}	138.92^{ab}	98.05^{efg}	138.92^{ab}	112.37^{e}	141.85^{ab}	115.61^{f}
Costa 04	111.11^{c}	104.78^{def}	129.87^{ab}	104.78^{cd}	129.87^{ab}	119.76^{ab}	131.60^{abcde}	129.04^{ab}
Bco-Sin-92	125.08^{abc}	104.74^{def}	135.23^{ab}	104.74^{gh}	135.23^{ab}	105.26^{cde}	138.91^{abcd}	115.61^{f}
Suprema 03	134.28^{a}	109.32^{bcd}	130.77^{ab}	109.32^{fg}	130.77^{ab}	106.98^{de}	145.99^{abcde}	123.46^{bcde}
Jamu 96	119.8^{abc}	100.81^{efg}	131.78^{ab}	100.81^{efg}	131.78^{ab}	112.37^{ab}	133.36^{a}	119.06^{def}

*Different letters indicate significant statistical differences ($p < 0.05$) among means by column.

Conclusions

The interaction of genotype/planting location affected water absorption capacity, cooking time and hardening tendency of analysed chickpea seeds. Peleg's model of water absorption predicted the variability of rehydration parameters in fresh and HTC chickpea from 18 chickpea seeds genotypes, grown on four planting locations of Mexico's Northwest, with good fittings. Also, this interaction affected rehydration kinetic parameters: maximum water absorption capacity ($(WAC)_{max}$), water absorption constant (K) and maximum velocity of water absorption (V_{max}), and time to reach the middle maxim water absorption capacity, calculated by Peleg's model in fresh and HTC chickpea seeds. Also, accelerated store (37±1 °C, 100% relative humidity, 8 days) of chickpea seeds produced changes on kinetics parameters of water absorption by development of HTC phenomenon. In this work, Peleg's model was mathematically modified to obtain new equations and predict kinetic parameters of water absorption in chickpea seeds. Also, the derived equations can be used as a non-destructive technique for the estimation of microstructural changes carried out by water intake of chickpea, which represents the object of further studies.

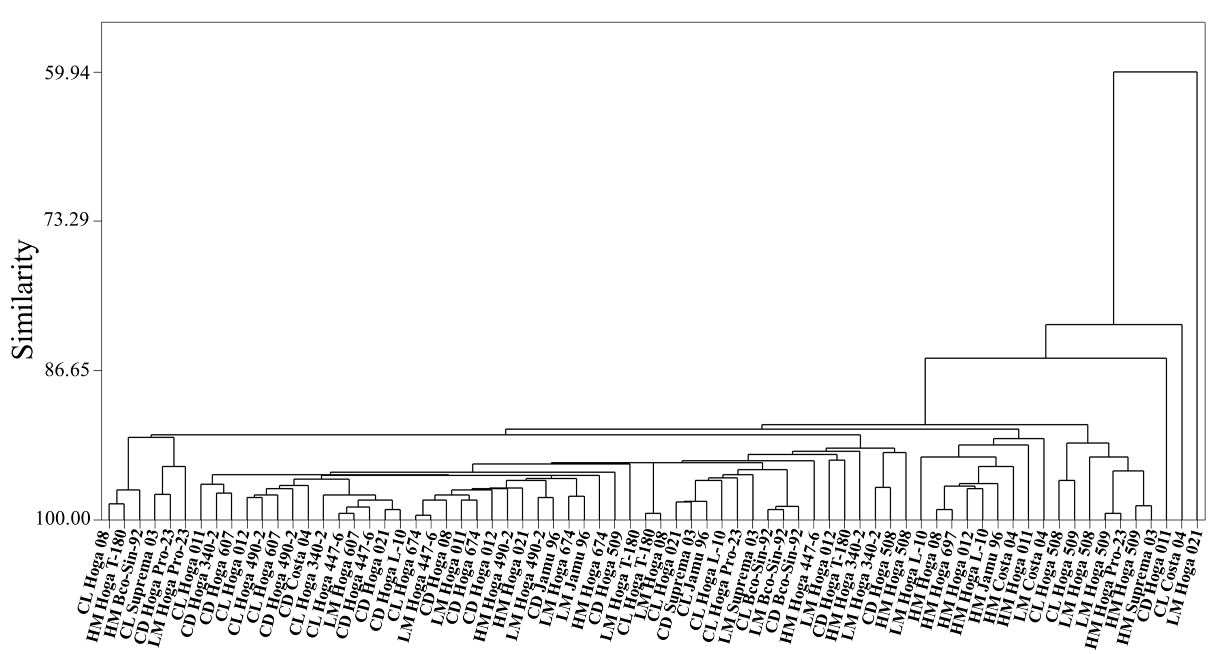

Fig. 4. Dendrogram obtained for the interaction chickpea genotype/planting location, using similarities among modified Peleg's constant (K) values. Letters before genotype designation denote planting locations: Culiacan (CL), Los Mochis (LM), Hermosillo (HM) and CD (Cd. Obregon).

Table 2. Water absorption constant K (h), and maximum velocity of water absorption V_{max} (g adsorbed water/h) calculated by Peleg's model of the interaction of chickpea genotype/planting location of fresh and hard-to-cook (HTC) chickpea seeds.

	Culiacan				**Los Mochis**				**Hermosillo**				**Cd. Obregon**			
Genotype/ location	**Fresh** K	**HTC** K	**Fresh** V_{max}	**HTC** V_{max}	**Fresh** K	**HTC** K	**Fresh** V_{max}	**HTC** V_{max}	**Fresh** K	**HTC** K	**Fresh** V_{max}	**HTC** V_{max}	**Fresh** K	**HTC** K	**Fresh** V_{max}	**HTC** V_{max}
Hoga 08	2.32^{cd}	1.51^{cde}	53.45^{defg}	67.1^{efgh}	2.52^{cde}	2.02^{cd}	54.89^{defgh}	55.67^{fg}	2.49^{bcdef}	2.39^{abc}	55.42^{abc}	49.88^{gh}	2.16^{b}	1.79^{bc}	63.51^{cdef}	64.81^{ef}
Hoga 011	2.04^{ef}	1.51^{cde}	58.31^{bcde}	66.09^{efgh}	2.1^{fghij}	1.87^{def}	61.97^{cd}	58.03^{efg}	2.52^{bcdef}	2.61^{a}	53.16^{abcd}	46.53^{h}	1.92^{bcde}	2.19^{a}	65.8^{abcde}	60.61^{f}
Hoga 012	1.83^{f}	1.66^{bc}	63.45^{b}	58.37^{h}	1.56^{j}	1.67^{efg}	87.3^{a}	60.14^{def}	2.63^{abcd}	2.36^{abc}	49.39^{bcd}	50.99^{gh}	2.09^{bcd}	1.77^{bcd}	60.83^{ef}	65.03^{ef}
Hoga 021	1.99^{ef}	1.3^{def}	56.85^{bcdef}	75.34^{de}	2.24^{fghi}	3.59^{a}	59.2^{cdef}	26.39^{h}	2.29^{ef}	1.89^{de}	54.58^{abcd}	57.41^{efg}	2.03^{bcd}	1.65^{bcde}	60.98^{ef}	71.44^{de}
Hoga 340-2	1.95^{ef}	1.64^{bc}	59.39^{bcd}	67.31^{efgh}	2.58^{cd}	1.79^{def}	53.22^{fghi}	66.7^{de}	2.67^{abc}	1.98^{de}	49.93^{abcd}	59.91^{defg}	1.97^{bcd}	1.47^{cdef}	64.39^{bcdef}	77.52^{cd}
Hoga 447-6	2^{ef}	1.69^{bc}	61.85^{bc}	63.5^{fgh}	2.18^{fghi}	1.84^{def}	61.2^{cde}	67.11^{de}	2.36^{def}	2.11^{cd}	56.29^{ab}	55.22^{fgh}	1.97^{bcd}	1.7^{bcde}	65.82^{abcde}	69.69^{def}
Hoga 490-2	1.86^{f}	1.62^{bcd}	62.66^{b}	72.1^{defg}	2.13^{fghij}	1.64^{fg}	65.21^{bc}	79.41^{c}	2.25^{f}	1.83^{def}	57.66^{a}	65.64^{bcde}	1.86^{cde}	1.55^{bcdef}	71.18^{abc}	73.63^{de}
Hoga 508	2.58^{ab}	1.39^{cde}	50.6^{efg}	80.79^{cd}	2.99^{a}	1.41^{gh}	47.75^{hi}	79.83^{c}	2.73^{ab}	1.76^{ef}	51.82^{abcd}	67.31^{bcde}	2.56^{a}	1.86^{b}	56.67^{f}	63.94^{ef}
Hoga 509	2.67^{a}	1.39^{cde}	49.63^{fg}	80^{cd}	2.84^{ab}	1.43^{gh}	50.76^{ghi}	82.85^{bc}	2.85^{a}	1.58^{fg}	49.15^{bcd}	73.03^{abc}	2.13^{bc}	1.45^{ef}	66.39^{abcde}	87.35^{b}
Hoga 607	1.87^{f}	$1.7b^{c}$	62.83^{b}	62.12^{gh}	1.99^{hij}	1.68^{efg}	72.32^{b}	68.58^{d}	2.48^{bcdef}	2.37^{abc}	49.01^{bcd}	49.15^{gh}	1.91^{bcde}	1.46^{def}	64.55^{bcdef}	73.67^{de}
Hoga 674	2.18^{cde}	1.83^{ab}	54.23^{cdefg}	63.49^{fgh}	2.29^{efg}	1.99^{cd}	58.13^{cdefg}	61.72^{def}	2.39^{def}	1.98^{de}	54.79^{abc}	62.89^{cdef}	2.12^{bc}	1.83^{b}	63.74^{bcdef}	69.09^{def}
Hoga T-180	2.51^{b}	2.03^{a}	47.51^{g}	57.82^{h}	2.37^{def}	1.79^{def}	53.76^{efghi}	69.57^{d}	2.3^{ef}	1.54^{fg}	52.4^{abcd}	69.76^{abcd}	1.69^{e}	1.71^{bcde}	70.74^{abcd}	67.42^{def}
Hoga L-10	1.86^{f}	1.31^{def}	63.29^{b}	94.1^{ab}	2.69^{bc}	2.23^{bc}	46.84^{i}	57.49^{efg}	2.56^{bcde}	2.36^{abc}	50.76^{abcd}	51.17^{gh}	2.01^{bcd}	1.64^{bcde}	65.86^{abcde}	73.92^{de}
Hoga Pro-23	2.08^{def}	1.33^{def}	58.03^{bcde}	75.74^{de}	2.27^{efgh}	1.15^{hi}	61.43^{cde}	98.08^{a}	2.85^{a}	1.44^{g}	47.45^{cde}	74.58^{ab}	2.4^{a}	1.27^{fg}	59.18^{ef}	91.03^{b}
Costa 04	1.18^{g}	1.44^{cde}	94.25^{a}	73.33^{def}	2.23^{fghi}	2.44^{b}	58.31^{cdefg}	49.12^{g}	2.41^{cdef}	2.48^{ab}	56.19^{ab}	49.43^{gh}	1.8^{de}	1.5^{cdef}	72.99^{a}	86.68^{bc}
Bco-Sin-92	1.97^{ef}	1.06^{f}	63.86^{b}	99.01^{a}	1.95^{ij}	1.07^{i}	69.53^{b}	98.38^{a}	2.35^{def}	1.45^{g}	56.67^{ab}	78.02^{a}	1.95^{bcde}	1.1^{g}	71.74^{ab}	106.01^{a}
Suprema 03	2.35^{bc}	1.24^{ef}	57.15^{bcdef}	88.6^{bc}	2.04^{ghij}	1.17^{hi}	69.9^{b}	91.42^{ab}	2.84^{a}	1.55^{fg}	46.49^{d}	71.2^{abc}	1.99^{bcd}	1.26^{fg}	73.28^{a}	113.29^{a}
Jamu 96	1.95^{ef}	1.31^{cde}	61.54^{bc}	81.01^{cd}	2.24^{fghi}	1.97^{cde}	59.11^{cdef}	58.06^{efg}	2.46^{bcdef}	2.29^{bc}	55.73^{ab}	53.38^{fgh}	2.13^{bc}	1.69^{bcde}	62.7^{def}	70.93^{def}

*Different letters indicate significant statistical differences ($p < 0.05$) among means by column.

Furthermore, this work is useful to identify chickpea varieties with low hardened tendency that might help in genetic improvement programs for the development of new chickpea genotypes. It is remarkable that the study aids to select the adequate genotypes for the soil type and further technological purposes.

Nomenclature

CT	cooking time, min
DC	weight of dried cotyledons, g
DMW	weight of dry material, g
DSC	weight of dried seed coat, g
K	water absorption constant, h
K_1	Peleg's velocity constant
K_2	Peleg's capacity constant
MSW	weight of soaked material, g
M_0	initial water content, g water/100 g dry sample
M_t	water content at a certain time, g water/100 g dry sample
t	time, h
$t_{1/2W}$	time to reach half of maximum water absorption capacity, h
V_{max}	maximum velocity of water absorption, g absorbed water/h
WAC	water absorption capacity, g water/100 g dry sample
$(\text{WAC})_{max}$	maximum water absorption capacity, g water/100 g dry sample

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