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Volume and density of whole soybean products during hot-air thermal treatment in fluidised bed

R. Martín Torrez Irigoyen [a], Sergio A. Giner [a,b,c,*]

[a] Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA), Facultad de Ciencias Exactas, Universidad Nacional de La Plata, Calle 47 y 116 (1900) La Plata, Provincia de Buenos Aires, Argentina
[b] Facultad de Ingeniería, Universidad Nacional de La Plata, Argentina
[c] Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, Argentina

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ABSTRACT

Soybeans contribute to healthy nutrition because of the high proportion and quality of proteins. Its oil content is considerably lower than in peanuts, restricting energy intake. To produce a whole soybean snack, four type of samples were processed by first increasing the water content and then reducing it by hot-air fluidisation: moistened–dried at 60 °C (MD), soaked–dried at 60 °C (SD), soaked and dried–toasted at 140 °C (SDT) and soaked–cooked and dried–toasted at 140 °C (SCDT). A semi-theoretical model was proposed to describe volume and density as a function of moisture during fluidisation. An equilibrium shrinkage coefficient *a* was determined. Volume expansion achieved by increasing the moisture content was not totally lost during fluidisation, allowing for lighter products, whose density decreased with the reduction in moisture. As the overall treatment was more severe (SCDT > SDT > SD > MD), shrinkage coefficients increased, up to 0.75. The SCDT sample became crispy and glassy after cooling.

1. Introduction

Soybeans (*Glycine max*) provide healthy nutrition. Their protein content (38–44% w/w) is higher than in cereals (8–15% w/w) and exhibits a better amino acid profile (Kashaninejad et al., 2008). Most of the engineering research carried out for soybean deals with postharvest operations as hot temperature drying (Mensah et al., 1985; Zeng et al., 1996), or analyses defatted high-protein soyflour or edible oil as main processing products (Erickson, 1995). Less attention have been paid to the processing stages leading to ready-to-eat whole soybean snacks, where the requirement of grain integrity is essential. Therefore, for such end-use, the freshly harvested soybeans should be dried with unheated air using slow specific airflows to prevent grain splitting in storage and subsequent stages of processing (Hansen et al., 1996).

In many western countries, consumption of whole soybean products is scarce. Today's lifestyles, especially in urban areas, are not compatible with the extended preparation time required to cook and inactivate the antinutritional factors (Soponronnarit et al., 2001).

The evident trend towards the consumption of dehydrated, crispy, ready-to-eat snacks (Aguilera et al., 2003) may justify a process whereby soybeans can be precooked-inactivated and dried or toasted to produce a low moisture, porous product. The glassy state (Bhandari and Howes, 1999) required for such a foodstuff is facilitated by the scarce content of low-molecular weight sugars in soybeans.

Fluidisation may be utilised for the dehydration–toasting step, due to its capacity to apply a uniform thermal treatment to the grain, as tested in wheat drying by Giner and Calvelo (1987) and, for soybean postharvest drying, by Kitic and Viollaz (1984). Giner and Demichelis (1988) have found a high energy recovery potential in fluidisation processes, so this stage can be an adequate alternative from the energy expenditure viewpoint. Osella et al. (1997) and Soponronnarit et al. (2001) have proposed hot-air soybean fluidisation as a drying/inactivation technique and recommend air inlet temperatures of about 140 °C. However, no studies have been found on the hot-air fluidisation of previously soaked or cooked soybean for producing a whole grain snack.

To this end, the main objective was to study a three stage procedure of soaking, cooking and fluidised-bed drying/toasting at 140 °C. A Specific objective is to measure and model soybean volume and density as a function of moisture content during fluidisation with well-founded expressions. In order to analyse the structural changes, volumes and densities thus measured were compared with those from two-stage processes as moistening and drying at 60 °C, soaking and drying at 60 °C and soaking and

* Corresponding author at: Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA), Facultad de Ciencias Exactas, Universidad Nacional de La Plata, Calle 47 y 116 (1900) La Plata, Provincia de Buenos Aires, Argentina. Tel.: +54 221 4249287; fax: +54 221 42890741.
E-mail address: saginer@ing.unlp.edu.ar (S.A. Giner).

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Nomenclature

a	average equilibrium shrinkage coefficient
a_s	average equilibrium swelling coefficient
D_e	equivalent diameter (m^3)
m_d	dry mass (kg)
m_{TP}	total mass of whole soybeans (kg)
m_{wev}	mass of water evaporated (kg water)
m_0	initial mass of particles (kg)
N_{TP}	total number of particles
V_0	initial particle volume, m^3 in decreasing moisture content model
V_i	initial particle volume, m^3 for increasing moisture content model
V_{TP}	total volume of particles (m^3)
V_{wa}	volume of absorbed water (m^3)
V_{wev}	volume of water evaporated (m^3)
W	moisture content (kg water/kg dry matter)
W_0	initial moisture content (kg water/kg dry matter)

Greek symbols

π	pi
ρ_w	water density (kg/m^3)
ρ_0	initial density of particles (kg/m^3)

fluidised-bed drying/toasting at 140 °C. Results will be discussed in the light of the glass transition theory.

2. Theoretical considerations

2.1. Mathematical model for the relationship between soybean volume and moisture content

2.1.1. Increasing moisture contents

A low moisture product of volume V_i and moisture content W_i may be moistened, soaked or cooked in water to produce swelling

$$V = V_i + a_s V_{wa} \tag{1}$$

where V_{wa} is the volume of absorbed water and a_s an average equilibrium swelling coefficient, which would represent the fraction of the complete volume expansion underwent by the sample during swelling. Thus, a factor equal to unity would indicate that the sample expanded 1 mm^3 per each mm^3 of absorbed water, after equilibration. Replacing in Eq. (1) the value V_{wa} by the relationship between the mass of water absorbed (m_{wa}) and its density (ρ_w), the following expression is obtained

$$V = V_i + a_s \frac{m_{wa}}{\rho_w} \tag{2}$$

In turn, m_{wa} can be expressed as the product of dry matter and the moisture content difference between the current state and the initial conditions $m_d\,(W - W_i)$

$$V = V_i + a_s \frac{m_d(W - W_i)}{\rho_w} \tag{3}$$

Considering that the dry matter is calculated using the mass of product at a given moisture content, i.e., $m_d = m_i/(1 + W_i)$

$$V = V_i + a_s \frac{m_i(W - W_i)}{(1 + W_i)\rho_w} \tag{4}$$

By expressing $m_i = \rho_i V_i$, and rearranging, relationship between volume and moisture content is found

$$\frac{V}{V_i} = \left[1 + a_s \frac{\rho_i(W - W_i)}{\rho_w(1 + W_i)}\right] \tag{5}$$

The corresponding density model $\rho = m/V$ requires previous mathematical development in its numerator. The mass of product is expressed first in terms of its dry mass and moisture content. Then, this dry mass is replaced by a relationship involving the initial mass and moisture content and, finally, the initial mass is written as the product of initial density and initial volume

$$\rho = \frac{m}{V} = \frac{m_d}{V} = \frac{\frac{m_i}{(1+W_i)}}{V} = \frac{m_i}{(1 + W_i)V} = \frac{\rho_i V_i}{(1 + W_i)V} \tag{6}$$

By replacing V in Eq. (6) by its expression of Eq. (5), the final form of the density model for increasing moisture contents is attained

$$\rho = \rho_i \frac{(1 + W)}{\left[1 + W_i + a_s \frac{\rho_i(W - W_i)}{\rho_w}\right]} \tag{7}$$

2.1.2. Decreasing moisture contents

2.1.2.1. Volume–moisture relationship. If water is removed by evaporation from a wet soybean grain, the grain volume can be described by

$$V = V_0 - aV_{wev} \tag{8}$$

where V_0 is the initial volume in m^3, i.e., the grain volume at a moisture content W_0, in kg water/kg dry matter, V_{wev} the volume of water evaporated and a an average shrinkage factor that may vary from 0 (constant volume) to 1 (shrinkage equivalent to volume of water evaporated). This is an equilibrium factor because grain volume is measured after the moisture gradient relaxes. The $a = 1$ behaviour (complete collapse) is usually observed for products in the rubbery state (Mayor and Sereno, 2004) and, provided the density of dry matter is higher than that of water, implies an increase of food density for decreasing moistures. Conversely, if $a = 0$, the product may be in the glassy state, for instance during freeze drying (Bhandari and Adhikari, 2009), leading to a decrease in density for decreasing moistures.

By expressing the volume of water evaporated in terms of the corresponding mass and density, the following equation is found

$$V = V_0 - a\frac{m_{wev}}{\rho_w} \tag{9}$$

The mass of water evaporated can be represented in terms of the water lost by the grain, i.e., $m_d\,(W_0 - W)$, where m_d is the solid dry mass and W the moisture content. Therefore, the volume relationship becomes

$$V = V_0 - a\frac{m_d(W_0 - W)}{\rho_w} \tag{10}$$

The dry mass m_d may be written as $m/(1 + W)$, and, particularly, in terms of the initial conditions $m_0/(1 + W_0)$. Besides, replacing m_0 by $\rho_0 V_0$, the volume–moisture relationship can be rewritten as

$$\frac{V}{V_0} = 1 - a\frac{\rho_0(W_0 - W)}{\rho_w(1 + W_0)} \tag{11}$$

This expression can be fitted to experimental data of product volume as a function of moisture content in order to determine the shrinkage factor *a*.

2.1.2.2. Modelling whole soybean density as a function of moisture content. The product density model $\rho = m/V$ is arrived at by expressing the product mass as $m = m_d\,(1 + W)$. As in Eq. (11) m_d was written as $\rho_0\,V_0/(1 + W_0)$. The volume V was replaced by Eq. (11). By cancelling factors and rearranging, the resulting expression predicts

$$\rho = \rho_0 \frac{(1+W)}{\left[1 + W_0 - a\frac{\rho_0(W_0 - W)}{\rho_w}\right]} \tag{12}$$

3. Materials and methods

3.1. Material

Soybeans variety Don Mario 5.5 i were kindly provided by Don Mario Semillas (Don Mario Seeds Company), Chacabuco, Provincia de Buenos Aires, Argentina (http://www.donmario.com).

3.2. Experimental plan

In order to design a process to prepare an inactivated, ready-to-eat whole soybeans, the two most likely routes are soaking and fluidised-bed drying–toasting at 140 °C (SDT) or soaking, cooking and fluidised-bed drying–toasting at 140 °C (SCDT). However only for comparison of structural changes as the variation of density and volume with moisture content, additional treatments were studied as soaking and drying at 60 °C (SD) and moistening (an increase of moisture in the postharvest range) and drying at 60 °C (MD).

3.3. Determination of moisture content

Moisture content was measured in triplicate by an oilseed-specific whole grain method at atmospheric pressure (AOCS Ac 2-41, 130 °C for 3 h). With this purpose a mechanical convection oven (air velocity, 0.25 m/s) was utilised. Moisture content results were expressed in kg water/kg dry matter, units that are often referred to as "decimal dry basis" or "dec., d.b".

3.4. Sample moistening

Moistened samples were produced for studying the behaviour of grain volume and density during fluidisation, in a moisture range corresponding to postharvest practices as drying and aeration and to compare its shrinkage coefficient with those obtained for soaked or soaked–cooked samples. To moisten the soybeans, the amount of water added was calculated by a mass balance to increase the moisture content from the value at reception, 0.113 to 0.210 dec., d.b. This sample was then fluidised at 60 °C as described in Section 3.9.

3.5. Soaking of soybean grains

Grains were visually inspected to remove foreign materials and then washed twice by immersion in hot water (90 °C) for 1 min. Samples were allowed to reach room temperature and were then immersed in drinking water, using a water to soybean mass ratio of 2:1, and allowed to soak for 24 h at 10 °C. This procedure was recommended by the 2002 argentine government for soybean intended for food (González de Duhalde, 2003).

3.6. Cooking

The soaked soybeans were immersed in boiling water for 45 min, then removed and allowed to drain the water in excess (González de Duhalde, 2003).

3.7. Surface drying

To facilitate fluidisation of particles during further drying or drying–toasting, the soaked or soaked–cooked soybeans were surface-dried in thin layer using a mechanical convection oven at 50 °C for 10 min.

3.8. Fluidised-bed equipment

Fig. 1 is a drawing of the purpose-built experimental fluidised-bed dryer. It consists of five main components: a thermally insulated drying chamber, 0.10 m internal diameter and 0.30 m in height, a micromanometer Testo 525 (range: 0–25 hPa, error 0.2% full scale) to measure differences in air pressure across the bed that ensures adequate fluidisation, a hot wire anemometer TSI Mod. 1650 to record the air velocity flowing through the bed, a temperature controller, Novus brand Mod. N321-J/Kit with and a vector inverter system to control and vary the frequency of alternating current supplied to a Siemens electric motor (maximum angular speed, 2800 rev/min) directly connected to a centrifugal fan.

3.9. Drying and drying/toasting in fluidised bed

Drying and drying–toasting processes were carried out with air inlet temperatures of 60 and 140 °C, at an average air velocity of 2 m/s to cause a high degree of mixing and, therefore, uniform treatment of the bed. The fixed bed height of products was 0.10 m. For drying at 60 °C, soybean samples were removed at 5, 10, 15, 20, 60, 80, 120 and 180 min, while, in drying–toasting at

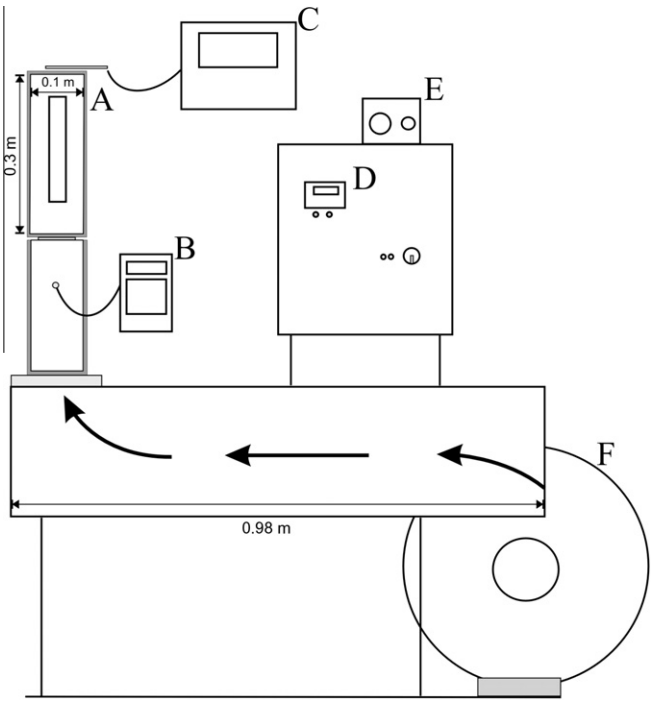

Fig. 1. (A) The drying chamber, (B) micromanometer TESTO 525, (C) hot wire anemometer TSI Mod. 1650, (D) temperature controller, (E) vector inverter, and (F) Fan (arrows indicate the direction of hot air).

140 °C, sampling times were 3, 7, 10, 20, 30, 40 and 60 min. Once removed, the samples were placed inside sealed containers for 24 h at 10 °C to allow for moisture equilibration. While this period is not required for moisture content determination, it is necessary for measuring equilibrium volume and density of the treated soybeans. All experiments were conducted in triplicate. The drying toasting temperature of 140 °C is below the limit for protein losses suggested by Hsu and Satter (1995).

3.10. Determination of whole soybean density and volume

Density (ρ) and volume (V) of equilibrated whole soybeans were determined by pycnometry using bidistilled water. A purpose-built 100 mL glass pycnometer was employed, which was added with 20 g samples. Density (ρ) was calculated as

$$\rho = \frac{m_{TP}}{V_{TP}} \tag{13}$$

where m_{TP} is the total mass of whole soybeans, previously weighed in a precision digital balance (±0.01 g) and V_{TP} the total volume of particles in m^3, determined by volume displacement in the pycnometer. The average particle volume, in turn, was determined by:

$$V = \frac{V_{TP}}{N_{TP}} \tag{14}$$

where N_{TP} is the total number of soybean grains in the sample.

The equivalent diameter D_e, defined as the diameter of a sphere with the same volume as the soybean, was calculated from the grain volume

$$D_e = \left(\frac{6V}{\pi}\right)^{\frac{1}{3}} \tag{15}$$

3.11. Determination of the thermal history of soybeans during fluidisation

Fluidisation is recognised to strongly mix the particulate product (Giner and Calvelo, 1987). Besides, as heat transfer is considerably faster than mass transfer, their surface temperature is very close to the average (Giner and Mascheroni, 2001). On these grounds, soybean temperature was considered an exclusive function of time, being measured throughout the fluidised-bed treatment by a non-contact infrared thermometer Testo 830 T2 (Testo AG, Germany).

3.12. Statistical analysis

Triplicate experiments were carried out for each fluidisation condition, measuring particle volume and density as a function of moisture content. Different conditions were compared by the Tukey's test (Montgomery, 1991), at a confidence level of 95%.

4. Results and discussion

4.1. Description of the changes observed during soaking and cooking

Table 1 shows the volume and density of raw, soaked and cooked whole soybeans (in this work, "cooked" means cooked after soaking), along with their equivalent diameter. Density of soaked soybeans is lower than that of raw soybeans because the grain swells and behaves as a mixture of dry matter, with higher density and water, with lower density. Therefore, as the moisture content of soaked soybean is higher, its density becomes lower. By fitting the volume model (Eq. (5)) to the experimental data of Table 1 as a function of moisture content, an average equilibrium swelling coefficient of 0.912 was determined by least squares (standard error of the parameter = 0.005). with a coefficient of determination, r^2 of 0.999, suggesting good agreement with results.

Table 1
Physical parameters of raw, soaked and cooked whole sobyean.

Whole soybeans	W (dec., d.b.)	ρ (kg/m^3)	V ($\times 10^7$ m^3)	D_e ($\times 10^3$ m)
Raw-low moisture	0.071	1186.30	1.285	6.261
Raw	0.113	1190.23	1.348	6.362
Soaked	1.450	1082.19	3.079	8.377
Cooked	1.494	1069.66	2.982	8.289

4.2. Description of the changes observed in the samples during fluidisation

Table 2 lists particle volume and equivalent diameter as a function of moisture content for fluidised-bed treatments (drying at 60 °C or drying–toasting at 140 °C) applied to moistened, soaked or cooked samples.

Volume of the moistened sample decreases by only 3.05% over fluidised-bed drying at 60 °C for a moisture content reduction of 48.8% (from 0.213 to 0.109 dec., d.b.) providing a shrinkage ratio of 0.0625 between both quantities (sample MD). In turn, the volume of the soaked soybeans decreased during fluidised-bed drying at 60 °C by 19.2% for a moisture reduction of 87.5% (from 1.45 to 0.182 dec., d.b.), thus exhibiting a higher ratio, 0.219. Concerning the sample pretreated by soaking and then dried–toasted at

Table 2
Pycnometric volume and equivalent diameter of whole soybean products during fluidised bed drying or drying–toasting carried out after moistening, soaking or cooking.

Sample	W (dec., d.b.)	V ($\times 10^7$ m^3)	D_e ($\times 10^3$ m)
Moistened and dried at 60 °C (MD)	0.213	1.475	6.556
	0.186	1.507	6.603
	0.181	1.510	6.608
	0.165	1.502	6.597
	0.142	1.410	6.450
	0.119	1.440	6.510
	0.109	1.430	6.480
Soaked and dried at 60 °C (SD)	1.450	3.079	8.380
	1.065	2.786	8.103
	0.880	2.579	7.898
	0.862	2.558	7.875
	0.824	2.507	7.823
	0.516	2.610	7.929
	0.388	2.608	7.927
	0.241	2.570	7.888
	0.182	2.536	7.853
Soaked and dried–toasted at 140 °C (SDT)	1.450	3.079	8.380
	0.867	2.619	7.939
	0.613	2.199	7.489
	0.304	2.049	7.314
	0.115	2.108	7.384
	0.061	2.013	7.271
	0.043	1.967	7.216
	0.034	2.198	7.488
Soaked–cooked and dried–toasted at 140 °C (SCDT)	1.494	2.896	8.288
	0.832	2.385	7.315
	0.792	2.192	7.423
	0.711	1.906	7.140
	0.273	1.895	7.127
	0.102	1.781	6.982
	0.056	1.749	6.906
	0.026	1.630	6.778

140 °C by fluidisation (SDT), the volume shrank by some 30% as a consequence of an almost total moisture reduction, 97.6% (from 1.45 to 0.034 dec., d.b.). This led to an even higher ratio of 0.307. Finally, the sample treated by soaking and cooking, experienced a volume shrinkage of 43.7% during fluidised-bed drying toasting, causing a moisture content reduction of 98.2%, and the highest shrinkage ratio, 0.445 (Sample SCDT).

Table 3
Fitting of the soybean volume model as a function of moisture content (Eq. (11)) during fluidised-bed treatment for determining an average shrinkage coefficient *a*. Standard error of parameter fitting is given in parenthesis.

Treatment	Shrinkage coefficient *a*	r^2
Moistening and drying at 60 °C (MD)	0.248 (0.152)	0.999
Soaking and drying at 60 °C (SD)	0.389 (0.048)	0.997
Soaking and drying–toasting at 140 °C (SDT)	0.567 (0.031)	0.997
Soaking, cooking and drying–toasting at 140 °C (SCDT)	0.745 (0.050)	0.994

Therefore, the shrinkage ratio during fluidised-bed treatment increased for higher initial moisture content and increasing treatment temperature. It is considered here that the shrinkage ratio, an experimental indicator, was higher for processing conditions that promoted product softening.

Concerning the shape of whole soybeans, samples were observed to swell and deform during soaking or cooking to a typical beany shape. These samples then shrank during drying or drying–toasting, to a more radial but now irregular geometry owing to the combination of moisture gradients, high temperature, seedcoat cracking and, in drying–toasting, partial seedcoat loss. Conversely the sample that was merely moistened and then fluidised at 60 °C in the postharvest range from 0.21 to 0.103 dec., d.b. retained the rounded shape almost unaltered. Changes in food structure during dehydration were investigated by Aguilera et al. (2003) and Lewicki (2006).

Shrinkage was represented here by relationships of $V/V_{0,}$ as a function of W instead of W/W_0 (Ratti, 1994). Recent contribution in glass transition theory have demonstrated that structural parameters present better correlation with moisture content.

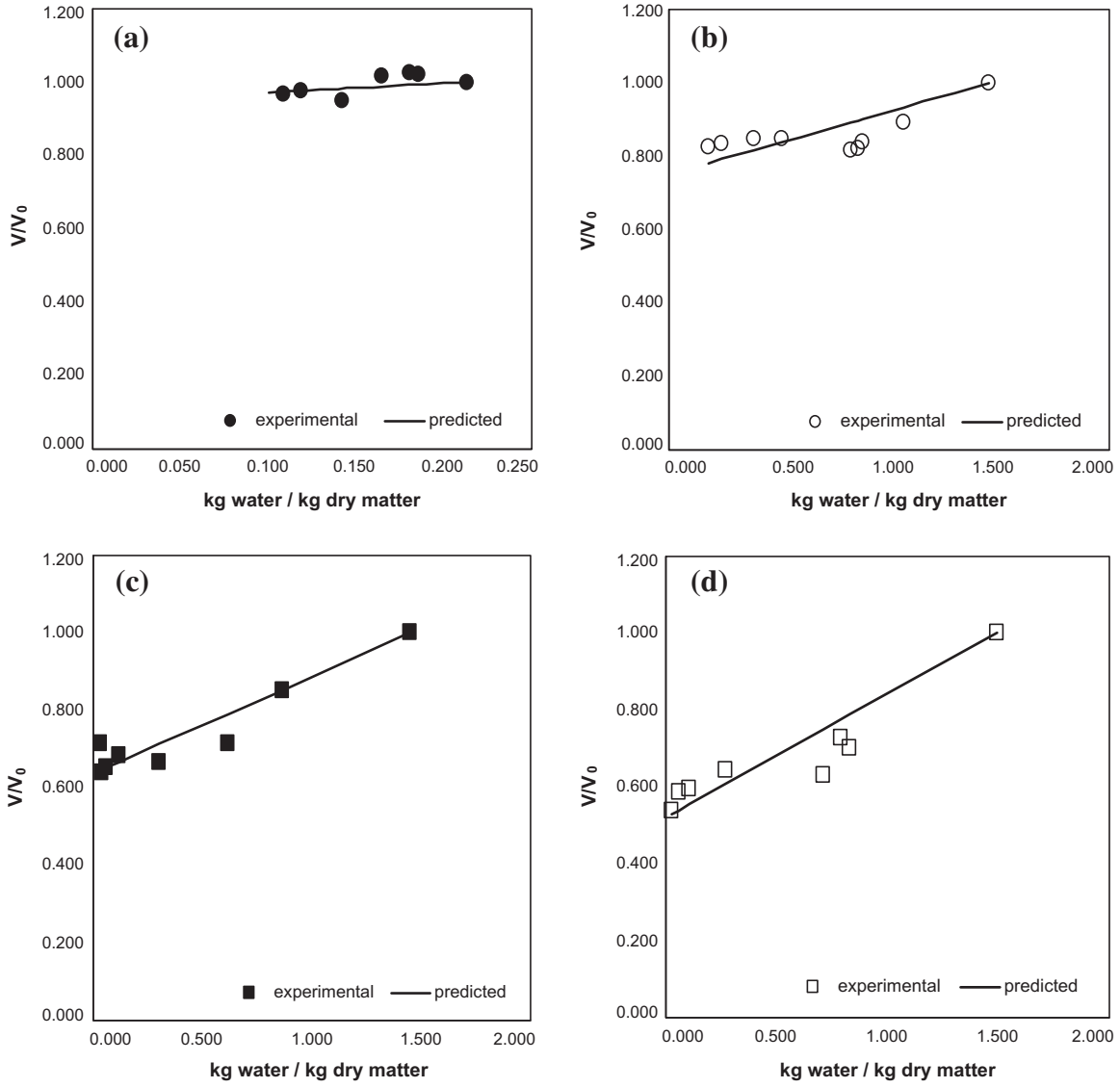

Fig. 2. Whole soybean grain volume (normalised with the initial value) as a function of moisture content during fluidisation. Values predicted by Eq. (11) (solid line) and experimental data (symbols) are plotted for the following treatments (a) moistening and drying at 60 °C, (b) soaking and drying at 60 °C, (c) soaking and drying–toasting at 140 °C, and (d) soaking, cooking and drying–toasting at 140 °C.

4.3. Determination of the equilibrium shrinkage factor a during fluidised-bed treatments

Table 3 shows the results of one-parameter fitting of the volume model (Eq. (11)) to the experimental data of V/V_0 as a function of W. The equilibrium shrinkage coefficient a was determined for each treatment by the least squares procedure. This model provides an accurate prediction for the moistening–drying (MD) treatment (Fig. 2a) where the shrinkage factor was 0.248 (Table 3). This means that the particle shrinks 0.25 mm^3 per each mm^3 of water removed. Concerning the soaked and dried sample (SD) (Fig. 2b) its shrinkage coefficient was 0.389, higher than in MD possibly due to the softer structure of soaked grains. Treatment SDT (Fig. 2c) provides a shrinkage coefficient of 0.567, which denotes a more substantial collapse due to the higher fluidisation temperature. With regard to the SCDT process (Fig. 2d), the average shrinkage factor was 0.745. This may have been caused by the combined softening action of previous cooking and high temperature drying/toasting. Therefore, the quantitative determination of an equilibrium shrinkage factor as a fraction of full collapse during fluidised-bed treatments is congruent with the calculation of the experimental shrinkage ratios in the preceding Section 4.2. Roos (1995a,b) and Aguilera (2003), who studied products under the microscope, have suggested that many foods undergo some structural modifications when dried to low moisture contents.

4.4. Prediction of particle densities as a function of moisture content

In Fig. 3, experimental whole soybean densities were plotted as a function of moisture content, together with model-predicted values (Eq. (12)). This expression utilises the experimental initial density and the equilibrium shrinkage coefficients of Table 3. Density values decrease with the reduction of moisture content in all fluidised-bed treatments, in agreement with previous research by Kashaninejad et al. (2008), who studied four raw soybean varieties in the postharvest moisture range (0.087–0.316 kg water/kg dry matter). Other authors have also found similar behaviours in millet seeds (Baryeh, 2002), quinoa seeds (Vilche et al., 2003), and cocoa

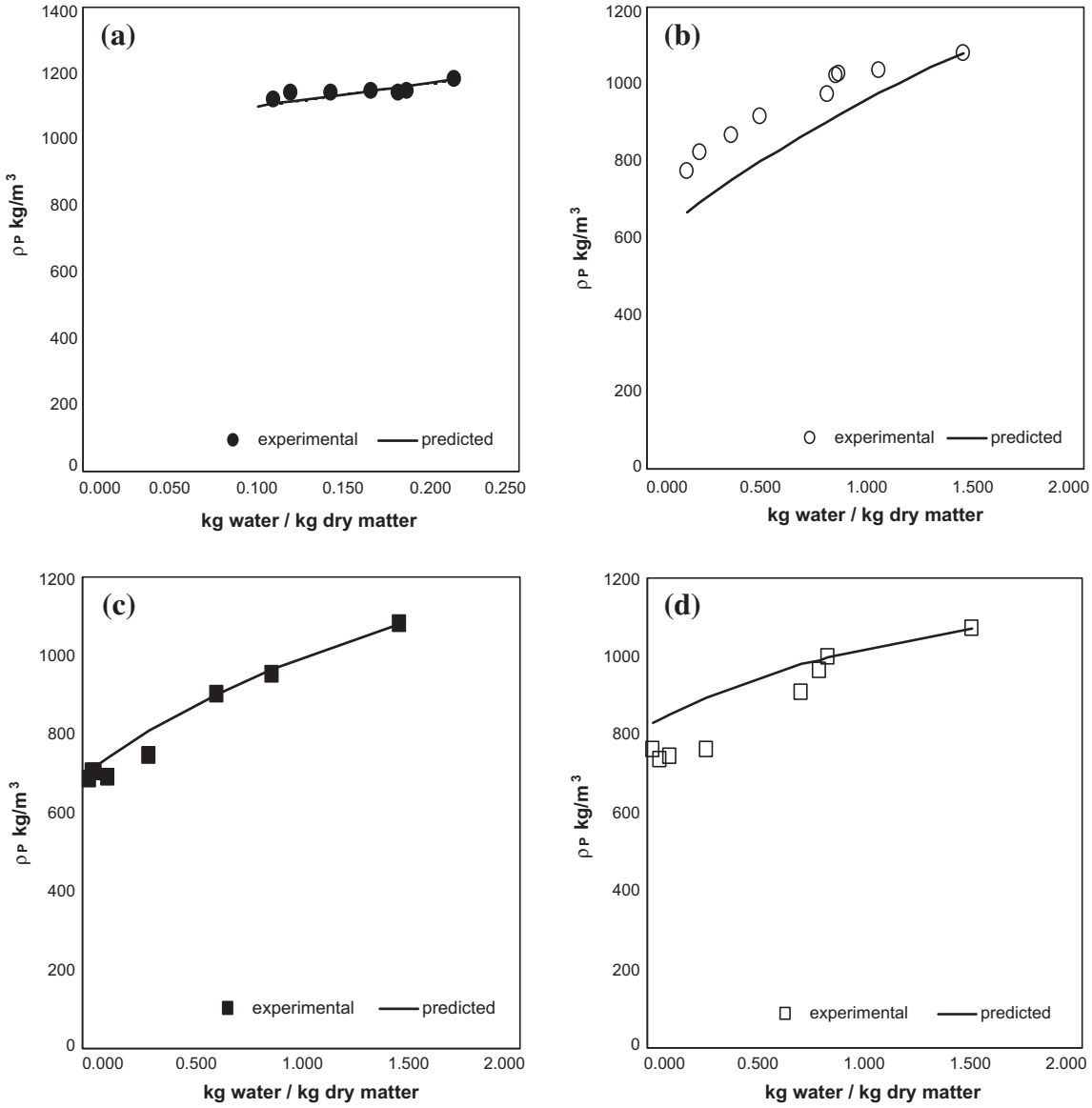

Fig. 3. Whole soybean grain density as a function of moisture content. Values predicted by Eq. (12) (solid line) and experimental data (symbols) for the following treatments (a) moistening and drying at 60 °C, (b) soaking and drying at 60 °C, (c) soaking and drying–toasting at 140 °C, and (d) soaking, cooking and drying–toasting at 140 °C.

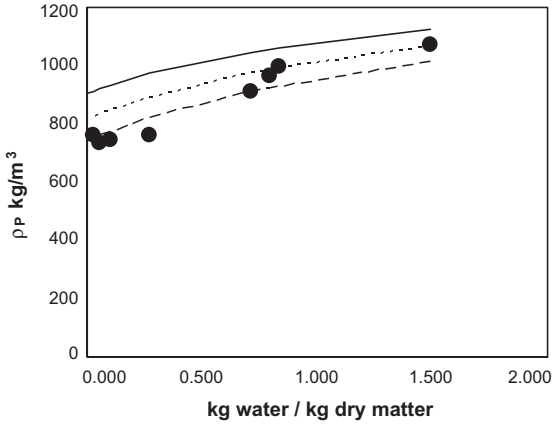

Fig. 4. Density of soaked–cooked whole soybean, as a function of moisture content during fluidisation drying–toasting at 140 °C. Values calculated by Eq. (12) using the following initial densities (ρ_0) (1016.2: - - - - -; 1066.7: · · · · ·; 1123.1: —— kg/m^3). Experimental (pycnometric) values (●) are also included. Calculated values showed a substantial sensitivity to changes in ρ_0, even within the experimental error.

beans (Bart-Plange and Baryeh, 2003). They described the density as a function of moisture with empirical linear models.

Concerning the statistical analysis, the Tukey's test indicated that curves of soybean volume and density for decreasing moisture contents during fluidisation were significantly different ($p < 0.05$).

Predictions of Eq. (12) are accurate for moistened–dried (MD) and soaked–dried–toasted (SDT). However, in soaked–dried grains (SD) calculated densities were lower than the experimental values, while, in soaked–cooked–dried–toasted samples (SCDT), an opposite situation is found, with predictions being higher than measured data. As the general predictive quality was fair but somewhat irregular, a sensitivity study was carried out by varying the initial density (ρ_0) in Eq. (12) for the SCDT sample. Three values were tested: ρ_0, the experimental value, 1.05 ρ_0 and 0.95 ρ_0, i.e., this variation in ρ_0 (±5%) may well be within the experimental error and is amplified to ±10% in the density predicted at $W = 0$. The results were plotted in Fig. 4. Given this strong sensitivity, a semi-empirical version of Eqs. (11) and (12) was considered more suitable. The modification consisted of replacing the product [a ρ_0] by one fitting parameter, K_v. Thus, Eq. (11) transforms into Eq. (16):

$$\frac{V}{V_0} = 1 - K_v \frac{(W_0 - W)}{\rho_w (1 + W_0)} \tag{16}$$

Results of the fitting are listed in Table 4. Although predictions of Eq. (16) are equally satisfactory to those of Eq. (11), it provides the fitting coefficient K_v that is required in the modified density model to be inserted instead of [a ρ_0]

$$\rho = K_\rho \frac{(1 + W)}{\left[1 + W_0 - K_v \frac{(W_0 - W)}{\rho_w}\right]} \tag{17}$$

In turn, Eq. (17) was fitted to the experimental density- moisture content data, using K_ρ as fitting parameter, replacing ρ_0. Results of the least squares procedure are listed in Table 5.

Predictions of Eq. (17) were plotted as a function of moisture content during fluidised-bed treatment in Fig. 5, for the four treatments carried out (MD, SD, SDT and SCDT). The predictive quality of the modified density model was more stable and allowed improved predictions compared with Eq. (12).

Table 4
Alternative fitting of the soybean volume model as a function of moisture content (Eq. (16)) during fluidised-bed treatment to determine a semi-empirical parameter K_v, related to the product of the shrinkage coefficient and the initial product density.

Treatment	K_v	r^2
Moistening and drying at 60 °C (MD)	292.92 (179.34)	0.999
Soaking and drying at 60 °C (SD)	421.39 (51.77)	0.997
Soaking and drying–toasting at 140 °C (SDT)	614.13 (33.64)	0.997
Soaking, cooking and drying–toasting at140 °C (SCDT)	797.18 (53.09)	0.992

Table 5
Fitting of the soybean density model as a function of moisture content (Eq. (17)) during fluidised-bed treatment to determine a semi-empirical parameter K_ρ, related to the initial product density. In this procedure, values of parameter K_v (already listed in Table 4) were used as data.

Treatment	K_ρ	r^2
Moistening and drying at 60 °C (MD)	1183.31 (6.21)	1.000
Soaking and drying at 60 °C (SD)	1180.87 (21.21)	0.997
Soaking and drying–toasting at 140 °C (SDT)	1055.37 (11.22)	0.997
Soaking, cooking and drying–toasting at140 °C (SCDT)	999.70 (22.73)	0.996

4.5. Glass transition implications for the soaked, cooked and fluidised-bed dried–toasted sample

Soybeans are complex systems and their general behaviour is governed by the phase transition of polymers as carbohydrates and proteins which are affected by the water content. Water acts as a plasticiser, lowering the glass transition temperature (T_g) of the matrix that includes it (Bhandari and Howes, 1999). In view of the decrease of density with moisture content, the most relevant structural change during the fluidised-bed treatment are the creation of pores that were absent in the raw material, leading to an easier-to-eat, crispy product. Preliminary calculations (data not shown) of T_g suggest that SCDT soybeans would be glassy after cooling Table 6.

An apparent shrinkage coefficient a_a was estimated by the relationship $K_v \approx K_\rho\, a_a$, which arises on modifying Eq. (11) into Eq. (16) and Eq. (12) into Eq. (17). As values of a_a (Table 6) agree with those of a listed in Table 4, the semiempirical, modified models (Eqs. (16) and (17)) retain its physical meaning.

5. Conclusions

A three stage procedure of soaking, cooking and fluidised-bed drying/toasting at 140 °C (SCDT) was evaluated to develop a ready-to-eat soybean snack, along with a similar, two-stage method in which no cooking was attempted (SDT). Another two processing routes were studied to comparatively assess the variation of whole soybean volume and density as a function of moisture during fluidisation: soaking–drying at 60 °C (SD), and moistening followed by fluidised-bed drying at 60 °C (MD).

Models of grain volume and density as a function of moisture content, based in physically-founded concepts were deduced to interpret soybean expansion during soaking, and shrinkage during fluidised-bed drying or drying–toasting. Swelling or shrinkage coefficients were determined by fitting the volume models to experimental data. The swelling coefficient was 0.912 indicating that the grain expanded almost the same volume as that of absorbed water.

The shrinkage coefficients were 0.248 (MD), 0.389 (SD), 0.567 (SDT) and 0.745 (SCDT). As the overall treatment was more severe (SCDT > SDT > SD > MD) the shrinkage coefficients were higher,

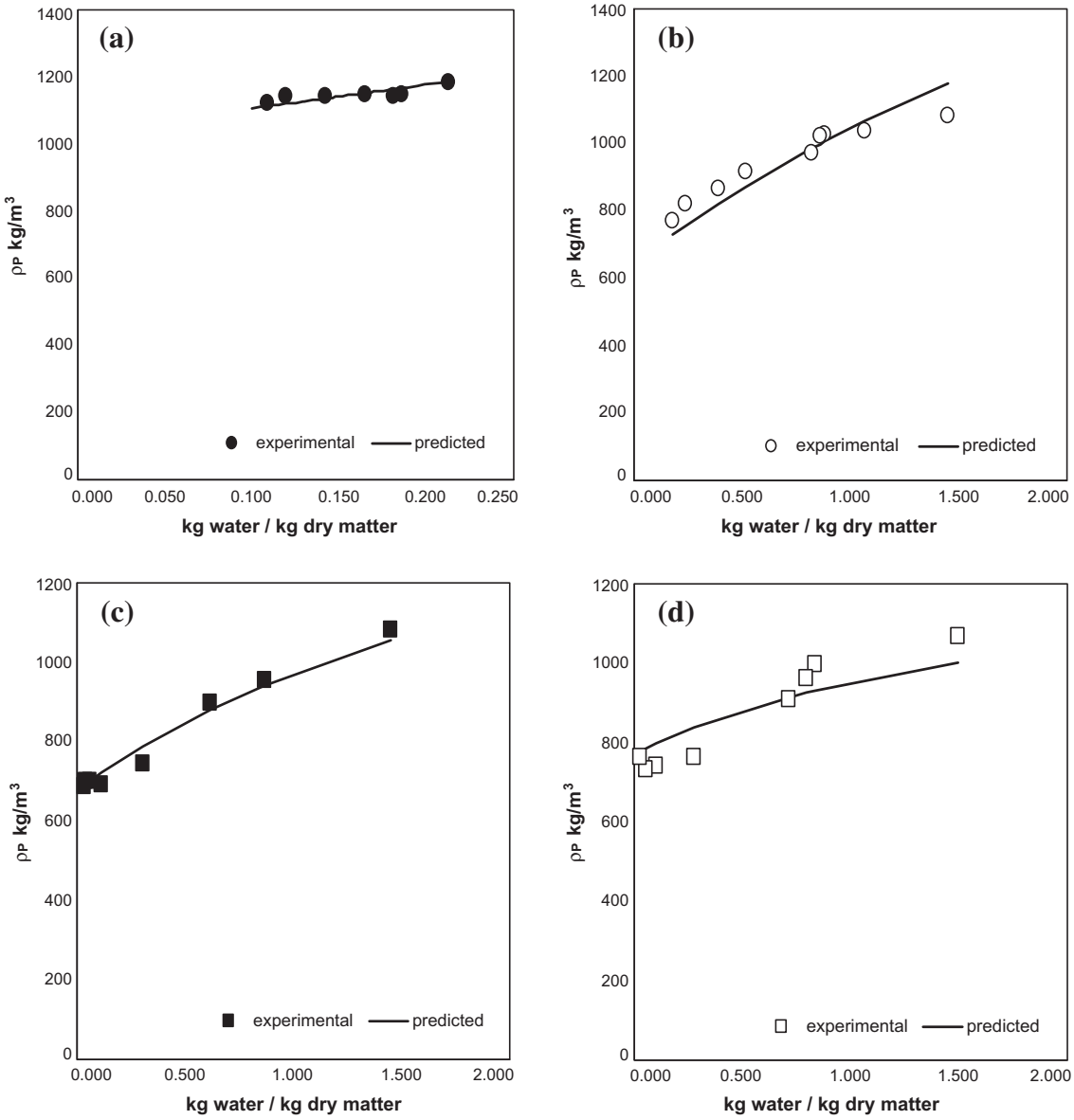

Fig. 5. Whole soybean grain density as a function of moisture content. Values predicted by Eq. (17) (solid line) and experimental data (symbols) for the following treatments (a) moistening and drying at 60 °C, (b) soaking and drying at 60 °C, (c) soaking and drying–toasting at 140 °C, and (d) soaking, cooking and drying–toasting at 140 °C.

Table 6
An apparent shrinkage coefficient a_a was estimated by the relationship $K_v \approx K_\rho\ a_a$, which arises on modifying Eq. (11) into Eq. (16) and (12) into Eq. (17). As values of a_a (Table 6) agree with those of a listed in Table 3, the semiempirical, modified models (Eq. (16) and (17)) retain its physical meaning.

Treatment	Apparent shrinkage coefficient a_a
Moistening and drying at 60 °C (MD)	0.247
Soaking and drying at 60 °C (SD)	0.357
Soaking and drying–toasting at 140 °C (SDT)	0.582
Soaking, cooking and drying–toasting at140 °C (SCDT)	0.797

possibly because the tissue structure was softer (more rubbery), experiencing a higher degree of collapse during dehydration.

As coefficients were higher for swelling than for shrinkage, volume of grains after fluidisation did never recover the volume it had before soaking. This favours the preparation of lighter products.

To improve prediction accuracy, the model of soybean density as a function of moisture during water removal may require the definition of new parameters closely related to soybean density of soaked, cooked or moistened soybean, and to the equilibrium shrinkage coefficient.

Preliminary calculations have suggested that SCDT soybean would be glassy after cooling.

Future research is planned to study the possible relationships between the glass transition temperature of product with textural and structural characteristics, and with nutritional retention.

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