Physical characterization and fluidization design parameters of wheat germ

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ABSTRACT

Wheat germ is the embryo of de wheat seed, it contains a high tocopherol and protein content, and high quality proteins and fatty acids. Also, wheat germ has a considerable enzymatic activity that limits its shelf life. The aims of the study were to physically and sorptionally characterize wheat germ particles, select the more convenient model to describe the relationship between moisture content and water activity of wheat germ and to determine their design parameters of thermal fluidization process with air. The principal axes of the particle were measured by image analysis, and their dimensions and geometric parameters were calculated. Four isotherm models were fitted to experimental data. GAB model was the more accurate to explain the experimental data. The fixed bed density and the void fraction were measured. The fluid-dynamic studies permitted to determine laminar (277.46 ± 17.48) and turbulent (7.79 ± 0.69) coefficients of the Ergun equation and the minimum fluidization velocity (0.35 ± 0.02 m/s).

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1. Introduction

Wheat production is an important economic crop in Argentina, of which 14 million tons are produced per year being 5.8 million tons of this wheat ground to obtain wheat flour in 2016 (FAIM, 2017). This industry activity produces a big quantity of wheat germ as a milling by-product. Wheat germ is the embryo of de wheat seed, representing about 2–3 g/100 g of the whole grain weight. The germ contains between 8 and 14 g/100 g of oil. (Capitani et al., 2011). Wheat germ contain high quality proteins and fatty acids, a high tocopherol content, vitamins B, dietary fiber, essential amino acids, and functional phytochemicals such as flavonoids and sterols (Marti et al., 2014). Furthermore, the large quantities of wheat flour produced by Argentinian wheat milling industry every year result into an abundant and low cost by-product with an excellent nutritional quality.

Despite of these remarkable nutritional features, wheat germ has a considerable activity due to lipoxygenase and lipase enzymes (Shurpalekar and Rao, 1977). These enzymes deteriorate wheat germ oil quality generating acidity and volatile compounds, which limit wheat germ shelf life to a few days (Sjövall et al., 2000).

Therefore, a process to stabilize the wheat germ has to be devised. Different techniques can be found: application of heat (thermal processes) (Ferrara et al., 1991; Gili et al., 2017), irradiation (Jha et al., 2013), dehydration processes (Rothe, 1963) or else by chemical preservation, as, for instance by adding some chemical compound as antioxidant (Barnes, 1948) or alkalis (Grandel, 1959). Thermal processes have demonstrated to be effective to stabilize wheat germ, one of these, fluidization, provides an intense heat and mass transfer between material and the hot air, which imply a uniform treatment to the bed being fluidized. (Giner and Calvelo, 1987).

The physical characteristics of wheat germ flakes (low density and non-sticky surface) make it in a suitable material to be stabilized by fluidization.

Yöndem-Makasc ıoglu et al. (2005) used a spouted bed (a special type of fluidized bed) to stabilize wheat germ. These authors found that a thermal treatment can increase the shelf life of raw wheat germ by a factor of 20 and golden color and pleasant nutty flavor can be imparted by light roasting. However, no mathematical modeling for fluid bed drying of germ was proposed in the

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Notation

A_p	Surface area of particle, m^2
a_w	Water activity
C, K, N	Coefficients specific to individual equations (Eqs. (3) and (4))
D	Diameter of fluidization chamber, m
D_p	Effective diameter of particle, m
D_e	Equivalent diameter of particle, m
f_c	Coulson factor for wall effect, dimensionless
g	Average acceleration of gravity, m s^{-2}
K_1	Laminar coefficient in Ergun equation
K_2	Turbulent coefficient in Ergun equation
L_{mf}	Height of fluidized bed at the minimum fluidization velocity, m
L_0	Fixed bed height, m
l_1	Longest axis of wheat germ particle, mm
l_2	Intermediate axis of wheat germ particle, mm
l_3	Shortest axis of wheat germ particle, mm
l_m	Average of l_2 and l_3, mm
M_a	Molar mass of air, kg kmol^{-1}
p	Atmospheric pressure at sea level, 1.01325×10^5 Pa
R	Gas constant, 8314 J kmol^{-1} K^{-1}
s	Standard error of the estimate
T_c	Temperature, °C
T_k	Temperature, K
V_0	Air superficial velocity, m s^{-1}
V_{mf}	Minimum fluidization velocity, m s^{-1}
V_f	Operating fluidization velocity, m s^{-1}
V_p	Particle volume, m^3
W	Wheat germ moisture content, kg water/kg dry matter
W_m	Monolayer moisture content, dry basis

Greek symbols

π	Ratio of a circle's circumference to its diameter (3.14159265 …)
Δp	Static pressure drop across the bed, Pa
ε_0	Fixed void fraction, dimensionless
ε_{mf}	Bed void fraction at minimum the fluidization velocity, dimensionless
ρ_p	Particle density, kg m^{-3}
ρ_{B0}	Fixed bed density, kg m^{-3}
ρ_a	Air density, kg m^{-3}
μ_a	Air viscosity, kg m^{-1} s^{-1}
ψ	Sphericity factor, dimensionless

Acronyms

GAB	Guggenheim, Anderson and de Boer
BET	Brunauer, Emmett and Teller
FAIM	Federación Argentina de la Industria Molinera
H-T	Henderson-Thompson

literature. A proper model and optimization of the fluidization drying process requires a knowledge of physical characteristics of particles and the fluidization design parameters. Another important tool to model this process and predict the storage conditions are the moisture sorption isotherms at different temperatures. The moisture sorption isotherm of food relates its moisture content (in either desorption or adsorption) to the water activity (a_w) at a definite temperature and it experimentally measured under equilibrium conditions. Several models have been used by researchers to describe the moisture isotherms of food and agricultural materials, as the Brunauer, Emmett and Teller (BET), Guggenheim−Anderson−de Boer (GAB). The latter, has become a widely used expression in food and grain technology, representing an evolution of the classical BET theory of multi-layer adsorption, so physical foundations are clear. The Modified Oswin model and the Modified Henderson or Henderson-Thompson model, are frequently employed to model sorption experimental data (Aviara et al., 2006).

Therefore, the objectives of this work were characterize physically and sorptionally wheat germ particles, select the more convenient model to describe the relationship between moisture content and water activity of wheat germ and to determine their design parameters of thermal fluidization process with air.

2. Materials and methods

2.1. Material

Wheat germ was supplied by local milling industry (JOSE MINETTI Y CIA. LTDA. S.A.C.I, Córdoba, Argentina) after grain milling (2014 harvest).

2.2. Preliminary operations

Wheat germ was sieved (EJR 2000, Zonytest®) to separate the wheat germ from bran and flour particles, the retention percentage of wheat germ was 93.3 ± 0.3 (g/100 g of wheat germ). The wheat germ particles retained on 20 mesh-size (0.841 mm). In order to reduce enzymatic activity and oil degradation until the heat treatment, the samples were stored at −18 °C in a three-layer (polyester, aluminum and polyethylene) package with barriers against oxygen and light until further use (no more than 30 days). Some structural and fluidization properties were analyzed in order to evaluate the possible effect of wheat germ freezing on the laboratory results. No significant changes were found on the major axes of wheat germ particles (measured as described in section 2.5) neither structural changes were detected from the images before and after freezing. Also, no changes in the fluidization pattern and velocity were observed as consequence of the storage of germ at −18 °C. Therefore, no significant effect of the frozen storage methodological approach was detected on wheat germ physical properties.

2.3. Moisture content

Moisture content was determined according to standard method of American Oil Chemistry Society (2009).

2.4. Sorption and desorption curves

The desorption and adsorption equilibrium moisture contents of wheat germ was determined by gravimetric method using a Dynamic Vapour Sorption instrument, model advantage 1 (Surface Measurement Systems Ltd, London, UK) at 24.7 °C and 33.7 °C. Briefly, the humidity inside the temperature-controlled chamber was regulated varying the flow of a dry gas (nitrogen) through a

humidification stage. The mass changes were measured with a microbalance housed inside of temperature-controlled chamber. Four theoretical models were fitted to the experimental data:

1) Guggenheim, Anderson and de Boer (GAB) isotherm equation based on the theory of multi-layer adsorption, has been widely used to describe the sorption behavior of different foods (Giner and Gely, 2005), (Eq. (1)).

$$W = \frac{W_m \, C \, K_G \, a_w}{(1 - K_G \, a_w)(1 - K_G \, a_w + C \, K_G \, a_w)} \qquad (1)$$

2) Brunauer, Emmett and Teller (BET) model, it describes the adsorption phenomena at monolayer level. (Aviara et al., 2004), (Eq. (2)).

$$W = \frac{W_m \, C \, a_w}{(1 - a_w)(1 - a_w + C \, a_w)} \qquad (2)$$

3) Henderson-Thompson, adopted as one of the standard models the American Society of Agricultural Engineers (ASAE) for the description of the equilibrium moisture content−water activity data of cereals (Eq. (3)).

$$W = 0.01 \left(-\frac{\ln(1 - a_w)}{K\,(T + C)} \right)^{\frac{1}{N}} \qquad (3)$$

4) Modified Oswin, this model includes the temperature dependence and is relatively simple. (Giner and Gely, 2005) Eq. (4).

$$W = 0.01 \frac{K + C\,T}{\left(\frac{1}{a_w} - 1 \right)^{\frac{1}{N}}} \qquad (4)$$

2.5. Geometric characterization by image analysis

The major axes of wheat germ particles were measured by image analysis. The pictures were taken with a Canon Power Shot S70 digital camera mounted on Leica S8 APO magnifying glass using a resolution of 7.1 mega pixels. Two photographs from each wheat germ particle (50 particles) were taken, one with flakes being observed in plan view and another in side view. Each photograph included a circumference with known diameter as reference (0.0006 m). The obtained images were processed using the software ImageJ 1.48v (available as freeware from http://rsb.info.nih.gov/ij/).

An ellipsoidal geometry was chosen for wheat germ particles. To calculate the particle surface area (A_p) and the particle volume (V_p), the three major axes were used as data to the following formula (Gastón et al., 2002):

$$A_p = \frac{\pi}{2} l_1 l_m \left[\frac{l_m}{l_1} + \frac{1}{U} \sin^{-1} U \right] \qquad (5)$$

where

$$U = \frac{\left(l_1^2 - l_m^2 \right)^{1/2}}{l_1} \qquad (6)$$

$$l_m = \frac{(l_2 + l_3)}{2} \qquad (7)$$

$$V_p = \frac{\pi}{6} \, l_1 l_2 l_3 \qquad (8)$$

The sphericity factor (ψ) was calculated by de following formula (Torrez Irigoyen and Giner, 2011):

$$\psi = \frac{\pi D_e^2}{A_p} \qquad (9)$$

where D_e is the equivalent diameter of wheat germ particle, which represents the diameter of a sphere with the same volume as the wheat germ particle.

$$D_p = \psi D_e \qquad (10)$$

The effective diameter (D_p) represents a diameter of sphere with the same surface-to-volume ratio as that of the wheat germ particle (Torrez Irigoyen and Giner, 2011). The value of D_p is relevant as characteristic particle dimension for the fluid-dynamic studies of fixed beds.

2.6. Particle classification

A widely accepted classification for powder particles is that proposed by Geldart (1973), which takes into account two of the more important features of the particles as particle density and size. As a function of these characteristics of the particle, Geldart proposed four groups: A, B, C and D. A powders, exhibit large bed expansion after minimum fluidization and before bubbling; are sometimes termed as slightly cohesive or catalyst type. B powders present bubbling at minimum fluidization velocity with a small bed expansion. C group particles are called cohesive and its powders are difficult to fluidize. D powders are large particles that can form stable spouted beds (Barbosa-Cánovas et al., 2010). Wheat germ particles were classified (taking account of its characteristics) in the Geldart's classification to know the type of fluidization that's should be expected.

2.7. Fluidized bed dryer

The equipment used (Fig. 1) was a purpose-built fluidized-bed dryer, built in the workshop of the Faculty of Engineering, National University of La Plata, Argentina (Torrez Irigoyen and Giner, 2011). It is made up of (i) a thermally insulated drying chamber, 0.10 m internal diameter and 0.30 m in height with a double glazing inspection window; (ii) hot wire anemometer to record the superficial air velocity through the bed (0−20 m/s, with an error of 0.03 m/s), (iii) a micromanometer Testo 525 (0−25 hPa, with an error of 0.2% at full scale) to measure differences in air pressure across the bed; (iv) a Novus Model N321 temperature controller; and (v) a centrifugal fan, powered with a Siemens electric motor (maximum angular speed, 2800 rev/min). Two nickel-plated copper resistance U-shaped, 8 mm in diameter each, forms the resistor bank. This resistor bank is capable to heat the air until 325 °C. The Air velocity was controlled through the fan speed, regulated by a frequency inverter WEG Model CFW-08, Brazil.

2.8. Determination of fixed bed density and void fraction

Fixed bed density was measured in the drying chamber with the wheat germ particles. One hundred grams of wheat germ was weighted (1500 g capacity OHAUS precision balance, readability,
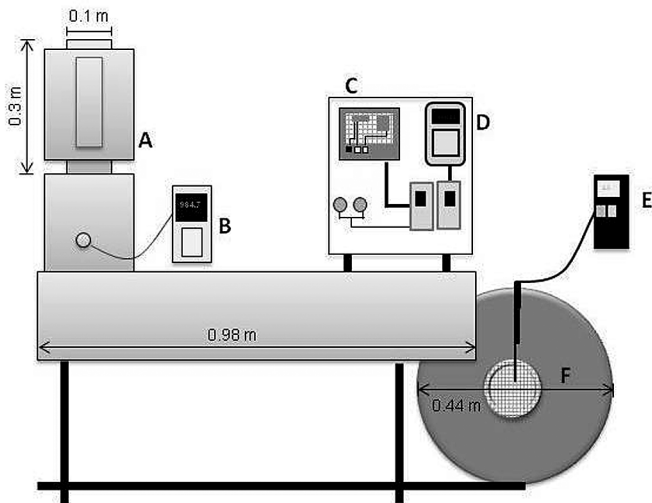
Fig. 1. (A) Thermally insulated drying chamber with double glazing for inspection. (B) Micromanometer Testo 525. (C) Temperature controller Novus Model N321. (D) Velocity controller. (E) Hot wire digital anemometer Testo 425. (F) Centrifugal fan.

0.01 g) and loaded to the drying chamber. Particles were carried to fluidized condition and then were brought to fixed bed condition again; this step was done in order to standardize bed packing.

The fixed bed height ($L_0 = 0.03\ m$) was measured (n = 3) and fixed bed density (ρ_{B0}) was calculated dividing the wheat germ mass by the bed volume, formed by the volume of particles (understood as envelope volume) plus the voids. The mass of air in the voids was neglected.

The ratio of fixed bed density to the particle density (ρ_p) provides the fraction of the bed occupied by wheat germ particles. Consequently, the fixed bed void fraction (ε_0) was calculated by the following formula:

$$\varepsilon_0 = 1 - \frac{\rho_{B0}}{\rho_p} \tag{11}$$

2.9. Study of the fluid dynamics in fixed and fluidized bed conditions

The minimum fluidization velocity (V_{mf}) of wheat germ particles was determined as a parameter based on experimental data. To this end, the pressure drop through the bed, as a function of superficial air velocity, in a range of comprising the fixed bed zone, transition zone between fixed and fluidized states, and the fluidized bed region was measured at 25 °C a with the instrument mentioned in Section 2.6.

Fixed bed data were used to determine the two-parameter (K_1 and K_2) of Ergun (1952) expression (Eq. (13)). Then, the V_{mf} value was determined by a mathematical procedure (Torrez Irigoyen and Giner, 2011) from fluidized and fixed states, as is described in the following section.

2.10. Determination of parameters of the Ergun equation

The behavior of wheat germ particles into the fluidization chamber was analyzed by the measurement of air pressure drop and of superficial air velocity. The air pressure drops per unit bed height ($\Delta p/L_0\ (1-\varepsilon_0)$) were plotted as a function of superficial air velocity (V_0).

The Coulson factor (f_c) was used to correct the V_0 (multiplying it

by f_c) in the fixed region. This factor takes into account possible wall effects caused by loose bed packing near the chamber walls (Coulson et al., 1991).

$$f_c = \cfrac{1}{\left[1 + \cfrac{\left(\frac{4}{D}\right)}{2\left(\frac{6}{D_e}\right)}\right]^2} \tag{12}$$

For wheat germ particles f_c was 0.993 in consequence, the wall effects for this system was considered low.

For the fixed bed zone, an Ergun type equation (Ergun, 1952) was fitted to the experimental data:

$$\frac{\Delta p}{L_0(1-\varepsilon_0)} = K_1\frac{(1-\varepsilon_0)\mu_0}{D_p^2\varepsilon_0^3}V_0 + K_2\frac{\rho_a}{D_p\varepsilon_0^3}V_0^2 \tag{13}$$

The laminar and turbulent coefficients, K_1 and K_2, were determined for small inorganic particles by Ergun (1952) as 150 and 1.75, respectively. Delele et al. (2008) suggest that these values depend on product characteristics, particularly in large particles, and must be determined from experimental data fitting the Ergun type equation.

The adequate selection of fixed bed data was carried out in accordance with Torrez Irigoyen and Giner (2011). The Eq. (13) was divided in both members by V_0 in order to express it as a straight line.

$$\frac{\Delta p}{L_0(1-\varepsilon_0)V_0} = K_1\frac{(1-\varepsilon_0)\mu_0}{D_p^2\varepsilon_0^3} + K_2\frac{\rho_a}{D_p\varepsilon_0^3}V_0 \tag{14}$$

Therefore, by reorganizing the experimental data as shown in Eq. (14), and graphing them as function of V_0, the fixed bed zone behavior should be represented by a linear trend. Once the fixed bed data was "isolated", according to Torrez Irigoyen and Giner (2011) the quadratic form (Eq. (13)) was used as this usually provides better fitting than linear version Eq. (14). Fitting to the data was carried out using Statgraphic Centurion XV v 15.1.02, USA. The results of the fitting were obtained by the nonlinear least squares method.

2.11. Determination of minimum fluidization velocity

When the fluid velocity generates a pressure drop through the bed which, when multiplied by the cross sectional area equal the product weight in the fluid, the minimum fluidization velocity (V_{mf}) is reached. The product weight in the fluid was obtained from the difference between product weight and the buoyancy force in the fluid (Werther, 1999). After mathematical operations, the cross sectional area was cancelled out and the mathematical formula becomes:

$$\Delta p = \left(\rho_p - \rho_a\right)g\left(1 - \varepsilon_{mf}\right)L_{mf} \tag{15}$$

By assuming constant mass from the fixed bed and fluidized bed sides of the minimum fluidization velocity point the next mathematical expression becomes true

$$\left(1 - \varepsilon_{mf}\right)L_{mf} = (1 - \varepsilon_0)L_0 \tag{16}$$

By replacing Eq. (16) into Eq. (15) it could be obtained

$$\frac{\Delta p}{L_0(1-\varepsilon_0)} = \left(\rho_p - \rho_a\right)g \tag{17}$$

Then, the left member of Eq. (17) was replaced by the right member of Eq. (13) evaluated at V_{mf}, in consideration of the fact that V_{mf} nominally belongs to both states, fixed and fluidized states.

$$K_2 \frac{\rho_a}{D_p \varepsilon_0^3} V_{mf}^2 + K_1 \frac{(1-\varepsilon_0)\mu_0}{D_p^2 \varepsilon_0^3} V_{mf} - \left(\rho_p - \rho_a\right)g = 0 \qquad (18)$$

From this formula, V_{mf} is the solution having physical meaning. To obtain this result, the approximation $\varepsilon_{mf} \approx \varepsilon_0$ was employed because the determination of ε_{mf} is cumbersome during the onset of fluidization and the procedure do not usually provide a value reliably different from ε_0. The value of ρ_p was obtained from Kim et al. (2003).

Air viscosity (μ_0) and density (ρ_a) were calculated as a function of temperature with the next equations (Formisani et al., 1998).

$$\mu_0 = 1.735 \, x \, 10^{-5} + 4.318 \, x \, 10^{-8} \, T_C \qquad (19)$$

$$\rho_a = \frac{PM_a}{RT_K} \qquad (20)$$

3. Results and discussion

3.1. Sorption and desorption curves

Moisture content of wheat germ was 0.1368 ± 0.0015 kg water/kg of dry matter. DVS analysis categorized wheat germ as a very hygroscopic class IV material according to Callahan et al. (1982). The analysis was done at 25 °C and 33.7 °C, wheat germ presented an adsorption value of 18.71% (w/w) for 24.7 °C and 18.71% (w/w) for 33.7 °C at an a_w of 0.80. As this values are higher than 15% (w/w), the European Pharmacopeia classification is matched with Callahan et al. (1982) classification.

In Fig. 2 a sigmoid-shaped isotherm can be observed (type II according to Brunauer et al., 1940), following a typical sorptional behavior of foods. The adsorption occurs on nonporous powders or on powders with pore diameters larger than micro pores. The inflection point or knee of the isotherms, as was expected, occurs near the completion of the first adsorbed monolayer and with increasing relative pressure (Lowell and Shields, 1984). This point was found at a water activity values close to 0.4.

The desorption curve was observed to be slightly above the adsorption curve showing therefore some hysteresis. This phenomenon was observed for a_w values between 0 and 0.5 at 25 °C and between 0 and 0.25 at 33.7 °C. Hysteresis has been related to the nature and state of the components in a food, reflecting their potential for structural and conformational rearrangements (Yogendrarajah et al., 2015).

As was mentioned previously, wheat germ presented a high enzymatic activity. The lipase of wheat has an optimal water activity of 0.87 according to Rose and Pike (2006). Raw wheat germ had a moisture content of 0.1368 kg water per 1 kg of dry matter, this represent a water activity slightly above 0.7. At this level of water activity, the wheat germ presented a strong activity of lipase and lipoxygenase enzymes and it is possible that, with extended storage time, some microorganisms can grow. For most foods, the critical water activity zone (where microorganisms begin to grow) is 0.6–0.7 (Durance, 2002). For these reasons is advisable to store wheat germ in a 0.4–0.5 water activity range or, using the isotherm data, at moisture contents between 5 and 8% (d.b.).

Four sorption models, named and described previously in section 2.4, were fitted to the experimental data. The fitted parameters from Eq. (1) and Eq. (2) were presented in Table 1, and the fitted parameters from Eq. (3) and Eq. (4) were listed in Table 2. In both tables, the asymptotic standard error (ASE) of parameters are included in parentheses.

Adopting the coefficient of determination r^2 as a criterion to pre-select sorption equations, BET, GAB, modified Oswin and
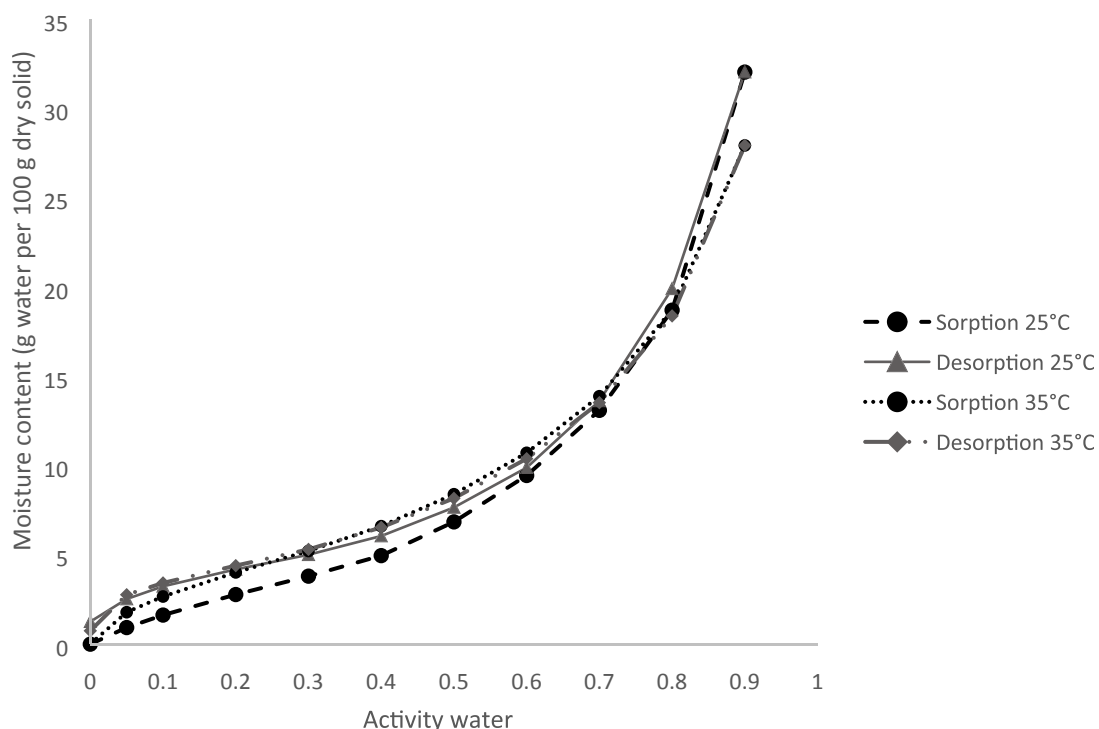

Fig. 2. Sorption and desorption curves of wheat germ particle at 25 °C and 35 °C.

Table 1
Parameters determined by fitting the GAB and BET model at the two analyzed temperatures.

	Temperature (°C)	W_m	K_G	C	r^2	s
BET	25	0.041 (0.001)	−	4.780 (0.560)	0.9963	0.0013
	35	0.046 (0.001)	−	10.068 (0.654)	0.9986	0.0009
GAB	25	0.050 (0.002)	0.945 (0.005)	3.098 (0.353)	0.9995	0.0022
	35	0.055 (0.001)	0.900 (0.005)	7.098 (0.726)	0.9994	0.0021

*BET 0.05< a_w < 0.50.

Table 2
Parameters determined by fitting the Henderson-Thompson and Oswin Modified models at the two analyzed temperatures.

	Temperature (°C)	K	C	N	r^2	s
H-T	25	0.0062 (0.0001)	0.175 (0.001)	0.785 (0.002)	0.9918	0.0087
	35	0.0117 (0.0003)	−27.745 (0.0001)	1.060 (0.001)	0.9891	0.0087
Oswin modified	25	0.035 (0.043)	0.286 (0.001)	1.454 (0.001)	0.9992	0.0027
	35	−105.15 (0.06)	3.376 (0.00001)	1.850 (0.001)	0.9989	0.0028

Henderson-Thompson (H-T) were found to be acceptable to reproduce the experimental isotherms for the wheat germ (r^2>0.9). Comparing GAB and BET monolayer value (W_m), the GAB value was approximately 22% higher than the BET at 24.7 °C and approximately 20% higher at 33.7 °C, which is in agreement with Timmermann et al. (2001) to several foods and foodstuffs.

It is important to highlight that the BET isotherm only explain the 0.01−0.50 range of a_w (Durance, 2002). This narrow range limits the applicability of this model so it was not considered appropriate to describe the adsorption phenomena in wheat germ.

Nevertheless, by analyzed the standard errors of the estimate (s), the GAB model becomes slightly more accurate with a value for s of 0.0022 decimal moisture content, d.b. at 24.7 °C and 0.0021 decimal moisture content, d.b. at 33.7 °C. This methodology of model selection was applied by Giner and Gely (2005). Henderson-Thompson and Modified Oswin, in spite of their simplicity, are acceptable for predicting the equilibrium moisture content of wheat germ, similar results for this models were published for soya bean and sunflower seeds by Aviara et al. (2004) and Giner and Gely (2005), respectively.
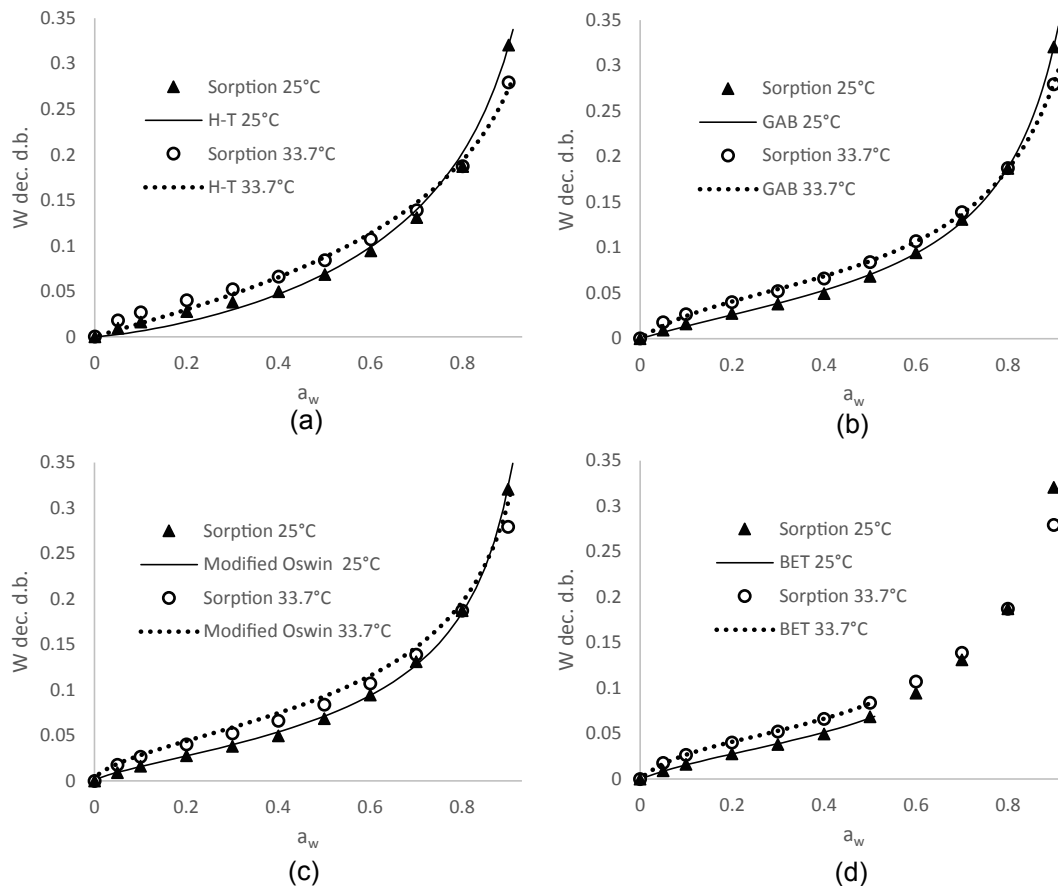
Fig. 3. Experimental moisture content of wheat germ particles (d.b.) as a function of water activity at 25 °C (▲) and 33.7 °C (○). Experimental and predicted values for each sorption model. a) Henderson-Thompson (H−T); b) GAB; c) Modified oswin and d) BET.
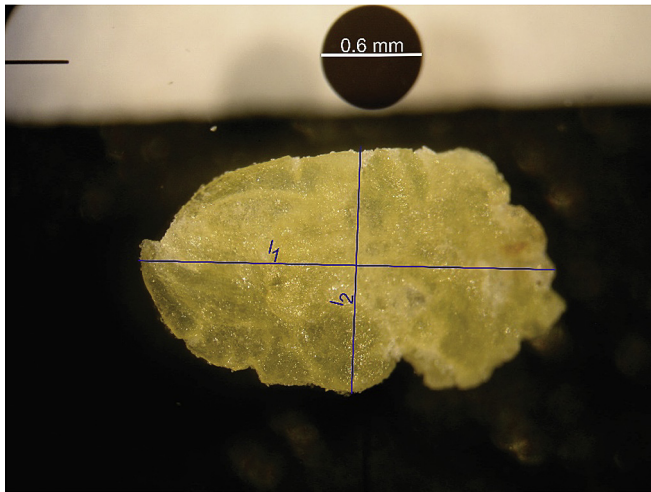
Fig. 4. Plan view of wheat germ particle with l_1 and l_2 mayor axes and circular reference point.

The behavior of fitted models is observed in Fig. 3, the equilibrium moisture content is compared at 25 °C and 33.7 °C with predictions by four isotherm models.

3.2. Geometric characterization by image analysis

A total of 50 particles of wheat germ were measured by image analysis. The three mayor axes were determined by considering the circular standard reference in the image (Fig. 4).

Table 3 shows the measures values of main axes, and the calculated values of surface area, particle volume, equivalent spherical diameter and effective diameter (Eqs. (5)–(10)).

3.3. Particle classification

According to wheat germ density (1234.23 kg/m^3) and size particle (0.623 mm) it is the limit region between group A and B, but according to the observed particle behavior during fluidization, wheat germ belongs to group B of Geldart's classification, since a bubbling at minimum fluidization velocity with a small bed expansion was observed.

3.4. Determination of Ergun parameters

The bed pressure drop per unit bed height was plotted as a function of superficial air velocity for wheat germ. At low velocities,

Table 3
Wheat germ properties determined by image analysis and calculated.

	Mean	Min	Max	Unit
l_1	2.28	1.65	3.39	mm
l_2	1.59	1.19	2.13	mm
l_3	0.29	0.17	0.41	mm
A_p	5.26	3.65	9.21	mm^2
V_p	0.49	0.24	0.97	mm^3
D_e	0.969	0.766	1.223	mm
D_p	0.623	0.366	0.849	mm
ψ	0.62	0.477	0.79	Dimensionless

n = 50.

Table 4
Fixed bed properties determined.

ρ_p	1234.23	kg/m^3
ρ_{B0}	413.83	kg/m^3
L_0	0.03	m
ε_0	0.664	Dimensionless

an increasing slope and concave shape of the curve was observed, being this behavior comparable with that reported by other authors (Torrez Irigoyen and Giner, 2011; Sau et al., 2007) which is a characteristic behavior of the fixed bed region. At higher velocities, as was expected for the fluidized region, the curve became horizontal.

The fixed bed zone was determined by arranging the experimental data as indicated by the left member of Eq. (14) as function of V_0. The fixed bed zone is characterized by a regular behavior, for this particle, this behavior pattern was presented up to 0.26 m/s after that, the observed behavior became irregular or transitional. Using this procedure, the fixed bed region was delimited in the velocity range of 0.05–0.26 m/s.

Once delimited the pure fixed bed zone, experimental data were utilized as indicated by the left member of Eq. (13) as a function of V_0 and then, the parabolic form of Ergun model (Eq. (13)) was fitted to these data using the bed void fraction and effective diameter of Table 4. The parameters obtained (K_1 and K_2) were 277.46 (17.48) and 7.79 (0.69) respectively, the corresponding ASE is between parenthesis. The corrected coefficient of determination (r^2) was 0.994.

As mentioned previously in section 2.9, K_1 and K_2 depend on particle characteristics, mainly surface roughness, size and shape (Escardino et al., 1974). The values obtained were higher than those reported by Torrez Irigoyen and Giner, (2011) for soybean grains. The value of K_1 determined here was lower than the obtained by Escardino et al. (1974) for wheat grains, while K_2 was greater than the corresponding value. This can be related to particle shape, the wheat germ particle is small and plane. These characteristics may have influenced the bed packing into the drying chamber, creating sharp changes in the direction of the air flow when percolating through the bed (Yang, 2003). Furthermore, wheat germ has a rough particle surface and this characteristic have also contributed to the large values of K_1 and K_2.

This has been in agreement with Molenda et al. (2005) who informed that the non-spherical shape of grains and random size distribution resulted in coefficients K_1 and K_2 being considerably greater than the theoretical values for spherical particles. This is in concordance with the results obtained in this work.

The predicted lines and experimental pressure drops (symbols) were plotted as a function of superficial air velocity using the parameters obtained from fitted Ergun equation (Fig. 5). The agreement of experimental and predicted values was satisfactory for the wheat germ particles.

3.5. Determination of V_{mf}

The minimum fluidization velocity was obtained from Eq. (18) using the measured particle data (D_p, ε_0). After solving the Eq. (18), the V_{mf} for wheat germ particles fluidized in air at ~25 °C was 0.35 ± 0.02 m/s. This minimum fluidization velocity, in the dryer utilized, correspond to 0.003 m^3/s approximately. This flow is very lower than the 0.011 m^3/s informed by Yöndem-Makascioğlu et al. (2005) to stabilize wheat germ in a spouted fluidized bed.
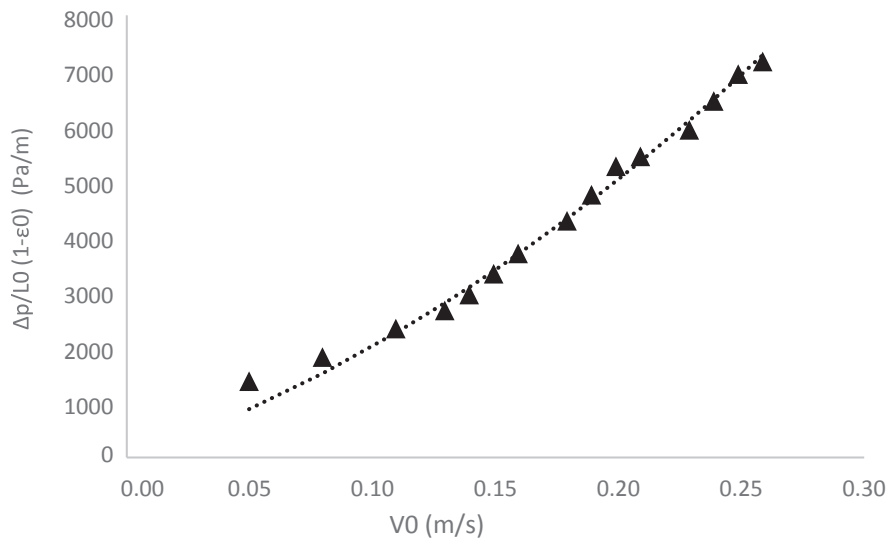
Fig. 5. Bed pressure drop per unit bed height as a function of superficial air velocity. Experimental (▲) and Ergun-predicted values (…).

4. Conclusion

In the present investigation, some geometrical properties (V_p, A_p, ψ, D_p, D_e) of wheat germ were characterized by image analysis. The wheat germ particle was classified as group B of Geldart's classification.

Four isotherm models were fitted to experimental sorption data, GAB model resulted the most accurate to explain the experimental behavior. The monolayer moisture content given by the GAB model was 0.050 ± 0.002 kg water per kg dry matter at 24.7 °C and 0.055 ± 0.002 kg water per kg dry matter at 33.7 °C. Wheat germ may be storage at a water activity of 0.4–0.5 (5–8% of moisture content) to avoid spoilage factors as enzymatic activity, lipid quality losses and microorganism growth.

The fixed bed density and the void fraction were measured. The fluid-dynamic characteristics of wheat germ in fixed bed was studied, the laminar and turbulent (K_1 and K_2) parameters of Ergun equation were fitted to the data and the minimum fluidization velocity of wheat germ determined at 25 °C to be 0.35 ± 0.02 m/s.

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