Moisture-dependent physical properties of barley grains

Mahmoud Tavakoli[1], Hamed Tavakoli[2], Ali Rajabipour[2], Hojat Ahmadi[2], Seyed Mohammad Taghi Gharib-Zahedi[3]

(1. *Department of Food Science and Technology, Faculty of Agriculture, University of Zabol, Zabol, Iran*; 2. *Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering & Technology, University of Tehran , P.O. Box* 4111, *Karaj* 31587-77871, *Iran*; 3. *Department of Food Science and Engineering, Faculty of Agricultural Engineering & Technology, University of Tehran, Karaj, Iran*)

Abstract: Designing equipment for processing, sorting, sizing and other post-harvest operations of agricultural products requires information about their physical properties. This study was carried out to evaluate the effect of moisture content on some physical properties of barley grains. Four levels of moisture content ranging from 7.34% to 21.58% (d.b.) were used. The average length, width, thickness, arithmetic mean diameter, geometric mean diameter, thousand grain mass, sphericity, surface area and repose angle increased from 8.91 to 9.64 mm, 3.30 to 3.74 mm, 2.58 to 2.98 mm, 4.93 to 5.45 mm, 4.23 to 4.75 mm, 44.48 to 51.30 g, 47.55% to 49.35%, 56.66 to 71.09 mm^2 and 31.16° to 36.90°, respectively, as moisture content increased from 7.34% to 21.58% (d.b.). The bulk density, true density and porosity were found to decrease with increasing moisture content. The static friction coefficient of the grains increased linearly against various surfaces (plywood, glass and galvanized iron sheet) as the moisture content increased. At all moisture content, the maximum friction was offered by plywood, followed by galvanized iron sheet and glass surface.

Keywords: barley, moisture content, angle of repose, coefficient of friction

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1 Introduction

Barley (*Hordeum vulgare* L.) is an ancient and important cereal grain crop. It ranks the fifth among all crops in dry matter production in the world today. In Iran, barley is also widely cultivated on approximately 1 817 572 hectares with an annual production of 2 900 Kt[10]. Historically, barley has been an important food source in many parts of the world, including the Middle East, North Africa and northern and eastern Europe (Iran, Morocco, Ethiopia, Finland, England, Denmark, Russia and Poland), and in Asia (Japan, India, Tibet and Korea)[5,21]. Due in part to the rise in prominence of wheat and rice,

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Biographies: Mahmoud Tavakoli, M.Sc. Department of Food Science and Technology, Faculty of Agriculture, University of Zabol, Zabol, Iran. E-mail: pardiss6000@gmail.com; **Ali Rajabipour,** associate professor in University of Tehran. His current research interest is Engineering Properties of Agricultural Products. Email: rajabipour@ut.ac.ir; **Hojat Ahmadi,** associate professor in University of Tehran. His current research interests are Machinery Fault Detection, Vibration & Oil Monitoring, Signal Processing, Precision Agriculture and System Maintenance. Email: hjahmadi@ut.ac.ir; **Seyed Mohammad Taghi Gharib-Zahedi,** Ph.D student. Department of Food Science and Engineering, Faculty of Agricultural Engineering & Technology, University of Tehran, Karaj, Iran. E-mail: s_zahedi63@yahoo.com.

Corresponding Author: Hamed Tavakoli, Ph.D student. Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering & Technology, University of Tehran , P.O. Box 4111, Karaj 31587-77871, Iran. E-mail: h8.tavakkoli@gmail.com. Tel.: 0098-261-2801011, Fax: 0098-261-2801011

barley is mainly used as feed, and for malting and brewing.

The physical properties of barley grain, like those of other grains and seeds, are essential for the design of equipment and the analysis of the behavior of the product during agricultural process operations such as handling, planting, harvesting, threshing, cleaning, sorting and processing. Principal axial dimensions of barley grain are useful in selecting sieve separators and in calculating grinding power during size reduction. They can also be used to calculate surface area and volume of grains, which are important during modeling of grain drying, aeration, heating, and cooling. Bulk density, true density, and porosity (the ratio of inter granular space to the total space occupied by the grain) play an important role in many applications such as design of silos and storage bins, separation from undesirable materials, separation and grading, and maturity evaluation. Flow-ability of barley grain is usually measured using the angle of repose (a measure of the internal friction between grains) that will be useful in hopper design, since the hopper wall's inclination angle should be greater than the angle of repose to ensure the continuous flow of the materials by gravity. The need for knowledge of friction coefficient of agricultural materials on various surfaces has long been recognized by engineers who are concerned with rational design of grain bins, silos and other storage structures[20].

In recent years, the physical properties have been studied for various crops such as sweet corn seed[6], linseed[25], faba bean grain[3], rough rice grain[12], jatropha seed[11], wheat grain[16] and cumin seed[21]. Öztürk and Esen[22] determined effect of moisture content (in the range of 10% to 14% d.b.) on bulk density, true density, angle of internal friction, porosity and static coefficient of friction of barley grain (var. *Fahrettinbey*). Review of literatures showed that there is a lack of information on physical properties of barley grains. Therefore, the objective of this study was to determine moisture dependence of some physical properties of barley grains, namely, linear dimensions, sphericity, surface area, thousand grain mass, bulk density, true density, porosity, angle of repose and static coefficient of friction on various surfaces.

2 Materials and methods

The barley variety, *Nosrat* (Figure 1), used for this study is one of the prevalent varieties in Iran. It was obtained from the Seed and Seedling Research Institute, Karaj, Iran. The samples were manually cleaned to remove foreign matter, including dust and dirt, as well as broken and immature grains. The initial moisture content of the samples was determined by oven drying at (103±1)℃ for 24 h[4]. The initial moisture content of the grains was 7.34% (d.b.).

Figure 1 Barley grains

The samples of the desired moisture contents were prepared by adding the amount of distilled water, Q, as calculated from the following relationship[6]:

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f}.$$

The samples were then transferred to separate polyethylene bags, and the bags were sealed tightly. The samples were kept at 5℃ in a refrigerator for a week to enable the moisture to be distributed uniformly throughout each sample. Before starting a test, the required quantities of the samples were taken out of the refrigerator and allowed to warm up to the room temperature for about 2 h. This rewetting technique to attain the desired moisture content in the grains has frequently been used[6,11,24]. All the physical properties of the grains were assessed at moisture levels of 7.34%, 12.11%, 16.82% and 21.58% (d.b.). For each moisture content, the length, width, thickness and mass of barley grain were measured in randomly selected 100 grains. The length, width and thickness of materials were measured using a digital caliper with an accuracy of 0.01 mm.

The average diameter of the grains was calculated by using arithmetic mean and geometric mean of the three axial dimensions. The arithmetic mean diameter, D_a, and geometric mean diameter, D_g, of the grains were calculated by using the following relationships[20]:

$$D_a = \frac{L+W+T}{3},$$

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

The sphericity, Φ, of barley grain was calculated by using the following relationship[20]:

$$F = \left[\frac{(LWT)^{1/3}}{L}\right]\times 100.$$

The thousand grains mass was determined using a digital electronic balance with an accuracy of 0.001 g. To evaluate the thousand grain mass, 100 randomly selected grains from each bulk sample were selected and averaged. The surface area of the grain, S, was found by analogy with a sphere of the same geometric mean diameter, using the following relationship[2, 24]:

$$S = p D_g^{\ 2}.$$

The true density defined as the ratio between the mass of the barley grains and the true volume of the grains, was determined using the toluene (C_7H_8) displacement method. The volume of toluene displaced was found by immersing a weighted quantity of soybean grains in the measured toluene[11,24]. The bulk density was determined using the mass/volume relationship, by filling an empty plastic container of predetermined volume and tare weight with the grains by pouring from a constant height (15 cm), striking off the top level and weighing[12].

The porosity of the grains, ε, was calculated from bulk and true densities using the relationship given by Mohsenin[20] as follows:

$$e = (1-\frac{r_b}{r_t})\times 100.$$

The angle of repose is the angle with the horizontal at which the material will stand when piled. This was determined by using the apparatus consisting of a plywood box of 140 mm×160 mm×35 mm and two plates: fixed and adjustable. The box was filled with the sample from a constant height (15 cm), and then the adjustable plate was inclined gradually allowing the grains to follow and assume a natural slope, this was measured as emptying angle of repose[27].

The static friction coefficients of the grains against three different surfaces, namely plywood, glass and galvanized iron sheet, were determined using a cylinder of diameter 75 mm and depth 50 mm filled with grains. With the cylinder resting on the surface, the surface was raised gradually until the filled cylinder just started to slide down[23]. The friction coefficient, μ, was calculated from the following relationship:

$$m = \tan a ,$$

where α is the angle of tilt in degrees.

Each physical property was determined with five replications. The results obtained were analyzed statistically using SPSS 13 software and figures were plotted in Microsoft Excel 2003.

3 Results and discussion

The mean values for the physical properties are presented in Table 1. The effect of moisture content on the length, width, thickness, arithmetic and geometric mean diameters, sphericity, surface area, angle of repose, bulk density, true density, thousand grain mass and static friction coefficient on various surfaces was significant at the 5% probability level, while the effect on the porosity was not significant (P＞0.05).

Table 1 Physical properties of barley grains at different moisture contents

Moisture content d.b.%	Average diameters/mm		Sphericity, %	1000 grain Mass, g
	Arithmetic mean, D_a	Geometric mean, Dg		
7.34	4.93 a (0.37)	4.23 a (0.33)	47.55 a (1.76)	44.48 a (1.95)
12.11	5.15 b (0.33)	4.43 b (0.30)	47.70 a (2.16)	46.36 a (1.05)
16.82	5.34 c (0.31)	4.64 c (0.27)	49.08 b (1.78)	45.87 a (1.14)

21.58	5.45 c (0.27)	4.75 c (0.24)	49.35 b (1.96)	51.30 b (1.12)

Note: Values in parentheses are standard deviations. Values in the same column followed by different letters (a-c) are significant ($P<0.05$).

3.1 Grain dimensions

Average values of the three principal dimensions of barley grain, namely length, width and thickness, determined in this study at different moisture contents are presented in Table 1. Each principal dimension appeared to be linearly dependent on the moisture content as shown in Figure 2. Very high correlation between the three principal dimensions and moisture content indicates that upon moisture absorption, the barley grain expands in length, width and thickness within the moisture range of 7.34% to 21.58% (d.b.). The average length, width and thickness of the 100 grains increased from 8.91 to 9.64 mm, 3.30 to 3.74 mm and 2.58 to 2.98 mm, respectively, as the moisture content increased from 7.34% to 21.58% (d.b.).

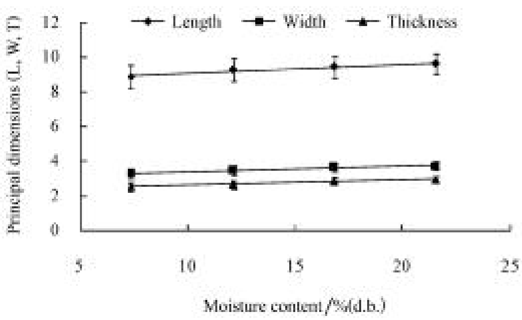

Figure 2 Variation of principal dimensions of barley grains with moisture content

The average diameters calculated by the arithmetic mean and geometric mean are also presented in Table 1. The average diameters increased with moisture content as axial dimensions. The arithmetic and geometric mean diameters ranged from 4.93 to 5.45 mm and from 4.23 to 4.75 mm as the moisture content increased from 7.34% to 21.58% (d.b.), respectively ($P<0.05$).

3.2 Sphericity

The values of the sphericity were calculated individually by using the data on geometric mean diameter and the major axis of the grain, and the results obtained are presented in Table 1. The sphericity of the grains increased linearly from 47.55% to 49.35% as the moisture content increased from 7.34% to 21.58% (d.b.). This suggests that as the grain's moisture content increases, its shape approaches to sphere shape. This is due to the differential dimensional changes of the three major dimensions as the grain absorbs moisture. The effect of moisture content on the sphericity was significant at 5% probability level. The relationship between sphericity (Φ) and moisture content (M) can be represented by the following equation:

$$F = 0.143M + 46.35 \quad (R^2=0.890).$$

Similar trends of increasing have been reported by most previous researchers such as Sacilik et al.[24] for hemp seed, Altuntaş and Yildiz[3] for faba bean grain and Garnayak et al.[11] for jatropha seed.

3.3 Thousand grain mass

The thousand grain mass of the grains increased linearly from 44.48 to 51.30 g ($P<0.05$) as the moisture content increased from 7.34% to 21.58% (d.b.) (Table 1). The thousand grain mass of cereal grains is a useful index to "milling outturn" in measuring the relative amount of dockage or foreign material in a given lot of grain, and the amount of shriveled or immature kernels[12]. The relationship between 1000 grain mass (m_{1000}) and the moisture content (M) can be represented by the following equation:

$$m_{1000} = 0.504M + 40.55 \quad (R^2=0.976).$$

A similar increasing trend has been reported by most previous researchers such as Kasap and Altuntaş[15] for sugarbeet seeds, Altuntaş and Yildiz[3] for faba bean grains, and Garnayak et al.[11] for jatropha seed.

3.4 Surface area

The surface area of barley grain increased linearly from 56.66 to 71.09 mm^2 (statistically important at $P<0.05$) when the moisture content increased from 7.34% to 21.58% (d.b.) (Figure 3). The surface area affects the rate of moisture loss during drying of grains, seeds, and other particulate materials. The rate of heat transfer to the material also significantly depends on the heat transfer surface. The smaller the volume of material per unit surface, the better its condition for rapid heat transfer[27]. The variation of moisture content (M) and surface area (S) can be expressed mathematically as follows:

$$S = 1.039M + 49.38 \quad (R^2=0.985).$$

A similar trend has been reported by Selvi et al.[25] for linseed, by Işik and Ünal[13] for red kidney bean grains, and by Garnayak et al.[11] for jatropha seed.

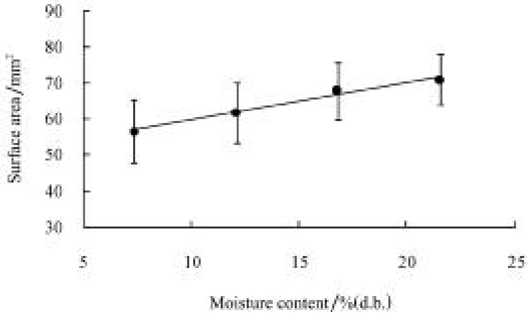

Figure 3 Variation of surface area of barley grains with moisture content.

3.5 Bulk density

The grains bulk density at different moisture levels varied from 714.33 to 660.41 kg/m^3 ($P<0.05$), which indicates a decrease in bulk density with an increase in moisture content from 7.34% to 21.58% (d.b.) (Figure 4). This was due to the fact that an increase in mass owing to moisture gain in the sample was lower than accompanying volumetric expansion of the bulk.

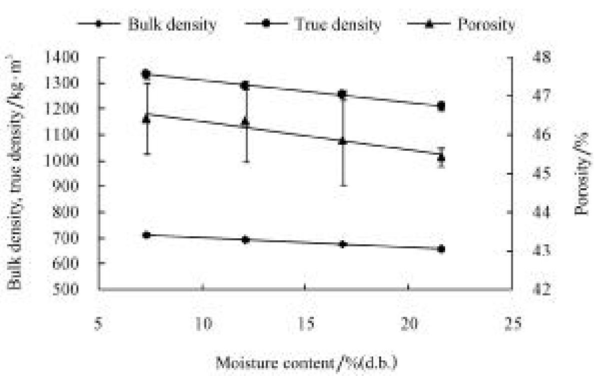

Figure 4 Variation of bulk density, true density and porosity of barley grains with moisture content

In precision agriculture, diverse approaches are used to determine the volume of the existing grain in a combine hopper. To determine the weight of product in the hopper, knowledge of bulk density is necessary. The bulk density of grains is also useful in the design of silos and storage bins[12]. The bulk density (ρ_b) of the grains was found to have the following linear relationship with the moisture content (M):

$$r_b = -3.718M + 740.3 \quad (R^2=0.995).$$

A similar decreasing trend in bulk density has been reported by Yalçin et al.[29] for pea seed, by Altuntaş and Demirtola[1] for some legumes seeds and by Garnayak et al.[11] for jatropha seed.

3.6 True density

The true density of barley grains at different moisture contents varied from 1210.51 to 1333.41 kg/m^3. The effect of moisture content on the true density of the grains showed a decrease with increasing moisture content ($P<0.05$) (Figure 4). The decrease in the true density was mainly due to the larger increase in grains volume compared to the increase in grains mass.

Pneumatic sorting tables are used to separate seeds of cereal crops by true density. Seeds of various impurities such as centourea, rye grass, field mustard and wild oats greatly differ in true density from the seeds of cereal crops. The true density of grain mixtures is determined either in solution or in suspension[18]. The moisture (M) dependence of the true density (ρ_t) was described by a linear equation as follows:

$$r_t = -8.587M + 1396 \quad (R^2=0.999).$$

Although the results were similar to those reported by Sacilik et al.[24] for hemp seed, by Yalçin et al. (2007) for pea seed, Cetin[7] for barbunia bean seed and by Altuntaş and Demirtola[1] for some legumes seeds, a converse trend was reported by Altuntaş and Yildiz[3] for faba bean grains and by Garnayak et al.[11] for jatropha seed.

3.7 Porosity

The porosity, or the percent of pore space between the grains, was calculated by using the data on the bulk and true densities of the barley grains. The porosity was found to decrease linearly from 46.42% to 45.44% with increasing moisture content (Figure 4). The reason for this decrease is that as the barley gains become more moisture, its volume increases; thus the number of grains in a fixed volume decreases. Since the number of grains per unit volume decreases, the porosity also decreases. The effect of moisture content on the porosity of barley grains, however, was not significant at 5% probability level. The porosity is the most important factor for packing and it affects the resistance to airflow through bulk seeds. The relationship between porosity value (ε)

and the moisture content (M) of the grains was obtained as:

$$e = -0.072M + 47.07 \quad (R^2=0.925).$$

Chandrasekar and Viswanathan[8], Deshpande et al.[9], Joshi et al.[14] and Kingsly et al.[17] reported similar trends in cases of coffee, soybeans, pumpkin seeds and dried pomegranate seeds, respectively.

3.8 Angle of repose

The values were found to increase from 31.16° to 36.90° ($P<0.05$) in the moisture range of 7.34%–21.58% (d.b.) (Figure 5). This increasing trend of repose angle with moisture content occurs because surface layer of moisture surrounding the particle holds the aggregate of grain together by the surface tension. The angle of repose is also important in designing the equipment for mass flow and structures for storage. The values of repose angle (θ) for barley grains bear the following relationship with its moisture content (M):

$$q = 0.393M + 28.24 \quad (R^2=0.992).$$

These results are similar to those reported by Kasap and Altuntaş[15], Altuntaş and Yildiz[3] and Garnayak et al.[11] for sugarbeet seeds, faba bean grains and jatropha seed, respectively.

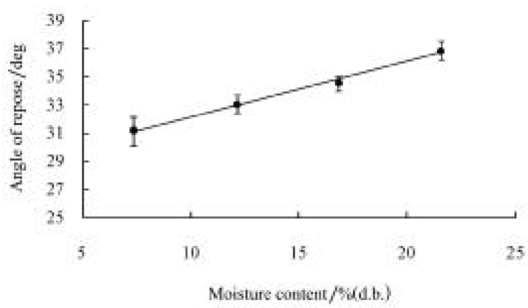

Figure 5 Variation of repose angle of barley grains with moisture content.

3.9 Static coefficient of friction

Figure 6 presents the static friction coefficients of the grains on three surfaces of plywood, glass and galvanized iron sheet against moisture content in the range of 7.34%–21.58% (d.b.). It is observed that the static coefficient of friction increased linearly with moisture content for all contact surfaces ($P<0.05$). The reason for the increased friction coefficient at higher moisture content may be owing to the water present in the grain, which offers a cohesive force on the surface of contact. Increases of 42.91%, 31.83% and 27.03% were recorded in the case of glass, galvanized iron sheet and plywood, respectively, as the moisture content increased from 7.34% to 21.58% (d.b.). At all moisture content, the maximum friction was offered by plywood, followed by galvanized iron sheet and glass surface. The least static coefficient of friction may be owing to smoother and more polished surface of the glass than the other materials tested. Plywood offered the maximum friction for rape seed, neem nut and Jatropha seed, and the coefficient of friction increased with the moisture content in each case[11,19,28].

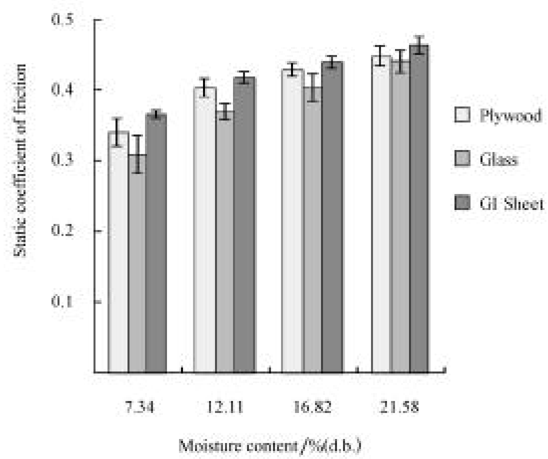

Figure 6 Effect of moisture content on static friction coefficient of barley grains against various surfaces

The friction coefficient is important in the design of conveyors because friction is necessary to hold the grains to the conveying surface without slipping or sliding backward. On the other hand, discharging requires less friction to enhance the discharging process. The relationships between static friction coefficient (μ) and the moisture content (M) on plywood (wd), galvanized iron sheet (gi) and glass (gl) can be represented by the following equations:

$$m_{wd} = 0.006M + 0.324 \quad (R^2=0.953),$$

$$m_{gi} = 0.007M + 0.297 \quad (R^2=0.922),$$

$$m_{gl} = 0.009M + 0.248 \quad (R^2=0.980).$$

4 Conclusions

The following conclusions are drawn from the investigation on moisture-dependent physical properties of barley grains for moisture-content range of 7.34% to 21.58% (d.b.).

The average length, width, thickness, arithmetic mean diameter, geometric mean diameter, thousand grain mass, sphericity, surface area and repose angle increased from 8.91 to 9.64 mm, 3.30 to 3.74 mm, 2.58 to 2.98 mm, 4.93 to 5.45 mm, 4.23 to 4.75 mm, 44.48 to 51.30 g, 47.55% to 49.35%, 56.66 to 71.09 mm^2 and 31.16° to 36.90°, respectively, as moisture content increased from 7.34% to 21.58% (d.b.). The bulk density, true density and porosity were found to decrease from 714.33 to 660.41 kg/m^3, 1333.41 to 1210.51 kg/m^3 and 46.42% to 45.44%, respectively, with increasing moisture content.

The static friction coefficient of the grains increased linearly against various surfaces: plywood (0.365–0.463), glass (0.308–0.440) and galvanized iron sheet (0.339–0.447) as the moisture content increased. At all moisture content, the maximum friction was offered by plywood, followed by galvanized iron sheet and glass surface.

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Nomenclature		
arithmetic mean diameter, mm	T	thickness, mm
geometric mean diameter, mm	W	width, mm
length, mm	W_i	initial mass of sample, kg
final desired moisture content of sample, % d.b.	ρ_b	bulk density, kg/m^3
initial moisture content of sample, % d.b.	ρ_t	true density, kg/m^3
mass of water added to sample, kg	μ	coefficient of friction
determination correlation	ε	porosity, %
surface area of grain, mm^2	Φ	sphericity, %

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