INDUSTRIAL CROPS AND PRODUCTS 28 (2008) 286–293

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/indcrop

Physical properties of chia (*Salvia hispanica* L.) seeds

Vanesa Y. Ixtaina[a,b], *Susana M. Nolasco*[a,*], *Mabel C. Tomás*[b,**]

[a] *Grupo de Investigaciones TECSE, Departamento de Ingeniería Química, Facultad de Ingeniería, UNCPBA, Av. Del Valle 5737, Olavarría, Buenos Aires B7400JWI, Argentina*

[b] *Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA), (CCT La Plata - CONICET) Facultad de Ciencias Exactas, UNLP, 47 y 116, La Plata, Buenos Aires 1900, Argentina*

ARTICLE INFO

Article history:
Received 11 February 2008
Received in revised form
14 March 2008
Accepted 23 March 2008

Keywords:
Chia seed
Physical dimensions
Coefficient of friction
Angle of repose

ABSTRACT

Physical properties of *Salvia hispanica* L. seeds were investigated and their application was also discussed. Physical properties were assessed for white and dark seed separately, except for the angle of repose and static coefficient of friction, which were determined for the seed mixture. The mean moisture content was 7.0% (dry basis). The average for the three characteristic dimensions, length, width and thickness was 2.11, 1.32 and 0.81 mm for dark seeds and 2.15, 1.40 and 0.83 mm for white seeds, respectively. The bulk density, true density and the porosity were between 0.667 and 0.722 g cm^{-3}, 0.931 and 1.075 g cm^{-3}, and 22.9 and 35.9%, respectively. The equivalent diameter ranged from 1.32 to 1.39 mm. The volume of single grain and sphericity ranged between 1.19 and 1.42 mm^3, and 62.2 and 66.0%, respectively. The geometric mean diameter ranged between 1.31 and 1.36 mm for dark and white chia seeds, respectively. This parameter could be used for the theoretical determination of seed volume and sphericity. One thousand seed mass averaged 1.323 g for dark seeds, and 1.301 g for white seed. The angle of repose varied between 16° and 18° whereas the value of static coefficient of friction was 0.28 on galvanized sheet and 0.31 on mild steel sheet.

1. Introduction

Salvia hispanica L., whose common name is chia, is an annual herbaceous plant that belongs to the *Lamiaceae* family, which is native from southern Mexico and northern Guatemala. It has been cultivated from tropical to subtropical regions. Although plants are little frost-tolerant, they can be grown in greenhouses in some parts of Europe (Huxley, 1992). Today, chia is grown commercially in Mexico, Bolivia, Argentina, Ecuador, and Guatemala. In Argentina, it is a summer-autumn crop that could be grown economically instead of non-profitable traditional crops in the north-western region (Coates and Ayerza, 1996).

Chia seeds have long been used by the Aztec tribes. They are important not only as food, but also for medicines and paints. It is traditionally consumed in Mexico and the southwestern United States, in a minor extent in South America, though is not widely known in Europe. They have been investigated and recommended due to their content of oil, protein, antioxidant and dietary fiber content (Palma et al., 1947; Earle et al., 1960; Bushway et al., 1981; Taga et al., 1984; Ayerza, 1995). The seed has about 25–38% oil by weight, and it contains the highest proportion of α-linolenic acid (~60%) compared to other natural source known to date (Palma et al., 1947; Ayerza, 1995), and also higher levels of protein (19–23%) than those of traditional cereals such as wheat (*Triticum aestivum* L.), corn

* *Corresponding author*. Tel.: +54 2284 451055; fax: +54 2284 451055.
** *Corresponding author*. Tel.: +54 221 4254853; fax: +54 221 4890741.
E-mail addresses: vanesaix@hotmail.com (V.Y. Ixtaina), snolasco@fio.unicen.edu.ar (S.M. Nolasco), mabtom@hotmail.com (M.C. Tomás).
0926-6690/$ – see front matter
doi:10.1016/j.indcrop.2008.03.009

Nomenclature

D_e	equivalent diameter of seed (mm)
D_g	geometric mean diameter of seed (mm)
L	length of seed (mm)
m	unit mass of seed (g)
R	aspect ratio (%)
S	seed surface area (mm^2)
T	thickness of seed (mm)
V	volume of one seed (mm^3)
W	width of seed (mm)
W_{1000}	thousand seed weight (g)
Greek letters	
α	angle of tilt (°)
ε	porosity (%)
θ	angle of repose (°)
μ	static coefficient of friction (dimensionless)
ρ_b	bulk density (g cm^{-3})
ρ_t	true density (g cm^{-3})
ϕ	sphericity of seed (%)

(*Zea mays* L.), rice (*Oryza sativa* L.), oats (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) (Coates and Ayerza, 1996).

The plant is day light sensitive and produces small white and dark seeds. Their shape is oval, measuring 2.0 mm × 1.5 mm (Rulfo, 1937 cited by Ayerza and Coates, 2005). Most of chia populations grown today contain a low percentage of white seeds. This type of seeds come from plants that produce only white seeds, which are encoded by a single recessive gene. Since *S. hispanica* has many uses similar to sesame (*Sesamum indicum* L.), the white seed coat may also have some modern commercial preference (Cahill and Provance, 2002). In general, there is a little size difference between these seeds, white seeds are somewhat larger than the black ones (Ayerza and Coates, 2005). Also, there are some differences in protein content and fatty acid composition between dark and white chia seeds (Ayerza, 1997; Ixtaina et al., 2006).

Chia is an important raw material to obtain functional foods due to its special characteristics, and it offers advantages over other available ω–3 sources (Coates and Ayerza, 1996).

Thus, in view of its considerable economic potential in foods and chemical industries, it is important to determine the physical properties of *S. hispanica* L. seeds. These properties are often essential to develop equipment for handling, transportation, drying, storage and other processes, such as oil extraction.

Thus, the knowledge on the morphology and size distribution of chia seeds is essential for an adequate design of the equipment for cleaning, grading and separation, moisture content for the development of the drying process, gravimetric properties for the design of equipment related to aeration, drying, storage and transport (Kachru et al., 1994). Bulk density determines the capacity of storage and transport systems while true density is useful for separation equipment; porosity of the mass of seeds determines the resistance to airflow during aeration and drying. Frictional properties, such as the angle of repose and the coefficient of external friction, are important for conveying systems, the design of grain bins and other storage structures whose operation is influenced by the compressibility and flow behaviour of materials (Kachru et al., 1994).

Research on physical and engineering properties has been reported for different types of seeds, such as soybeans (*Glycine max* L. Merr.) (Deshpande et al., 1993), cumin (*Cuminum cyminum* L.) (Singh and Goswami, 1996), sunflower (*Helianthus annuus* L.) (Gupta and Das, 1997), millet (*Pennisetum typhoides*) (Jain and Bal, 1997), locust bean (*Parkia fillicoidea* Welw.) (Olajide and Ade-Omowaye, 1999), high oleic sunflower seeds (Santalla and Mascheroni, 2003), quinoa (*Chenopodium album* L.) (Vilche et al., 2003), amaranth (*Amaranthus cruentus* L.) (Abalone et al., 2004), sesame (Tunde-Akintunde and Akintunde, 2004), rapeseed (*Brassica napus* L.) (Çahşir et al., 2005), African star apple (*Chrysophyllum albidum* G. Don.) (Oyelade et al., 2005), safflower (*Carthamus tinctorius* L.) (Baümler et al., 2006), flaxseed (*Linnum usitatissimum* L.) (Coşkuner and Karababa, 2007a), coriander (*Coriandrum sativum* L.) (Coşkuner and Karababa, 2007b), and wild sunflower (*Helianthus petiolaris* Nutt.) (Pérez et al., 2007). However, little information about chia seed is available in the literature.

The aim of this study was to determine some physical properties of *S. hispanica* L. seeds, namely: moisture content, linear dimensions, geometric mean diameter, sphericity, volume, surface area, thousand seed weight, true density, bulk density, porosity, angle of repose, static coefficient of friction against two surfaces. This knowledge is important to minimize the effect of an inadequate use of equipment that could affect the quality of the seed and its oil, and/or lead to high operation costs.

2. Materials and methods

Chia used in this study was a commercial seed from Salta (25° S and 65.5° W), Argentina. The seeds were cleaned manually and the foreign matter, such as stones, dirt and broken seeds, were removed. Seeds were packed in hermetic plastic vessels and stored at 5 °C until use. Before starting a test, the seeds were taken out of the refrigerator and allowed to warm up at room temperature.

2.1. *Moisture and oil content*

Moisture content of samples was determined according to AOAC approved vacuum oven method (AOAC, 1990). The whole seeds were ground and the oil was extracted with *n*-hexane as solvent (boiling point 68–72 °C) in a Soxhlet apparatus for 8 h, following IUPAC Standard Method 1.122 (IUPAC, 1992). A nitrogen stream removed the solvent in the extracted oils. Each oil sample was weighed to calculate the extraction yields. Reported values are means of three determinations.

2.2. *Types of seed by coat colour*

In order to determine the percentage of white and dark seeds, eight groups of 20 g each randomly selected were manually separated and weighed on an electronic balance with 0.001 g accuracy. Both types of seeds were stored separately to determine each physical parameter.

2.3. *Physical properties*

Physical properties of seeds were assessed for white and dark seeds separately, except for the angle of repose and static coefficient of friction, which were determined for the commercial pool of the seeds.

To determine size and shape of the seeds, 90 seeds of each colour were randomly selected from the seed pool. For each individual seed, three principal dimensions: length L, width W, and thickness T, all of them in mm were measured using a digital micrometer with a reading accuracy within 0.01 mm (Fig. 1). Since seed size was considered an important parameter in processing (Aviara and Haque, 2000), bulk samples were classified into three categories namely large ($L > 2.25$), medium ($2.00 < L \leq 2.25$) and small ($L \leq 2.00$) based on their length.

The bulk density (ρ_b), defined as the ratio of the mass sample of the seeds to its total volume, was determined using a modified standard test weight procedure (Singh and Goswami, 1996), by filling a 90-ml container with seeds that were poured from a height of about 150 mm at a constant rate, then the content was weighed. No separate manual compaction of seeds was done. The bulk density was calculated on the mass of the seeds and the volume of the container.

The true density (ρ_t), defined as the ratio of the mass of the sample of seeds to the solid volume occupied by the sample, was determined using an electronic balance reading to 0.0001 g and a pycnometer (50 ± 0.1 ml) (liquid displacement method) (Mohsenin, 1970). Xylene (density: $0.862 \pm 0.001\,\mathrm{g\,cm^{-3}}$) was used instead of water because it is absorbed by seeds to a lesser extent. Due to the short duration of the experiment, xylene absorption was found to be negligible and therefore seeds were not coated for its absorption prevention (Giner and Calvelo, 1987).

The porosity (ε) of the bulk seed is the fraction of the space in the bulk grain that is not occupied by the grain (Thompson and Isaacs, 1967). The percent porosity was calculated on the following relationship (Mohsenin, 1970):

$$\varepsilon = \left(\frac{\rho_t - \rho_b}{\rho_t}\right) \times 100. \qquad (1)$$

The volume of one seed (V) (mm^3) was determined according with the following relationship (Özarslan, 2002):

$$V = \left(\frac{m}{\rho_t}\right) 10^3 \qquad (2)$$

where m is the unit mass of the seed (in g) determined from the samples used to calculate the true density.

The equivalent diameter (D_e) of the sphere having the same volume of the seed and their sphericity (ϕ) were determined using the following expressions:

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

$$\phi = \left(\frac{D_e}{L}\right) \times 100. \qquad (4)$$

The three principal dimensions were used to calculate the geometric mean diameter (D_g) and surface area (S) of individual grains by assuming that the seeds were ellipsoid.

The geometric mean diameter in mm was determined by using the following expression (Mohsenin, 1970):

$$D_g = (LWT)^{1/3}. \qquad (5)$$

The surface area was determined (McCabe et al., 1986) as:

$$S = \pi D_g^2. \qquad (6)$$

To obtain more information about seed shape, aspect ratio (R) was calculated (Maduako and Faborode, 1990) as:

$$R = \frac{W}{L} \times 100 \qquad (7)$$

In order to determine the W_{1000}, eight sub-samples, each one consisting of 100 seeds, were randomly drawn from the bulk sample and weighed on an electronic balance with 0.001 g accuracy and then extrapolating this weight to 1000 seeds (Vilche et al., 2003; Tunde-Akintunde and Akintunde, 2004; Çahşir et al., 2005; Coşkuner and Karababa, 2007a).

The angle of repose (θ) was determined by using a plywood box (0.3 m of length, width and height), which had a removable front panel. The box was filled with seeds and the front panel was quickly removed, allowing the seeds to flow to their natural slope. The angle of repose was calculated from the measurements of the horizontal displacement distance of the seeds and the height of the heap (Dutta et al., 1988).

The static coefficient of friction was determined with respect to two different surfaces: galvanized sheet and mild steel sheet. These are common materials used for transportation, storage and handling operations of grains, pulses and seed construction of storage and drying bins. A hollow polyvinylchloride cylinder of 50 mm diameter and 50 mm high, open at both ends, was filled with seed samples and placed on an adjustable tilting table. The cylinder was raised about 2 mm above the base of the bulk seed so as not to touch the surface. The tilting surface was raised gradually by means of a screw device until the cylinder with seeds just started to slide down (Singh and Goswami, 1996). The angle of tilt (α) was read on a graduated scale and the coefficient of friction was calculated from the following relationship:

$$\mu = \tan \alpha. \qquad (8)$$

The angle of repose and the static coefficient of friction readings were replicated 10 times.

2.4. *Statistical analysis*

Results were analyzed for statistical significance at $p \leq 0.05$ by Student's t-test and one-way ANOVA followed by Tukey test, by using software Statgraphics Plus Version 4.0 (1999). The type of relationship between variables was determined by correlation analysis.

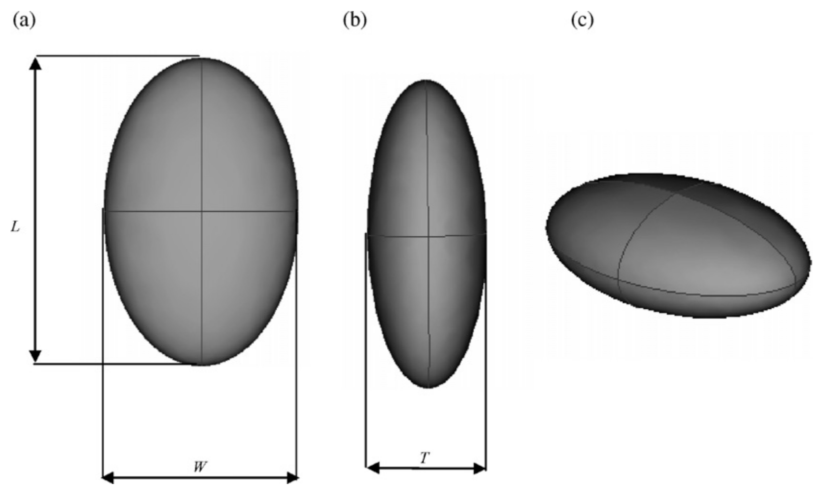

Fig. 1 – Characteristic dimensions of chia seeds: *L*, length; *W*, width; *T*, thickness (a) front view; (b) side view; (c) three-dimensional geometry.

3. Results and discussion

Dark seeds represented 91.3 ± 0.3% by mass of the samples studied. The average seed moisture was 7.0 ± 0.4% (d.b.) with 7.2 and 6.6% for dark and white seeds, respectively. The moisture content may suggest the storage stability of the seed. The oil yield was 32.7 ± 0.8% and 33.8 ± 0.7% for dark and white seeds, respectively. These values are within the same range than that reported in the literature for chia seeds (Palma et al., 1947; Ayerza, 1995).

These seeds presented three unequal semi-axes, and they may, therefore, be described as being scalene ellipsoid in shape. Table 1 shows the size distribution of the chia seed. Longitudinal dimension (L) ranged from 1.73 to 2.63 mm. The majority of chia seeds (about 59% of dark seed and 62% of white seed by number) were medium-sized ($2.00 \le L \le 2.25$ mm). The frequency distribution curves of length, width and thickness of the white and dark seeds showed a trend towards a normal distribution (Fig. 2).

The average seed width and thickness were 1.32–0.81 mm and 1.40–0.83 mm for dark and white seeds, respectively (Table 1). These measurements were in the same range than those reported by Rulfo (1937) for chia seeds. White seeds were significantly ($p \le 0.05$) broader and thicker than dark seeds (Table 2). However, no significant difference ($p > 0.05$) for the longitudinal dimension was detected between both types of seeds. The dimensions of chia seed were observed to lie within the same range to those of quinoa and rapeseed seeds (Vilche et al., 2003; Çahşir et al., 2005), higher than those of amaranth seeds (Abalone et al., 2004), and lower than those of cumin, pearl millet, sesame, safflower, flaxseed and coriander (Singh and Goswami, 1996; Jain and Bal, 1997; Tunde-Akintunde and Akintunde, 2004; Baümler et al., 2006; Coşkuner and Karababa, 2007a,b). The importance of these and other characteristic axial dimensions for determining aperture size and other parameters in machine design have been discussed by Mohsenin (1970).

The bulk density was between 0.667 and 0.722 g cm^{-3} (Table 3), though for white seeds was significantly lower ($p \le 0.05$) than the dark seeds (Table 2). The lower value of

Table 1 – Size distribution of dark and white chia seeds at the moisture content of 7.2% (d.b.) and 6.6% (d.b.), respectively (standard deviation in parentheses)

Particulars	Length (mm)	Percent of sample (by number) (%)	Length (mm)	Width (mm)	Thickness (mm)	Geometric mean diameter (mm)
Dark seeds						
Ungraded	1.76–2.42	100	2.11 (0.16)	1.32 (0.15)	0.81 (0.06)	1.31 (0.09)
Large	>2.25	17	2.33 (0.05)	1.36 (0.11)	0.84 (0.05)	1.38 (0.06)
Medium	2.00–2.25	59	2.13 (0.07)	1.35 (0.16)	0.82 (0.06)	1.33 (0.07)
Small	≤2.00	24	1.90 (0.08)	1.22 (0.13)	0.77 (0.05)	1.21 (0.07)
White seeds						
Ungraded	1.73–2.63	100	2.15 (0.16)	1.40 (0.12)	0.83 (0.06)	1.36 (0.07)
Large	>2.25	20	2.37 (0.09)	1.45 (0.11)	0.85 (0.06)	1.43 (0.06)
Medium	2.00–2.25	62	2.14 (0.07)	1.40 (0.13)	0.83 (0.06)	1.36 (0.05)
Small	≤2.00	18	1.93 (0.08)	1.34 (0.09)	0.81 (0.06)	1.27 (0.06)

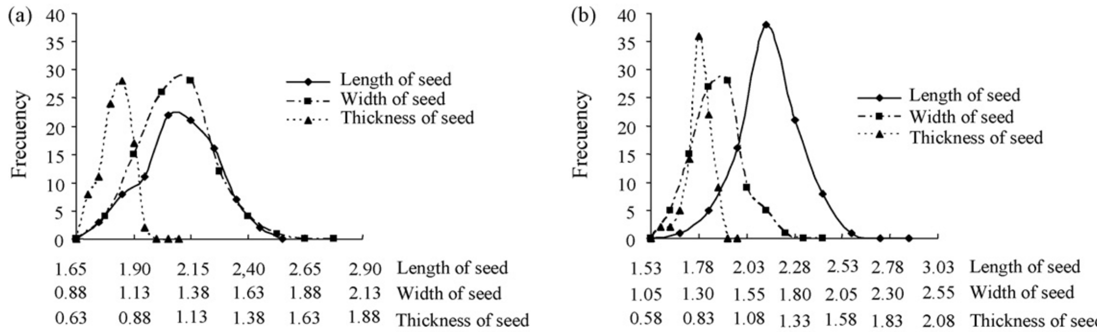

Fig. 2 – Frequency distribution curves of chia seed dimension at 7.0% average moisture content (d.b.): (a) dark seeds; (b) white seeds.

the bulk density applied to the white seed (0.667 $g\,cm^{-3}$) may be attributed to its bigger size. This parameter is important because it determines the capacity of storage and transport systems.

The true density and the porosity of chia seed were between 0.931 and 1.075 $g\,cm^{-3}$, and 22.9 and 35.9%, respectively (Table 3), with no significant differences between both types of seeds (Table 2). The true density was thus, higher than that of sunflower (Gupta and Das, 1997), safflower (Baümler et al., 2006) and coriander (Coşkuner and Karababa, 2007b), lower than that of soybeans (Deshpande et al., 1993), millet (Jain and Bal, 1997), amaranth (Abalone et al., 2004) and sesame (Tunde-Akintunde and Akintunde, 2004), but it was within the same range to that of quinoa (Vilche et al., 2003), cumin (Singh and Goswami, 1996) and flaxseed (Coşkuner and Karababa, 2007a).

The porosity of chia seeds was found to be in the same order as quinoa (Vilche et al., 2003) and coriander (Coşkuner and Karababa, 2007b). It must be noted that porosity of the mass of seeds determines the resistance to airflow during aeration and drying procedures.

Table 2 – Statistical analysis for some physical properties of dark and white chia seeds, moisture content of 7.2% (d.b.) and 6.6% (d.b.), respectively

Physical property	Degrees of freedom	$t_{calculated}$	p-Value
Length (mm)	178	1.92	0.06$^{n.s}$
Width (mm)	178	3.92	$1.3\times10^{-4**}$
Thickness (mm)	178	2.05	0.04*
Bulk density ($g\,cm^{-3}$)	4	6.9×10^{14}	$2.6\times10^{-59**}$
True density ($g\,cm^{-3}$)	4	0.18	0.86$^{n.s}$
Porosity (%)	4	−1.32	0.26$^{n.s}$
Equivalent diameter (mm)	4	0.26	0.80$^{n.s}$
Sphericity (%)	4	1.19	0.30$^{n.s}$
Volume (mm^3)	4	0.27	0.80$^{n.s}$
Geometric mean diameter (mm)	178	3.87	$1.5\times10^{-4**}$
Surface area (mm^2)	178	3.76	$2.3\times10^{-4**}$
Aspect ratio	178	2.55	0.0116*
1000 seed weight (g)	46	3.15	$2.9\times10^{-3**}$

n.s.: no significant.
* Significant at the level 5%.
** Significant at the level 1%.

The equivalent diameter and sphericity of the seeds ranged from 1.32 to 1.39 mm, and 62.2 to 66.0%, respectively (Table 3). No significant differences were found between dark and white seeds for both of these physical parameters (Table 2). The experimental sphericity of chia resulted to be lower than that of soybeans (Deshpande et al., 1993), millet (Jain and Bal, 1997), quinoa (Vilche et al., 2003), amaranth (Abalone et al., 2004), rapeseed (Çahşir et al., 2005) and coriander (Coşkuner and Karababa, 2007b), and higher than that of sunflower (Gupta and Das, 1997), sesame (Tunde-Akintunde and Akintunde, 2004) and safflower (Baümler et al., 2006). The sphericity of the chia seed is indicative of the low tendency of the shape towards a sphere.

The geometric mean diameter ranged from 1.10 to 1.54 mm, being these values lower than the length and width, and higher than thickness (Tables 1 and 3). L/T ratio exhibited the highest value, while the L/D_g and L/W ratio presented similar values. The coefficients of correlation showed that all the ratios were found to be highly significant (Table 4). This fact indicates that the length of the seed is positively related to its width, thickness and geometric mean diameter.

The following general expression can be used to describe the relationship among length, width and thickness of chia seed:

$$L = 1.58W = 2.60T \tag{9}$$

The surface area of a single seed (calculated by Eq. (6)) was $5.42 \pm 0.15\,mm^2$ and $5.79 \pm 0.12\,mm^2$ for dark and white seeds, respectively (Table 3), with significant differences ($p \le 0.05$) between both types of seeds (Table 2).

The equivalent and geometric mean diameters were compared and no significant differences ($p \ge 0.05$) were found between these parameters for chia seeds. Both methods were compared and it was assessed that the ellipsoid shape of the seed and the geometric mean diameter can be used for the theoretical determination of seed volume and sphericity.

The volume of single grain (V) was calculated by Eq. (2) and ranged between 1.19 and 1.42 mm^3. The volume and sphericity of the seed were also calculated like a sphere with diameter D_g and no significant differences ($p \ge 0.05$) were found with respect to the real volume (V) and sphericity (ϕ) of the seed.

Table 3 – Physical properties of dark and white chia seeds, the moisture content of 7.2% (d.b.) and 6.6% (d.b.), respectively

Physical property	N	Dark seeds				White seeds			
		Mean	Minimum value	Maximum value	S.D.	Mean	Minimum value	Maximum value	S.D.
Bulk density ($g\,cm^{-3}$)	3	0.722	0.722	0.722	0	0.667	0.667	0.667	0
True density ($g\,cm^{-3}$)	3	1.009	0.937	1.075	0.07	0.999	0.931	1.040	0.06
Porosity (%)	3	28.2	22.9	32.8	5.0	33.1	28.4	35.9	4.14
Equivalent diameter (mm)	3	1.35	1.32	1.39	0.03	1.34	1.32	1.38	0.03
Sphericity (%)	3	64.4	63.0	66.0	1.51	63.0	62.2	64.5	1.27
Geometric mean diameter (mm)	90	1.31	1.10	1.49	0.09	1.36	1.14	1.54	0.07
Surface area (mm^2)	90	5.42	3.78	7.01	0.73	5.79	4.10	7.47	0.58
Volume (mm^3)	3	1.30	1.19	1.42	0.11	1.27	1.21	1.38	0.09
Aspect ratio	90	62.7	48.0	81.8	7.0	65.3	52.6	79.4	6.4
1000 seed mass (g)	24	1.323	1.267	1.387	0.024	1.301	1.263	1.354	0.024

N: number of observation; S.D.: standard deviation.

Table 4 – Correlation of seed dimensions, with 7.0% average moisture content (d.b.)

Particulars	Ratio	Degrees of freedom	Correlation coefficient (*r*)	*p*-Value
L/W	1.58	178	0.341	0.0000****
L/T	2.60	178	0.306	0.0000****
L/D_g	1.60	178	0.712	0.0000****
W/T	1.66	178	0.223	0.0026***
W/D_g	1.02	178	0.790	0.0000****
T/D_g	0.62	178	0.658	0.0000****

***Significant at the level 0.1%.
****Significant at the level 0.01%.

The aspect ratio of chia seed was 62.7 ± 1.5% and 65.3 ± 1.3% for dark and white seeds, respectively (Table 3), with significant differences between both types of seeds. Considering the low aspect ratio (which relates the seeds width to length) and sphericity, it may be deduced that chia seeds would slide on their flat surfaces rather than roll. This tendency to either roll or slide is very important in the design of hoppers, because most flat seeds slide easier than spherical seeds, which roll on structural surfaces. Furthermore, the shape indices indicated that the chia seed may be treated as a scalene ellipsoid for an analytical prediction of its drying behaviour.

At the average moisture of 7.0% d.b., the one thousand seed weight values obtained for dark seeds (1.323 ± 0.010 g) were significantly greater ($p \leq 0.05$) that those found for white seeds (1.301 ± 0.010 g) (Tables 2 and 3). These values are lower than those reported for cumin (Singh and Goswami, 1996), millet (Jain and Bal, 1997), quinoa (Vilche et al., 2003), sesame (Tunde-Akintunde and Akintunde, 2004), rapeseed (Çahşir et al., 2005) and flaxseed (Coşkuner and Karababa, 2007a), but higher than those of amaranth seeds (Abalone et al., 2004). This parameter is useful in determining the equivalent diameter which can be used in the theoretical estimation of seed volume and in cleaning using aerodynamic forces.

The angle of repose of the chia seed varied between 16° and 18° (average 17.1 ± 0.4°). It is important to note that this frictional property for the chia seed is higher than that of 13° and 15° reported for locust bean and African star apple, respectively (Olajide and Ade-Omowaye, 1999; Oyelade et al., 2005); it is in the same range to that of 17° reported for oilbean seed (Oje and Ugbor, 1991), but much lower than those of sunflower, millet, quinoa, sesame, flaxseed and coriander (Gupta and Das, 1997; Jain and Bal, 1997; Vilche et al., 2003; Tunde-Akintunde and Akintunde, 2004; Coşkuner and Karababa, 2007a,b). The smooth outer surface and the shape of the seeds are apparently responsible for the relatively lower values of repose angle, and thus the easiness of the seeds to slide on each other.

The value of the static coefficient of friction was 0.28 ± 0.01 on galvanized sheet and 0.31 ± 0.01 on mild steel sheet. This may be due to the smoother surface of galvanized iron compared with mild steel. It appears that the static coefficient of friction for chia seed on galvanized iron surface was lower than that of cumin (Singh and Goswami, 1996), sunflower (Gupta and Das, 1997), sesame (Tunde-Akintunde and Akintunde, 2004), African star apple (Oyelade et al., 2005), flaxseed and coriander (Coşkuner and Karababa, 2007a,b) but higher than that of millet and quinoa seed (Jain and Bal, 1997; Vilche et al., 2003). On the other hand, rapeseed seeds (Çahşir et al., 2005) showed similar values for this frictional property to those of chia against galvanized iron.

4. Conclusions

The following conclusions were drawn from this investigation about the physical properties of chia seed at an average moisture content of 7.0% (d.b.). The frequency distribution curves of the axial dimensions tend a normal distribution. The average characteristic dimensions, length, width and thickness were 2.11, 1.32 and 0.81 mm for dark seeds, and 2.15, 1.40 and 0.83 mm for white seeds of chia, respectively. The bulk density ranged from 0.667 to 0.722 g cm^{-3}, the true density from 0.931 to 1.075 g cm^{-3} and the porosity from 22.9 to 35.9%. The equivalent diameter and volume of a single chia seed ranged between 1.32 and 1.39, and 1.19 and 1.42 mm^3, respectively. The geometric mean diameter averaged 1.31 and 1.36 mm for dark and white chia seeds, respectively. This parameter can be used for the theoretical determination of seed volume and sphericity. The shape of the grain was confirmed to be ellipsoid. The sphericity ranged from 62.2 to 66.0% while the average aspect ratio was 64.0%. One thousand seed mass averaged 1.323 g for dark seeds, and 1.301 g for white seeds. Chia seeds showed low values of angle of repose of 16–18° and coefficient of friction of 0.28 and 0.31 on galvanized sheet and meal steal sheet, respectively. In brief, this report deals with physical properties of *S. hispanica* seeds, enlarging the knowledge about this species and providing useful data for its industrial processing. Further studies should be conducted to investigate the moisture-dependent physical properties of chia seed.

Acknowledgments

This work was supported by grants from Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT), Argentina (PICT 2002–10768), Universidad Nacional de La Plata (UNLP) (11/X390) and Universidad Nacional del Centro de la Provincia de Buenos Aires (UNCPBA), Argentina.

The authors wish to thank to Natalia Raffaeli and Norma Tedesco for kindly helping with English grammar.

Author V.Y. Ixtaina is a recipient of a fellowship from the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

Author S.M. Nolasco is a Scientific and Technological Researcher and Professor at the Facultad de Ingeniería de la Universidad Nacional del Centro de la Provincia de Buenos Aires (UNCPBA), Argentina.

Author M.C. Tomás is a member of the career of Scientific and Technological Researcher of the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

REFERENCES

Abalone, R., Cassinera, A., Gastón, A., Lara, M.A., 2004. Some physical properties of Amaranth seeds. Biosyst. Eng. 89, 109–117.

Association of Official Analytical Chemists, AOAC, 1990. Official Methods of Analysis, 15th ed. Association of Official Analytical Chemists, Washington, DC.

Aviara, N.A., Haque, M.A., 2000. Moisture dependence of density, coefficient of friction and angle of repose of guna seed and kernel. J. Eng. Appl. 2, 44–53.

Ayerza Jr., R., 1995. Oil Content and fatty acid composition of Chia (*Salvia hispanica* L.) from five northwestern locations in Argentina. J. Am. Oil Chem. Soc. 72, 1079–1081.

Ayerza Jr., R., Coates, W., 1997. Selection and development of chia cultivars: initial results. In: Proceedings of the Annual Meeting of the Association for the Advancement of Industrial Crops, Saltillo, México.

Ayerza, R., Coates, W., 2005. Chia. Rediscovering a Forgotten Crop of the Aztecs, 1st ed. The University of Arizona Press, Tucson, Arizona, p. 197.

Baümler, E., Cuniberti, A., Nolasco, S.M., Riccobene, I.C., 2006. Moisture dependent physical and compression properties of safflower seed. J. Food Eng. 72, 134–140.

Bushway, A.A., Belyea, P.R., Bushway, R.J., 1981. Chia seed as a source of oil, polysaccharide, and protein. J. Food Sci. 46, 1349–1350.

Cahill, J.P., Provance, M.C., 2002. Genetics of qualitative traits in domesticated chia (*Salvia hispanica* L.). J. Hered. 93, 52–55.

Çahşir, S., Marakoğlu, T., Öğüt, H., Öztürk, Ö., 2005. Physical properties of rapeseed (*Brassica napus oleifera* L.). J. Food Eng. 69, 61–66.

Coates, W., Ayerza Jr., R., 1996. Production potential of Chia in northwestern Argentina. Ind. Crops Prod. 5, 229–233.

Coşkuner, Y., Karababa, E., 2007a. Some physical properties of flaxseed (*Linum usitatissimum* L.). J. Food Eng. 78, 1067–1073.

Coşkuner, Y., Karababa, E., 2007b. Physical properties of coriander seeds (*Coriandrum sativum* L.). J. Food Eng. 80, 408–416.

Deshpande, S.D., Bal, S., Ojha, T.P., 1993. Physical properties of soybean. J. Agric. Eng. Res. 56, 89–98.

Dutta, S.K., Nema, V.K., Bhardwaj, R.K., 1988. Physical properties of grain. J. Agric. Eng. Res. 39, 259–268.

Earle, F.R., Mc Guire, T.A., Mallan, J., Bagby, M.O., Wolf, I.A., 1960. Search for new industrial oils. Part 2. Oils with high iodine values. J. Am. Oil Chem. Soc. 37, 48.

Giner, S.A., Calvelo, A., 1987. Modelling of wheat drying in fluidized beds. J. Food Sci. 52, 1358–1363.

Gupta, R.K., Das, S.K., 1997. Physical properties of Sunflower seeds. J. Agric. Eng. Res. 66, 1–8.

Huxley, A.J., 1992. The New RHS Dictionary of Gardening. Mac Millan Press, London.

IUPAC, 1992. Standard methods for the analysis of oils, fats and derivates. In: Paquot, C., Hautffenne, A. (Eds.), International Union of Pure and Applied Chemistry, 7th ed. Blackwell Scientific Publications Inc, Oxford, UK.

Ixtaina, V.Y., Nolasco, S.M., Tomás, M.C., 2006. Caracterización de semillas y aceite de chia (*Salvia hispanica* L.). In: Proceedings of the II Congreso Internacional de Ciencia y Tecnología de los Alimentos, Córdoba, Argentina.

Jain, R.K., Bal, S., 1997. Physical properties of Pearl millet. J. Agric. Eng. Res. 66, 85–91.

Kachru, R.P., Gupta, R.K., Alam, A., 1994. Physico-chemical Constituents and Engineering Properties. Scientific Publishers, Jodhpur, India.

Maduako, J.N., Faborode, M.O., 1990. Some physical properties of cocoa pods in relation to primary processing. Ife J. Technol. 2, 1–7.

McCabe, W.L., Smith, J.C., Harriot, P., 1986. Unit Operations of Chemical Engineering. McGraw-Hill, New York.

Mohsenin, N.N., 1970. Physical Properties of Plant and Animal Materials. Gordon Breach Science Publishers, New York.

Oje, K., Ugbor, E.C., 1991. Some physical properties of oil bean seed. J. Agric. Eng. Res. 50, 305–313.

Olajide, J.O., Ade-Omowaye, B.I.O., 1999. Some physical properties of Locust bean seed. J. Agric. Eng. Res. 74, 213–215.

Oyelade, O.J., Odugbenro, P.O., Abioye, A.O., Raji, N.L., 2005. Some physical properties of African star apple (*Chrysophyllum alibidum*) seeds. J. Food Eng. 67, 435–440.

Özarslan, C., 2002. Physical properties of cotton seed. Biosyst. Eng. 83, 169–174.

Palma, F., Donde, M., Lloyd, W.R., 1947. Fixed oils of Mexico. Part 1. Oil of chia- *Salvia hispanica*. J. Am. Oil Chem. Soc. 24, 27.

Pérez, E.E., Crapiste, G.H., Carelli, A.A., 2007. Some physical and morphological properties of wild sunflower seeds. Biosyst. Eng. 96, 41–45.

Rulfo, J.M., 1937. La chia. Agricultura I, 28–37.
Santalla, E.M., Mascheroni, R.H., 2003. Physical properties of high oleic sunflower seeds. Food Sci. Technol. Int. 9, 435–438.
Singh, K.K., Goswami, T.K., 1996. Physical properties of Cumin seed. J. Agric. Eng. Res. 64, 93–98.
Statgraphics Plus Version 4.0., 1999, Statistical Graphic Corporation. Manugistics Inc., Rockville, USA.
Taga, M.S., Miller, E.E., Pratt, D.E., 1984. Chia seeds as a source of natural lipid antioxidants. J. Am. Oil Chem. Soc. 61, 928–931.
Thompson, R.A., Isaacs, G.W., 1967. Porosity determination of grains and seeds with air comparison pycnometer. Trans. ASAE 10, 693–696.
Tunde-Akintunde, T.Y., Akintunde, B.O., 2004. Some physical properties of Sesame seed. Biosyst. Eng. 88, 127–129.
Vilche, C., Gely, M., Santalla, E., 2003. Physical properties of quinoa seeds. Biosyst. Eng. 86, 59–65.