PAPER

MODELLING OF HYDRATION OF BEAN (*PHASEOLUS VULGARIS L.*): EFFECT OF THE LOW-FREQUENCY ULTRASOUND

L.R. LÓPEZ LÓPEZ[a], J.A. ULLOA*[a,b], P. ROSAS ULLOA[b], J.C. RAMÍREZ RAMÍREZ[c], Y. SILVA CARRILLO[d] and A. QUINTERO RAMOS[e]

[a]Posgrado en Ciencias Biológico Agropecuarias. Unidad Académica de Agricultura, Universidad Autónoma de Nayarit, Carretera Tepic-Compostela Km 9, CP 63780 Xalisco, Nayarit, México

[b]Centro de Tecnología de Alimentos, Universidad Autónoma de Nayarit, Ciudad de la Cultura Amado Nervo, C.P. 63155 Tepic, Nayarit, México

[c]Unidad Académica de Medicina Veterinaria y Zootecnia, Universidad Autónoma de Nayarit, Carretera a Chapalilla Km 3.5, CP 63700 Compostela, Nayarit, México

[d]Unidad Académica de Agricultura, Universidad Autónoma de Nayarit, Carretera Tepic-Compostela Km 9, CP 63780 Xalisco, Nayarit, México

[e]Departamento de Investigación y Posgrado, Facultad de Ciencias Químicas, Universidad Autónoma de Chihuahua, Circuito Universitario s/n, Campus Universitario No. 2, CP 31240 Chihuahua, Chihuahua, México

*Corresponding author. Tel. +52 3112118851; Fax +52 3112118861
E-mail address: arulloa5@gmail.com

ABSTRACT

Beans of six varieties were soaked in distilled water at 30 °C and exposed to ultrasound at powers of 5, 12 or 19 W, in addition to treatment control without ultrasound to attain the equilibrium moisture. From four model studied, the Weibull model presented the best fit (R^2 0.986-0.999) for the experimental data of the hydration kinetics. Soaking time was reduced from 52.6 % to 77.2 %, while the effective diffusivity was increased from 2.25 times to 3.50 times at 19 W, depending on the bean variety. The ultrasound power improved the hydration capability being suitable for possible use in industrial applications.

Keywords: beans, hydration, mathematical modelling, ultrasound, water diffusivity, Weibull´s model

1. INTRODUCTION

Common beans (*Phaseolus vulgaris* L.) are a grain legumes that belong to the family of *Fabaceae*. They provide an affordable source of protein (16-33%), almost two to three times that of cereals), and also are a rich source of dietary fibre, starch, minerals and vitamins (MKANDA e*t al*., 2007). Bioactive compounds present in common bean have been associated with the prevention and/or regulation of chronic degenerative diseases such as obesity, diabetes, coronary heart disease and cancer (CAMPOS-VEGA *et al*., 2010; PLANS *et al*., 2013).

On the other hand, the World Health Organization has issued several recommendations for reducing overweight, obesity and cardiovascular diseases that also are likely to reduce the risk of diet-related diseases, such as type 2 diabetes and obesity. These recommendations include the achievement of adequate intakes of non-starch polysaccharides through regular consumption of wholegrain cereals, legumes, fruits and vegetables (WHO/FAO, 2003). Of the leguminous plants consumed by humans, one of those of greatest importance on a worldwide level is the common bean (OLMEDILLA-ALONSO *et al*., 2013). Cooked dry beans along with whole grains have been emphasized as the primary nutritional shifts in food intake patterns to a plant-based diet by the 2010 Dietary Guidelines Advisory Committee (CAMPOS-VEGA *et al*., 2012).

Before the cooking step, beans are hydrated in water until maximum weight is reached (ULLOA *et al*., 2016). Hydration capacity is dependent on the ease of water absorption through the seed coat to the cotyledons (MKANDA *et al*., 2007). However, the soaking process is a time-consuming step, requiring approximately 12 h at room temperature (PIERGIOVANNI, 2011), and many attempts have been directed towards shortening it (Abu-Ghannam and McKenna, 1997).

Ultrasound power is a novel technology in the food industry, and research on its application is a rapidly growing field. Ultrasonic waves can cause a rapid series of alternative compressions and expansions similar to a sponge when it is squeezed and released repeatedly, a phenomenon known as cavitation (CHEMAT *et al*., 2011). Ultrasound cavitation results in the occurrence of microstreaming, which enhances heat and mass transfer (CÁRCEL *et al*., 2012).

Ultrasound applications were reported to enhances the hydration of chickpeas (YILDIRIM *et al*., 2011), sorghum grains (PATERO and AUGUSTO, 2015), and navy beans (GHAFOOR *et al*., 2014). However, as soaking conditions vary depending on the particular legume or food material, it is necessary for practical applications to characterise and optimise these conditions.

Therefore, the objective of the present study was to evaluate the effect of low-frequency ultrasound on the kinetics and modeling of the hydration of the six varieties of the most consumed beans in Mexico.

2. MATERIALS AND METHODS

2.1. Material

Common bean seeds from six varieties, which are highly consumed in Mexico (RODRÍGUEZ-LICEA *et al*., 2010) and classified as most preferred (Azufrado, Mayacoba, Pinto, Peruano Bola, Flor de Mayo and Negro Jamapa), were used for this study and were obtained from the Mercado de Abastos, located in Tepic, Nayarit, Mexico. These food legumes were separated from broken, small and split. Seeds were cleaned and size-graded manually. Samples were stored in hermetically sealed bags inside closed plastic jars at room temperature (25 °C) in a dark room.

2.2. Chemical and morphological characterization of the bean seeds

The chemical composition (moisture, protein, fat, ash, and carbohydrates) of the beans was determined following the official methods of the AOAC (2002). For the morphological characterization, 100 beans of each variety were selected, and the weight (*we*), length (*l*), width (*w*) and depth (*d*) were measured to determine the geometric mean diameter (G_m), arithmetic mean diameter (A_m), square mean diameter (S_m) and the radius of an equivalent sphere (*r*) according to the methods reported by GAFHOOR *et al*. (2014).

2.3. Seed coat content

To determine the percentage of the coat of the seeds, the TIZAZU and EMIRE (2010) method with some modifications was used. Thirty bean seeds were soaked in distilled water for 8 h, and the coat was removed manually, separating it from the cotyledon. The seed coats collected were dried in an oven at 60° C for 24 h, followed cooling in a desiccator. It was then weighed and the percentage of seed coat was calculated.

2.4. Ultrasound soaking treatments

A sample of 5 g of beans was used in each one of the three replicates. The bean samples were soaked in a 100-mL beaker with 50 mL of distilled water and exposed to ultrasound at powers of 5, 12 or 19 W (20 kHz, 30 °C), using a GE-130 ultrasonic processor (Cole Parmer, Vernon Hills, Connecticut, Illinois) provided of a titanium probe of 6 mm. At specific time intervals (10 min for ultrasound treatments and 30 min for control, until stabilization), the seeds were removed from the water, drained, superficially blotted with absorbent paper, weighed and returned to the water.

2.5. Modeling the kinetics of hydration

For fitting the moisture uptake of soaked bean, four models were used to estimate the parameters associated with each model. The list of the models, and the respective equations used in this study, is presented in Table 1. The best fitted model was determined by the highest coefficient of determination (R^2) and the lowest values of the root mean square error (RMSE) and chi-square (χ^2) amongst the predicted and experimental results (COX *et al*., 2012).

2.6. Effective diffusivity (D_{eff})

D_{eff} was determined according to the method reported by KAPTSO *et al*. (2008) with the following equation:

$$c = \frac{\pi^2 D_{eff}}{r^2} \qquad \text{Eq. 1}$$

Where D_{eff} (m^2/s) is the effective diffusivity, c (s^{-1}) is the rate constant of the water absorption of the mathematical model with the best fit and r (m) is the value of radius of the equivalent sphere.

Table 1. Models used to describe moisture content and rate of moisture uptake by effect of ultrasound.

Model and reference	Equation
Peleg (PELEG, 1988)	$\mathrm{M_t = M_0} + \left[\frac{\mathrm{t}}{\mathrm{c_1+c_2t}}\right]$ (2)
Sigmoid (LEAL-OLIVEIRA *et al*., 2013)	$\mathrm{M_t} = \frac{\mathrm{M_e}}{1+\exp[-\mathrm{k(t-\tau)}]}$ (3)
First order (GHAFOOR *et al*., 2014)	$\mathrm{MR} = 1 - \exp\,(-\mathrm{k_1t})$ (4)
Weibull (ZURA *et al*., 2013)	$\mathrm{MR} = 1 - \exp\left[-\left(\frac{\mathrm{t}}{\alpha}\right)^{\beta}\right]$ (5)

MR is the rate of moisture uptake, and is given by the equation: $MR = \frac{M_0-M_t}{M_0-M_e}$
where M_0 is the initial moisture content of the bean, M_t is the moisture content of bean at time t, and M_e is the final moisture content at equilibrium.
t is the hydration duration (in min), and the variables c_1, c_2, k_1, k, τ, α and β are the coefficients used in nonlinear regression analysis with the various models.

2.7. Statistical analysis

One-way analysis of variance and Tukey tests were performed to determine the difference between the values of seed morphological traits (*we, l, w, d*, G_{m}, A_{m}, S_{m} *and r*), chemical composition (moisture, proteins, fats, ashes and total carbohydrates), *%Cs* and the kinetic parameters of the soaking treatments (M_e and D_{eff}) of the different varieties of beans, using Statgraphics Plus 5.0 statistical package (Statistical Graphics Corp., MD, USA). Significance level were tested at P < 0.05.

3. RESULTS AND DISCUSSION

3.1. Chemical and morphological characterization of the bean seeds

Table 2 shows the results of *we*, *l*, *w*, *d*, G_{m}, A_{m}, S_{m} and *r* of the six bean varieties studied. According to the obtained results, the Azufrado bean variety presented the lowest values in the majority of the morphological characteristics studied, and the Mayocoba and Flor de Mayo varieties presented the highest values. Although Flor de Mayo and Azufrado beans had the highest *r* (0.41 cm) and the lowest *r* (0.30 cm), respectively, the majority of the varieties of bean used in this study presented a higher *r* value in comparison with the Navy bean (GHAFOOR *et al*., 2014).
Table 3 shows the chemical composition of the six varieties of beans studied. The values of the proximal composition of the six bean varieties of this study are similar to those reported by WANI *et al*. (2015) for other bean varieties, with the exception of the moisture content for the Mayocoba variety, which was the highest, and the fat content for the Pinto variety, which was the lowest.

3.2. Kinetics of water absorption

The water absorption kinetics of the different varieties of bean studied are shown in Fig. 1. The time to attain the *Me* ranged from 330 min to 660 min depending of the bean variety, being the shortest time for Mayacoba and longest time for Negro Jamapa. According to this finding, exposure to ultrasound reduced the soaking time of the bean; however, at a higher power of ultrasound, the time lapse was even lower. From the six different varieties of bean studied, after of the ultrasound treatments at 5W, 10 W and 19 W, the shortest and longest soaking times were 173 min and 280 min, 108 and 360 min, and 123 min and 313 min, respectively, corresponding to Mayacoba and Peruano Bola, Mayacoba and Negro Jamapa, and Pinto and Negro Jamapa.

Table 2. Characteristics of the six varieties of common bean *(Phaseolus vulgaris)* seeds.

Parameters	Bean varieties					
	Mayocoba	Azufrado	Pinto	Peruano Bola	Flor de Mayo	Negro Jamapa
we (g)	0.39 ± 0.03^{a}	0.25 ± 0.02^{d}	0.36 ± 0.05^{b}	0.32 ± 0.04^{c}	0.35 ± 0.06^{b}	0.24 ± 0.04^{d}
l (cm)	1.29 ± 0.06^{a}	1.08 ± 0.06^{c}	1.25 ± 0.08^{b}	1.03 ± 0.06^{d}	1.25 ± 0.01^{b}	0.96 ± 0.07^{e}
w (cm)	0.70 ± 0.04^{cd}	0.66 ± 0.03^{e}	0.73 ± 0.05^{b}	0.72 ± 0.03^{bc}	0.76 ± 0.05^{a}	0.69 ± 0.08^{d}
d (cm)	0.59 ± 0.05^{a}	0.47 ± 0.04^{d}	0.56 ± 0.05^{b}	0.61 ± 0.03^{a}	0.52 ± 0.04^{c}	0.53 ± 0.04^{c}
G_m (cm)	0.82 ± 0.04^{a}	0.70 ± 0.03^{d}	$0.79\pm.0.04^{ab}$	0.76 ± 0.03^{c}	0.79 ± 0.06^{b}	0.71 ± 0.04^{d}
A_m (cm)	0.86 ± 0.04^{a}	0.74 ± 0.03^{d}	0.85 ± 0.05^{ab}	0.78 ± 0.03^{c}	0.84 ± 0.06^{b}	0.73 ± 0.04^{b}
S_m (cm)	0.41 ± 0.01^{d}	0.37 ± 0.01^{e}	0.41 ± 0.01^{d}	0.84 ± 0.02^{b}	0.87 ± 0.04^{a}	0.80 ± 0.03^{c}
r (cm)	0.35 ± 0.01^{d}	0.30 ± 0.00^{e}	0.34 ± 0.02^{d}	0.39 ± 0.01^{b}	0.41 ± 0.02^{a}	0.37 ± 0.02^{c}

Values are given as means±standard deviation (n = 100). Different superscript letters in the same row indicate significant differences ($P < 0.05$).

we: weight; *l*: length; *w*: width; *d*: depth; G_m: geometric mean diameter; A_m: arithmetic mean diameter; S_m: square mean diameter; *r*: radius of an equivalent sphere.

Table 3. Seed proximate composition of the six varieties of common bean (*Phaseolus vulgaris*).

Component	Bean varieties					
	Mayocoba	Azufrado	Pinto	Peruano Bola	Flor de mayo	Negro Jamapa
Moisture (%)	12.8 ± 0.1^{a}	11.2 ± 0.1^{bc}	11.0 ± 0.4^{bcd}	11.4 ± 0.3^{b}	9.5 ± 0.1^{e}	8.9 ± 0.1^{f}
Fat (%)	1.6 ± 0.2^{bc}	2.1 ± 0.2^{b}	0.6 ± 0.1^{d}	4.7 ± 0.5^{a}	1.0 ± 0.1^{cd}	1.5 ± 0.1^{bcd}
Ash (%)	4.5 ± 0.1^{a}	4.8 ± 0.2^{a}	4.1 ± 0.1^{a}	4.5 ± 0.1^{a}	4.0 ± 0.2^{a}	4.6 ± 0.1^{a}
Protein (%, N x 6.25)	23.5 ± 0.5^{a}	23.6 ± 0.1^{a}	23.9 ± 0.5^{a}	23.8 ± 0.4^{a}	23.2 ± 0.2^{a}	23.9 ± 0.5^{a}
Total carbohydrates (%)	57.6±0.5	58.3±0.2	60.4±0.5	55.6±0.5	62.3±0.2	61.1±0.5

Values are given as means±standard deviation (n = 3). Different superscript letters in the same row indicate significant differences ($P < 0.05$).

On the other hand, the Azufrado and Peruano Bola bean varieties presented an initial lag phase or lateness (period with a low water absorption rate) for the 5 W ultrasound treatment and the control treatment, whereas the Pinto, Flor de Mayo and Negro Jamapa bean varieties presented initial lag phase for the ultrasound treatments of 5 W and 12 W, as well as the control treatment.

The behavior of the hydration kinetics of this study has been observed in the conventional soaking (25-55° C) of common bean by PIERGIOVANNI (2011), who classified the bean varieties into three groups as a function of the rate of hydration (fast, intermediate and slow); the fast and intermediate bean varieties did not present an initial lag phase, but the slow hydration bean varieties did have an initial lag phase. According to this classification, the Mayocoba bean variety can be considered to have a rapid hydration rate, in contrast to the rest of the bean varieties studied, even though with the application of the ultrasound power, especially at 19 W, the initial lag phase of the bean hydration of the varieties of

Azufrado, Pinto, Peruano Bola and Flor de Mayo was reduced. KAPTSO *et al*. (2008) reported that the application of ultrasound for soaking has an effect similar to increasing the soaking temperature, thus overcoming the defect of low water absorption observed in the seeds.

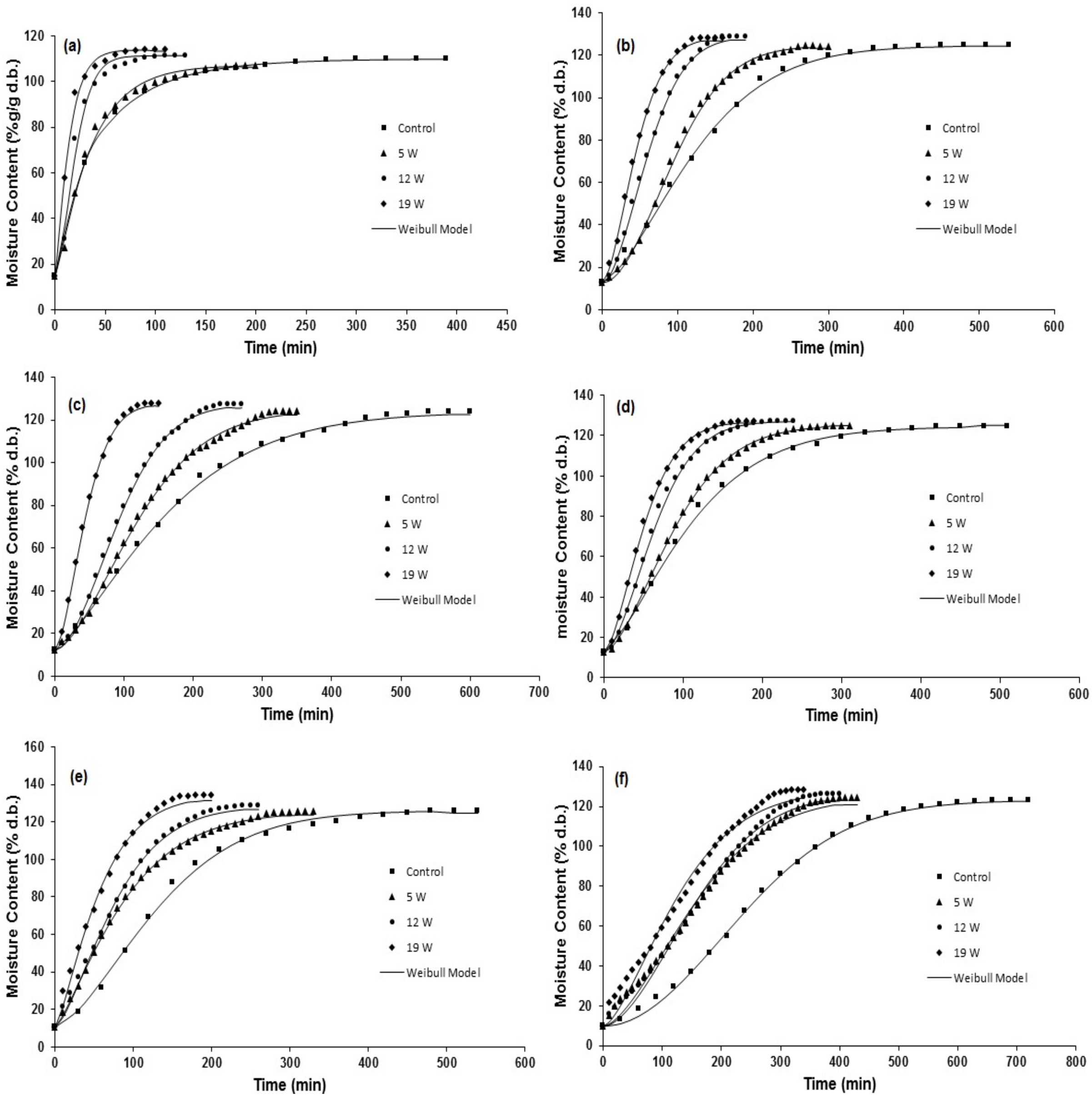

Figure 1. Water absorption kinetic of (a) Mayocoba, (b) Azufrado, (c) Pinto, (d) Peruano Bola, (e) Flor de Mayo and (f) Negro Jamapa bean varieties during soaking at different ultrasound powers. Solid lines represent the corresponding Weibull model fitted to the experimental data.

The statistical parameters generated from the application of the different mathematical models (Weibull, Peleg, First Order, and Sigmoid) describing the kinetics of water absorption for the bean varieties are presented in Table 4. In general, the Sigmoid model presented higher values of R^2 (0.998) and lower χ^2 (0.000) and *RSME* (0.019) than the Peleg and First Order models (Table 4); in addition, Sigmoid model can describe the initial lag phase followed by a high rate absorption phase and, finally, a stationary phase (LEAL-OLIVEIRA *et al*., 2013). However, the Weibull model presented the best fit, giving the highest values of R^2 (0.986-0.999) and the lowest of χ^2 (0.000-0.002) and *RSME* (0.013-0.044), in accordance with MARABI *et al*. (2003), who found that such model is one of the best for describing the kinetics of food hydration.

Table 4. Statistical parameters of the mathematical models fitted to the kinetics of hydration of six bean varieties.

Model	Ultrasound power (W)	Mayocoba			Azufrado			Pinto			Peruano Bola			Flor de Mayo			Negro Jamapa		
		R^2	χ^2	RSME	R^2	χ^2	RSME	R^2	χ^2	RSME	R^2	χ^2	RSME	R^2	χ^2	RSME	R^2	χ^2	RSME
Sigmoidal	Control	0.961	0.003	0.050	0.997	0.001	0.023	0.997	0.001	0.027	0.989	0.002	0.035	0.991	0.002	0.036	0.993	0.001	0.016
	5	0.970	0.002	0.046	0.998	0.000	0.019	0.996	0.001	0.024	0.996	0.001	0.022	0.987	0.002	0.039	0.996	0.001	0.020
	12	0.983	0.002	0.040	0.996	0.001	0.024	0.998	0.000	0.019	0.994	0.001	0.029	0.997	0.001	0.020	0.995	0.001	0.025
	19	0.985	0.002	0.036	0.996	0.001	0.024	0.997	0.001	0.023	0.985	0.002	0.040	0.992	0.001	0.034	0.995	0.001	0.028
First Order	Control	0.989	0.001	0.026	0.971	0.006	0.070	0.991	0.002	0.046	0.961	0.006	0.070	0.959	0.006	0.076	0.906	0.016	0.123
	5	0.990	0.001	0.026	0.921	0.013	0.110	0.940	0.009	0.091	0.949	0.007	0.084	0.981	0.002	0.046	0.933	0.010	0.095
	12	0.966	0.004	0.056	0.929	0.013	0.108	0.922	0.014	0.112	0.943	0.009	0.092	0.966	0.005	0.069	0.911	0.014	0.113
	19	0.991	0.001	0.028	0.949	0.009	0.090	0.951	0.009	0.087	0.956	0.007	0.080	0.977	0.004	0.059	0.942	0.008	0.087
Peleg	Control	0.994	0.000	0.020	0.977	0.004	0.062	0.994	0.002	0.038	0.973	0.004	0.059	0.962	0.006	0.075	0.959	0.007	0.081
	5	0.979	0.002	0.038	0.961	0.007	0.077	0.979	0.003	0.053	0.972	0.004	0.062	0.986	0.002	0.039	0.988	0.002	0.039
	12	0.948	0.006	0.070	0.975	0.005	0.064	0.971	0.005	0.067	0.959	0.007	0.078	0.986	0.002	0.0433	0.987	0.002	0.041
	19	0.979	0.002	0.044	0.980	0.004	0.056	0.979	0.004	0.057	0.970	0.005	0.059	0.993	0.001	0.031	0.993	0.001	0.031
Weibull	Control	0.995	0.000	0.017	0.996	0.001	0.022	0.999	0.000	0.013	0.997	0.000	0.0171	0.995	0.001	0.025	0.998	0.001	0.018
	5	0.991	0.001	0.025	0.997	0.001	0.022	0.998	0.000	0.016	0.999	0.001	0.010	0.997	0.001	0.018	0.991	0.001	0.033
	12	0.986	0.002	0.036	0.998	0.000	0.019	0.999	0.000	0.014	0.996	0.001	0.0213	0.996	0.001	0.021	0.991	0.002	0.035
	19	0.993	0.001	0.025	0.999	0.000	0.015	0.999	0.000	0.013	0.997	0.000	0.0163	0.993	0.001	0.033	0.984	0.002	0.044

Figure 1 also shows the kinetics of bean hydration fitted to the Weibull model where α is a scale parameter and β a shape parameter. The scale parameter defines the rate of moisture uptake process (α is the reciprocal of the process rate constant) and represents the time needed to accomplish the approximately 63% of the moisture uptake process, while the shape parameter is a behavior index, which depends on the process mechanism.

The kinetic parameters generated from the application of the different mathematical models for evaluating the hydration kinetics of beans by effect of the ultrasound treatment are shown in Table 5. According to the results obtained, the constants of hydration rate, k and k_1, of the Sigmoidal and First Order Models, respectively, were increased for effect of ultrasound power from 1.49 to 4.04 times and from 1.93 to 3.56 times in comparison with the control treatment, depending of the bean variety. Regarding Peleg's model, the first constant, c_1, which has been shown to be linked to the hydration was reduced for all bean varieties by effect of ultrasound in comparison with the control treatment. Therefore, the application of ultrasound and its increasing of power level improved the hydration properties such as reflected in the rate constants of the Sigmoidal, First Order and Peleg models.

In relation to the α parameter of Weibull model, its value decreased with increasing ultrasound power for all the bean varieties (Table 5), in agreement with the reported results by GHAFOOR *et al*. (2014) for Navy bean.

On the other hand, the values of kinetic parameter of hydration β of Weibull model (Table 5) for the soaking treatments of the different varieties of beans were high (0.834-1.995). According to MACHADO *et al*. (1999), the Weibull model predicts the initial lag phase of the hydration kinetics when β is greater than 1, as it was observed for the different treatments and bean varieties in this study, except for the control treatment in the Mayocoba variety.

3.3. Seed coat content

The Flor de Mayo and Mayacoba bean varieties presented the highest *%Cs* (9.85±0.62 and 8.82±0.62, respectively), followed by the Negro Jamapa (8.65±0.02), Peruano Bola (7.92±0.36), Azufrado (7.56±0.19) and Pinto (7.48±0.50) varieties bean. In this study, the varieties of bean with the first and third highest *%Cs* (Flor de Mayo and Negro Jamapa) required a higher soaking lapse to attain *Me* in comparison with the fourth and fifth highest *%Cs* (Peruano Bola and Azufrado). However, the time to attain *Me* of the Pinto variety with a *%Cs* lower than the Mayacoba variety was longer (Fig. 1).

On the other hand, the varieties of bean with a higher *%Cs* presented a higher coat rupture by effect of the ultrasound (Table 6). In the varieties of Azufrado, Pinto, Peruano Bola, Flor de Mayo and Negro Jamapa, the percentage of seeds with a higher percentage of coat rupture increased as the ultrasound power was higher (5, 12 and 19 W). The Negro Jamapa and Flor de Mayo varieties presented coat rupture in all soaking treatments, including the control. The results suggest that the percentage of the coat rupture depended on bean variety and the ultrasound power used in the soaking process, agreeing with the report of PAN *et al*. (2010).

Table 5. Kinetic parameters for the models fitted to the hydration kinetics data of six bean varieties.

Model	Soaking treatment	Bean varieties					
		Mayocoba	Azufrado	Pinto	Peruano Bola	Flor de Mayo	Negro Jamapa
Sigmoidal	Control	$k = 5.351 \times 10^{-2}$ $\tau = 26.906$	$k = 1.740 \times 10^{-2}$ $\tau = 104.356$	$k = 1.261 \times 10^{-2}$ $\tau = 131.756$	$k = 2.034 \times 10^{-2}$ $\tau = 87.458$	$k = 1.803 \times 10^{-2}$ $\tau = 114.714$	$k = 1.111 \times 10^{-2}$ $\tau = 225.728$
	5 W	$k = 5.433 \times 10^{-2}$ $\tau = 24.634$	$k = 2.666 \times 10^{-2}$ $\tau = 84.062$	$k = 1.900 \times 10^{-2}$ $\tau = 104.513$	$k = 2.571 \times 10^{-2}$ $\tau = 76.631$	$k = 2.267 \times 10^{-2}$ $\tau = 71.294$	$k = 1.436 \times 10^{-2}$ $\tau = 139.061$
	12 W	$k = 11.354 \times 10^{-2}$ $\tau = 16.368$	$k = 3.920 \times 10^{-2}$ $\tau = 54.383$	$k = 2.681 \times 10^{-2}$ $\tau = 82.217$	$k = 3.739 \times 10^{-2}$ $\tau = 56.192$	$k = 2.754 \times 10^{-2}$ $\tau = 65.193$	$k = 1.595 \times 10^{-2}$ $\tau = 143.056$
	19 W	$k = 15.757 \times 10^{-2}$ $\tau = 10.395$	$k = 5.020 \times 10^{-2}$ $\tau = 39.387$	$k = 5.100 \times 10^{-2}$ $\tau = 38.667$	$k = 4.524 \times 10^{-2}$ $\tau = 43.394$	$k = 3.540 \times 10^{-2}$ $\tau = 46.346$	$k = 1.659 \times 10^{-2}$ $\tau = 110.453$
First Order	Control	$k_1 = 2.458 \times 10^{-2}$	$k_1 = 0.750 \times 10^{-2}$	$k_1 = 0.576 \times 10^{-2}$	$k_1 = 0.8445 \times 10^{-2}$	$k_1 = 0.694 \times 10^{-2}$	$k_1 = 3.678 \times 10^{-3}$
	5 W	$k_1 = 2.711 \times 10^{-2}$	$k_1 = 0.945 \times 10^{-2}$	$k_1 = 0.742 \times 10^{-2}$	$k_1 = 1.051 \times 10^{-2}$	$k_1 = 1.060 \times 10^{-2}$	$k_1 = 5.729 \times 10^{-3}$
	12 W	$k_1 = 4.425 \times 10^{-2}$	$k_1 = 1.460 \times 10^{-2}$	$k_1 = 0.965 \times 10^{-2}$	$k_1 = 1.422 \times 10^{-2}$	$k_1 = 1.219 \times 10^{-2}$	$k_1 = 5.575 \times 10^{-3}$
	19 W	$k_1 = 6.848 \times 10^{-2}$	$k_1 = 2.000 \times 10^{-2}$	$k_1 = 2.050 \times 10^{-2}$	$k_1 = 1.808 \times 10^{-2}$	$k_1 = 1.703 \times 10^{-2}$	$k_1 = 7.121 \times 10^{-3}$
Peleg	Control	$c_1 = 23.619$ $c_2 = 0.959$	$c_1 = 123.560$ $c_2 = 0.568$	$c_1 = 160.676$ $c_2 = 0.569$	$c_1 = 100.512$ $c_2 = 0.626$	$c_1 = 123.575$ $c_2 = 0.558$	$c_1 = 329.984$ $c_2 = 0.321$
	5 W	$c_1 = 30.503$ $c_2 = 0.884$	$c_1 = 123.423$ $c_2 = 0.374$	$c_1 = 156.812$ $c_2 = 0.3657$	$c_1 = 102.118$ $c_2 = 0.471$	$c_1 = 81.568$ $c_2 = 0.564$	$c_1 = 223.034$ $c_2 = 0.274$
	12 W	$c_1 = 18.995$ $c_2 = 0.818$	$c_1 = 79.673$ $c_2 = 0.328$	$c_1 = 123.713$ $c_2 = 0.3115$	$c_1 = 69.255$ $c_2 = 0.505$	$c_1 = 79.689$ $c_2 = 0.468$	$c_1 = 234.070$ $c_2 = 0.159$
	19 W	$c_1 = 10.078$ $c_2 = 0.868$	$c_1 = 54.001$ $c_2 = 0.402$	$c_1 = 51.482$ $c_2 = 0.4301$	$c_1 = 54.229$ $c_2 = 0.506$	$c_1 = 52.746$ $c_2 = 0.475$	$c_1 = 163.072$ $c_2 = 0.297$
Weibull	Control	$\alpha = 42.481$ $\beta = 0.834$	$\alpha = 141.833$ $\beta = 1.493$	$\alpha = 181.544$ $\beta = 1.336$	$\alpha = 124.212$ $\beta = 1.372$	$\alpha = 150.984$ $\beta = 1.534$	$\alpha = 286.092$ $\beta = 1.995$
	5 W	$\alpha = 37.404$ $\beta = 1.076$	$\alpha = 110.515$ $\beta = 1.838$	$\alpha = 139.957$ $\beta = 1.607$	$\alpha = 102.955$ $\beta = 1.593$	$\alpha = 96.963$ $\beta = 1.259$	$\alpha = 182.245$ $\beta = 1.6121$
	12 W	$\alpha = 23.207$ $\beta = 1.514$	$\alpha = 71.718$ $\beta = 1.732$	$\alpha = 107.840$ $\beta = 1.788$	$\alpha = 74.790$ $\beta = 1.660$	$\alpha = 86.939$ $\beta = 1.425$	$\alpha = 183.437$ $\beta = 1.880$
	19 W	$\alpha = 15.019$ $\beta = 1.159$	$\alpha = 52.644$ $\beta = 1.599$	$\alpha = 51.570$ $\beta = 1.588$	$\alpha = 58.377$ $\beta = 1.545$	$\alpha = 62.154$ $\beta = 1.287$	$\alpha = 146.326$ $\beta = 1.483$

3.4. Equilibrium moisture content (*Me*)

The varieties of beans studied presented a *Me* that oscillated from 107.18 to 133.99 % d.b. (Table 6). The *Me* in the soaking control treatments increased for all the bean varieties, except for Peruano Bola (Table 6). The effect caused by the ultrasound power in the bean hydration is similar to the effect caused by the increase of temperature for the conventional soaking of bean (SHAFAEI *et al.*, 2014), sesame seeds (KHAZAEI and MOHAMMADI, 2009), rice (CHEEVITSOPON and NOOMHORM, 2011), and Botswana Bambara (JIDEANI and MPOTOKWANA, 2009).

Table 6. Effect of soaking treatment on the hydration properties of beans at 30 °C.

Variety/Property	Soaking treatments			
	Control	**5 W**	**12 W**	**19 W**
Mayocoba				
Me (% g/g d.b.)	110.08^{b}	107.18^{c}	111.46^{ab}	113.98^{a}
Rupture of coat (%)	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}
D_{eff} (x 10^{-10} m^2/s)	4.845^{c}	5.501^{c}	8.852^{b}	13.717^{a}
Azufrado				
Me (% g/g d.b.)	124.47^{b}	124.32^{b}	128.60^{a}	128.38^{a}
Rupture of coat (%)	0.0^{b}	0.0^{b}	0.0^{b}	5.0^{a}
D_{eff} (x 10^{-10} m^2/s)	0.380^{d}	0.488^{c}	0.752^{b}	1.026^{a}
Pinto				
Me (% g/g d.b.)	123.72^{b}	124.46^{b}	127.24^{a}	127.69^{a}
Rupture of coat (%)	0.0^{b}	0.0^{b}	0.0^{b}	16.6^{a}
D_{eff} (x 10^{-10} m^2/s)	1.097^{d}	1.413^{c}	1.839^{b}	3.847^{a}
Peruano Bola				
Me (% g/g d.b.)	124.47^{a}	125.08^{a}	127.18^{a}	126.96^{a}
Rupture of coat (%)	0.0^{b}	0.0^{b}	0.0^{b}	1.5^{a}
D_{eff} (x 10^{-10} m^2/s)	2.135^{b}	2.616^{b}	4.168^{a}	4.633^{a}
Flor de mayo				
Me (% g/g d.b.)	125.96^{b}	125.59^{b}	128.39^{ab}	133.99^{a}
Rupture of coat (%)	15.5^{c}	29.0^{b}	40.0^{a}	49.0^{a}
D_{eff} (x 10^{-10} m^2/s)	1.967^{c}	3.056^{b}	3.414^{b}	5.025^{a}
Negro Jamapa				
Me (% g/g d.b.)	123.07^{c}	124.68^{bc}	126.22^{ab}	128.05^{a}
Rupture of coat (%)	1.6^{b}	10.0^{a}	13.3^{a}	21.6^{a}
D_{eff} (x 10^{-10} m^2/s)	0.711^{c}	1.287^{b}	1.275^{b}	1.60^{a}

Values are given as means±standard deviation (n = 3). Different superscript letters in the same row indicate significant differences ($P < 0.05$).

3.5. Effect of ultrasound on the effective diffusivity (D_{eff})

To calculate D_{eff} (Eq. 6), the inverse of α was used ($1/\alpha$) as the rate constant of water absorption. Table 6 shows the effects of the ultrasound treatments during the bean soaking process on D_{eff} for the distinct studied varieties.

The soaking treatment with ultrasound at 19 W obtained the highest values of D_{eff} for all bean varieties. The increase of D_{eff} observed in this study as the ultrasound power was increased is congruent with a study on chickpeas, where the value of D_{eff} of the soaking control treatment at 30 °C was 1.87 x 10^{10} m^2/s and it was increased with the application of ultrasound to values of 2.10 x 10^{10} and 2.62 x 10^{10} (m^2/s) for the soaking treatments at 25 kHz and 100 W and 25 kHz and 300 W, respectively (YILDIRIM *et al*., 2011).
The increase of the absorption of water during the assisted soaking process with ultrasound is due to the formation of microscopic channels in the grains, which reduce the internal resistance to mass transference (FUENTE-BLANCO *et al*., 2006).
In this study we observed that increasing the ultrasound power in the soaking treatments of the beans generated a proportional increase on the values of D_{eff} (Fig. 2), in similarity to the proportional increasing of the water absorption during soaking of bean by effect of increase of temperature (SHAFAEI *et al*., 2014).

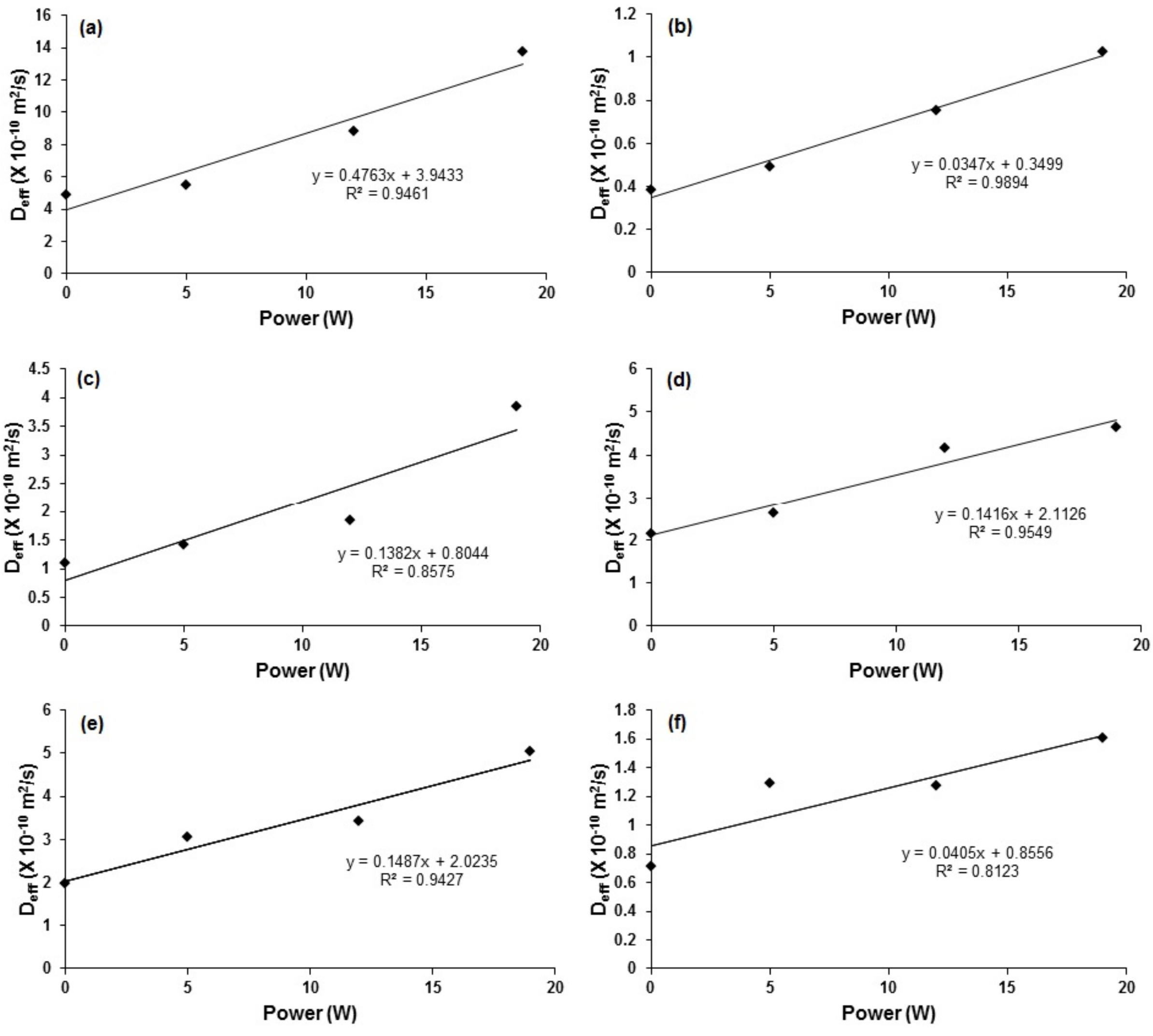

Figure 2. Effect of low frequency ultrasound power (20 kHz) on the D_{eff} in the soaking of the Mayocoba (a), Azufrado (b), Pinto (c), Peruano Bola (d), Flor de mayo (e) and Negro Jamapa (f) bean varieties.

4. CONCLUSIONS

The application of ultrasound reduced the lapse of soaking in the six varieties of beans studied, although the reduction depended of the bean variety and the ultrasound power. The soaking treatment at 19 W presented the highest values of D_{eff}, *Me* and the least time to attain *Me*. However, this ultrasound treatment also presented coat rupture of the beans, in different proportion, except for the Mayocoba variety. Of the models used, the Weibull model presented the best fit for the experimental data of the hydration kinetics, in the different soaking treatments and for the majority of the bean varieties.

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REFERENCES

Abu-Ghannam, N. and McKenna, B. 1997. Hydration kinetics of red kidney beans (*Phaseolus vulgaris* L.). J. Food Sci. 62, 520-523.

AOAC. 2002. "Official Methods of Analysis of AOAC International" Association of Official Analytical Chemists, Gaithersburg, MD.

Campos-Vega R., Loarca-Piña G. and Oomah B.D. 2010. Minor components of pulses and their potential impact on human health. Food Res Int. 43:461-482

Campos-Vega R., Vergara-Castañeda H.A. and Oomah B.D. 2012. In: "Beans: Nutrition, Consumption and Health: Functional Food Sources: Beans in Sight". E. Popoescu, I. Golubev (Ed.), p 1-56. Nova Science Publishers, New York.

Cárcel J.A., García-Pérez J.V., Benedito J. and Mulet A. 2012. Food process innovation through new technologies: Use of ultrasound. J. Food Eng. 110: 200-207.

Cheevitsopon E. and Noomhorm A. 2011. Kinetics of hydration and dimensional changes of brown rice. J. Food Process Pres. 35:840-849.

Chemat F., Huma Z. and Khan M.K. 2011. Applications of ultrasound in food technology: Processing, preservation and extraction. Ultrason Sonochem. 18:813-835.

Cox S., Gupta S. and Abu-Ghannam N. 2012. Effect of different rehydration temperatures on the moisture, content of phenolic compounds, antioxidant capacity and textural properties of edible Irish brown seaweed. LWT-Food Sci Technol. 47:300-307.

Fuente-Blanco, S.D.L., Riera-Franco de Sarabia E., Acosta-Aparicio V.M., Blanco-Blanco A. and Gallego-Juárez J.A. 2006. Food drying process by power ultrasound. Ultrasonics 44: e523-e527.

Ghafoor M., Misra N.N., Mahadevan K. and Tiwari B.K. 2014. Ultrasound assisted hydration of navy beans (*Phaseolus vulgaris*). Ultrason Sonochem. 21:409-414.

Jideani V.A. and Mpotokwana S.M. 2009. Modeling of water absorption of Botswana Bambara varieties using Peleg's equation. J. Food Eng 92:182-188.

Kaptso K.G., Njintang Y.N., Komnek A.E., Hounhouigan J., Scher J. and Mbolung C.M.F. 2008. Physical properties and rehydration kinetics of two varieties of cowpea (*Vigna unguiculata*) and bambara groundnuts (*Voandzeia subterrânea*) seeds. J. Food Eng. 86: 91-99.

Khazaei J. and Mohammadi N. 2009. Effect of temperature on hydration kinetics of sesame seeds (*Sesamum indicum* L.). J. Food Eng 91:542-552.

Leal-Oliveira A., Gouveia-Colnaghi B., Zucatti-da-Silva E., Romáo-Gouvêa I., Lopes-Vieira R. and Duarte-Augusto P.E. 2013. Modelling the effect of temperature on the hydration kinetic of Adzuki beans (*Vigna angularis*). J. Food Eng 118:417-420.

Machado M.F., Oliveira F.A. and Cunha L.M. 1999. Effect of milk fat and total solids concentration on the kinetics of moisture uptake by ready-to-eat breakfast cereal. Int. J. Food Sci. Tech. 34: 47-57.

Marabi A., Livings S., Jacobson M. and Saguy. I. 2003. Normalized Weibull distribution for modeling rehydration of food particulates. Eur. Food Res. Technol. 217: 311-318.

Mkanda A.V., Minnaar A. and Kock H.L. 2007. Relating consumer preferences to sensory and physicochemical properties of dry beans (*Phaseolus vulgaris*). J. Sci. Food Agric. 87:2868-2879.

Olmedilla-Alonso B., Pedrosa M.M., Cuadrado C., Brito M., Asensio-S-Manzanera C. and Asensio-Vegas, C. 2013. Composition of two Spanish common dry beans (*Phaseolus vulgaris)*, 'Almonga' and 'Curruquilla', and their postprandial effect in type 2 diabetics. J. Sci. Food Agric. 93:1076-1082.

Pan Z., Atungulu G.G., Wei L. and Haff R. 2010. Development of impact acoustic detection and density separations methods for production of high quality processed beans. J. Food Eng. 97:292-300.

Patero T. and Augusto P.E.D. 2015. Ultrasound (US) enhances the hydration of sorghum (*Sorghum bicolor*) grains. Ultrason. Sonochem 23:11-15.

Peleg, M. 1988. An empirical model for the description of moisture sorption curves. J. Food Sci. 53:1216-1217.

Piergiovanni A.R. 2011. Kinetic of water adsorption in common bean: considerations on the suitability of Peleg's model for describing bean hydration. J. Food Proc. Pres. 35:447-452.

Plans M., Simó J., Casañas F., Sabaté J. and Rodriguez-Saona L. 2013. Characterization of common beans (*Phaseolus vulgaris* L.) by infrared spectroscopy: comparison of MIR, FT-NIR and dispersive NIR using portable and benchtop instruments. Food Res. Int. 54:1643-1651.

Rodríguez-Licea G., García-Salazar J.A., Rebollar-Rebollar S. and Cruz-Contreras A.C. 2010. Preferencias del consumidor de frijol (*Phaseolus vulgaris* L.) en México: factores y características que influyen en la decisión de compra diferenciada por tipo y variedad. Paradigma Económico 2:121-145.

Shafaei S.M., Masoumi A.A. and Roshan H. 2014. Analysis of water absorption of bean and chickpea during soaking using Peleg model. Journal of the Saudi Society of Agricultural Sciences DOI: 10.1016/j.jssas.2014.08.003.

Tizazu H. and Emire S. 2010. Chemical composition, physicochemical and functional properties of lupin (*Lupinus albus*) seeds grown in Ethiopia. Afr. J. Food Agric. Nutr. Dev. 10: 3029-3046.

Wani I.A., Sogi D.S., Wani A.A. and Gill B.S. 2015. Physical and cooking characteristics of some Indian kidney bean (*Phaseolus vulgaris* L.) cultivars. Journal of the Saudi Society of Agricultural Sciences DOI: 10.1016/j.jssas.2014.12.002.

WHO/FAO. 2003. Diet, Nutrition and the Prevention of Chronic Diseases. WHO Technical Report Series 916, Geneva.
Yildirim A., Öner M.D. and Bayram M. 2011. Fitting Fick's model to analyze water diffusion into chickpeas during soaking with ultrasound treatment. J. Food Eng. 104:134-142.

Zura L., Uribe E., Lemus-Mondaca R., Saavedra-Torrico, J., Vega-Gálvez, A. and Di Scala K. 2013. Rehydration capacity of Chilean papaya (*Vasconcellea pubescens*): Effect of process temperature on kinetic parameters and functional properties Food Bioprocess Technol. 6:844-850.

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