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Effective engineering properties in the design of storage structures of postharvest dry bean grain

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ABSTRACT. Selected engineering properties (physical and mechanical) of dry bean under non-irrigation and drip-irrigation were determined and compared. These properties are necessary for the design of equipments for harvesting, processing, transporting, estimating loads in storage structures for crops and flow problems in silos such as arching, ratholing, irregular flow and segregation. Some engineering characteristics such as: average length, width, thickness, the geometric mean diameter, sphericity, surface area, volume, thousand grain mass (M_{1000}), bulk and true densities, porosity, angle of internal friction, static coefficient of friction, Poisson ratio and pressure ratio were studied. The highest average values for physical properties were recorded at drip-irrigation, the lowest average values at non-irrigation. Differences between both irrigation systems for physical properties were statistically significant, but differences for sphericity of irrigation systems were not significant. The highest average values for mechanical properties (angle of internal friction, static coefficient of friction and pressure ratio) were recorded at drip-irrigation, the lowest average values at non-irrigation. Differences between both irrigation systems for mechanical properties were statistically significant. According to the research results, it is recommended the use of the data obtained from the drip-irrigated plots in the design of handling equipments and storage facilities for dry bean.

Keywords: dry bean, physical properties, mechanical properties, statistical analysis

Propriedades efetivas de engenharia nas estruturas de armazenagem pós-colheita dos grãos secos de feijão

RESUMO. Foram determinadas e comparadas as propriedades selecionadas de engenharia (físicas e mecânicas) do feijão seco submetido à não-irrigação ou à irrigação por gotejamento. As propriedades são necessárias para o projeto de equipamentos de colheita, processamento, transporte, estimação de cargas nas estruturas de armazenamento para problemas de produtos agrícolas e seu fluxo em silos, compreendendo obstrução por arqueamento, descarga limitante, fluxo irregular e segregação. Foram analisadas algumas características de engenharia, tais como a média do cumprimento, largura e espessura, a média do diâmetro, esfericidade, área de superfície, volume, massa de mil grãos (M_{1000}), volume grosso, densidade, ângulo de fricção interna, coeficiente estático de fricção, razão de Poisson e de pressão. Os mais altos valores médios para propriedades físicas foram registrados para irrigação por gotejamento e os mais baixos valores médios aconteceram com a não-irrigação. As diferenças para propriedades físicas entre os dois sistemas de irrigação foram estatisticamente significativas, ao contrário das diferenças para esfericidade da irrigação os quais não foram significantes. Os mais altos valores médios para as propriedades mecânicas (ângulo da fricção interna, coeficiente estático de fricção e razão de pressão) foram detectados na irrigação por gotejamento e os mais baixos valores médios na não-irrigação. Foram estatisticamente significativas as diferenças entre os dois sistemas de irrigação. Os resultados mostram que é recomendável a utilização de dados obtidos da irrigação por gotejamento no projeto de uso dos equipamentos e de armazenamento para o feijão seco.

Palavras-chave: feijão seco, propriedades físicas, propriedades mecânicas, análises estatísticas.

Introduction

Dry bean is one of the world's major sources of edible legume. Leading producers include India, Brazil, Mexico, China and the United States (FAOSTAT, 2009). In 2008, nearly 20 million tons of dry beans were produced in 28 million ha in the world. Turkey has about 97848 ha of dry bean harvesting area, 154630 tonnes of dry bean production per year (FAOSTAT, 2009).

Grain legumes occupy an important place in human nutrition, especially in the dietary pattern of low-income groups of people in developing countries. Legumes, considered as poor man's meat, are generally good sources of nutrients (THARANATHAN; MAHADEVAMMA, 2003). They are an important and inexpensive source of protein, dietary fiber and starch for a large part of the world's population, mainly in developing countries (PERLA et al., 2003; SHIMELIS; RAKSHIT, 2005). Among the commonly consumed food legumes, dry beans (*Phaseolus vulgaris* L.) occupy an important place in human nutrition in Black Sea and Middle Anatolian regions of Turkey (TOPAK et al., 2009).

Dry bean is sensitive to water stress unlike other common crops (BOUTRAA; SANDERS, 2001). Irrigation is therefore an essential component of dry bean production systems in both arid and semi-arid regions. Net water requirement for a 90-100 d dry bean crop ranges from 350-500 mm depending upon the soil, climate and cultivar (ALLEN et al., 2009).

In the quality classifications and storage operations of dry bean, visual evaluation (dimensions, size, etc.) and analytical evaluation (moisture content, bulk density, angle of internal friction, etc.) related to physical and mechanical properties, can be necessary (BOUMANS, 1985; KORUNIC et al., 1996).

To design the equipment used in seedling, harvesting, transportation, storage and processing of dried dry bean there is a need to know various physical and mechanical properties as a function of moisture content (TAVAKOLI et al., 2009). The physical and mechanical properties of dry bean grains are to be known for the design and improvement of storage strucutres, relevant machines and facilities for harvesting, storing, handling and processing. The dimensions, size and mechanical behaviour of dry bean are important for designing of separating, harvesting, sizing and grinding machines. Bulk density, angle of internal friction, porosity and pressure ratio affects the structures loads (vertical and horizontal loads acting by product on silo wall) and the is important in designing of drying and aeration (natural and mechanical), store systems (silos and warehouses) and transporting structures. The coefficient of friction (static and dynamic) of the grain against the various surfaces is also necessary in designing of conveying, grain flow (mass and hopper) and storage structures (ALTUNTAŞ; YILDIZ, 2007; IXTAINA et al., 2008). These properties have been investigated for locust bean seed (OGUNJIMI et al., 2002), bean (PERLA et al., 2003), Africa oil bean seed (ASOEGWU et al., 2006), faba bean (ALTUNTAŞ; YILDIZ, 2007), barbunia bean (CETIN, 2007), soybean (KIBAR; ÖZTÜRK, 2008) and many others.

The objective of this research was to determine the effect of dry bean at irrigation systems (non-irrigation, drip irrigation) on physical properties (length, width, thickness, sphericity, surface area, volume, bulk density, true density and porosity) and mechanical properties (angle of internal friction, static coefficient of friction, Poisson ratio and pressure ratio).

Material and methods

Experimental design and sample preparation

The field experimental design was a completely randomized block design with three replications. Drip irrigation method was used to irrigate the plots. The variety of dry bean used in the present study was obtained from the crop grown, as a representative of commercial processing, during 2009 in the Bafra lowland zone (41° 35' N, 35° 56' E) of Samsun city, Turkey, which is at an altitude of 20 m. The total average annual rainfall of the lowland is 770 mm (TUMAS, 2009).

The dry beans were sown in May 2009 and harvested in September of the same year. Samples were collected after harvest mature whole raw beans and sun drying them. The dry beans were cleaned manually to remove all foreign matter such as dust, dirt, stones and chaff as well as immature, broken seeds. The initial moisture content of dry bean after harvest was determined by oven drying at 80 ± 5°C for 24h (AOAC, 1984). The dry bean obtained was placed in desiccator and stored at room temperature (23 ± 2°C) before use.

Determination of physical properties

To determine the average size of dry beans, a sample of 100 dry beans was randomly selected. The length (L), width (W) and thickness (T) were measured using a digital caliper reading to ± 0.01 mm accuracy.

According to Mohsenin (1980) and Kibar et al. (2010) the degree of sphericity (%), can be expressed as follows:

$$\phi = \left(\frac{D_g}{L}\right) x100 \quad (1)$$

where:

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

Surface area (S) in the samples depend on shape of bean and was determined using Equation 2 as described by McCabe et al. (1986), and Jain and Bal (1997).

$$S = \pi D_g^2 \quad (2)$$

Volume (V) of the dry bean was determined using Equation 3 as described by Sreenarayanan et al. (1985), and Jain and Bal (1997).

$$V = \frac{\pi(WT)L^2}{6\left(2L - \sqrt{WT}\right)} \quad (3)$$

The M_{1000} was determined using a digital electronic balance having an accuracy of ± 0.01 g. To evaluate the thousand grain mass, 100 grains were randomly selected from the bulk sample were averaged (TUNDE-AKINTUNDE; AKINTUNDE, 2004; TAVAKOLI et al., 2009).

To determine the bulk density of the experimental samples at non-irrigation and drip-irrigation, the method defined by Mohsenin (1980), and Singh and Goswami (1996) was used. Weight of a bulk density container of 1000 ml volume and 108 mm height was used to determine bulk density. The bulk density container was filled up to 5 cm above the top. The dry beans were then allowed to settle into the container and the bulk density was calculated from the following Equation 4:

$$\rho_b = \frac{G_2 - G_1}{V_b} \quad (4)$$

The liquid displacement method, as described by Singh and Goswami (1996), Öğüt (1998), and Kibar and Öztürk (2009), was used to determine the true density of dry bean samples. In this method, toluene, C_7H_8 (bulk density of toluene at 20°C is 0.87 g cm^{-3}) was used in place of water because it is absorbed to a lesser extent by dry beans and its surface tension (25.52 mN m^{-1} at 20°C) is low. To calculate true density, the air dried weight for samples was first determined. The samples were then submerged in toluene and the displacement volume was determined. In the second stage, the true density of samples was calculated by using Equation 5 as follows:

$$\rho_t = \frac{m_s + m_w}{V_s + V_w} \quad (5)$$

The porosity of dry bean was calculated from bulk and true densities using Equation (6) the relationship given by Mohsenin (1980) and Nelson (2002) as follows:

$$P = \left(\frac{\rho_t - \rho_b}{\rho_t}\right) x100 \quad (6)$$

Determination of mechanical properties

To determine the angle of internal friction of dry bean samples the direct shear method was used according to Uzuner (1996), Zou and Brusewitz (2001), Molenda et al. (2002), Mani et al. (2004), and Kibar and Öztürk (2009). The velocity used during the experiment was 1.16x10^{-5} m s^{-1} and the angle of internal friction of samples was calculated by using Equations 7, 8 and 9.

$$\sigma = \frac{N}{A} * 100 \quad (7)$$

$$\tau = \frac{T_s}{A} * 100 \quad (8)$$

$$\tau = (c + \sigma \, x \tan\varphi) \quad (9)$$

The static coefficients of friction of dry beans were determined according to the method of Kibar and Öztürk (2009). Wood, galvanized steel and concrete (C30) surfaces were used as friction surfaces. During the experiment, the test surface moved at a low velocity (0.024 m s^{-1}). The surfaces were driven by a 12 V, adjustable direct current motor and strength of friction was measured by using a digital dynamometer (Figure 1).

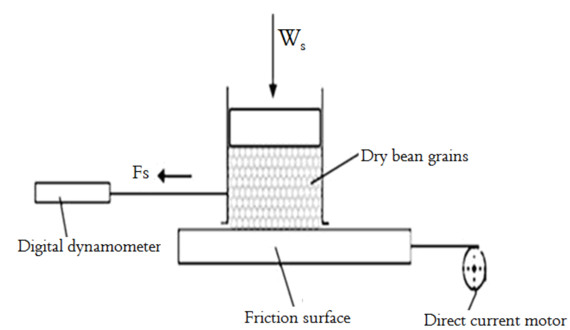

Figure 1. Apparatus to measure the force required to cause two surfaces to slide.

Strength of friction has been taken into consideration as an important parameter to determine static coefficients of friction. Static coefficient of friction was calculated from the constant strength of friction read in the digital dynamometer after movement occurred at the interface. The static coefficients of friction of dry bean samples were calculated by using Equation 10.

$$\mu_s = \frac{F_s}{W_s} \quad (10)$$

The Poisson ratio were calculated with Equation (11) developed by Qu et al. (2001).

$$\nu = \frac{1-\sin\varphi}{2-\sin\varphi} \tag{11}$$

In this study, the equalities developed by Kézdi (1962), Lohnes (1993) and Eurocode 1 (2003) were used to determine the pressure ratio of dry bean. Accordingly, the three methods were also evaluated in the study. Theoretical equalities relating to this issue are given at Equations 12, 13 and 14. These equalities are:
according to Kézdi (1962):

$$k_K = 1 - \sin\varphi \tag{12}$$

according to Lohnes (1993):

$$k_L = \frac{(1-\sin\varphi)x(1+\frac{2}{3}x\sin\varphi)}{1+\sin\varphi} \tag{13}$$

according to Eurocode 1 (2003):

$$k_E = 1.1x(1-\sin\varphi) \tag{14}$$

Statistical analysis

Some engineering properties of dry bean were determined at non-irrigation and drip-irrigation with at least three replications. Mean, minimum, maximum, standard deviations and t test were calculated by Statistical Package for Social Science (SPSS) 10.0 software. In order to estimate statistical differences between the non-irrigation and drip-irrigation the Student's t-test and Principal Component Analysis (PCA) were applied to investigate the factor structure of irrigation conditions.

Results and discussion

The initial moisture content of dry bean after harvest was determined as a 7.2% (dry basis, db) for drip-irrigated system while for non-irrigated system was 6.1% (db). According to obtained data, moisture content of dry bean is important. Because, the moisture content are highly affected by the physical and mechanical parameters of dry bean (OGUNJIMI et al., 2002; VALVERDE et al., 2006; ALTUNTAŞ; YILDIZ, 2007). Grain moisture content has deep influence on the mechanical properties of grain. Changing the moisture content of grain influences shear stress-strain characteristics, and consequently the determination of strength parameters: the angle of internal friction (φ) and the cohesion (c) (MOLENDA; HORABIK, 2005).

Figure 2 showed that the dimension values of dry bean for both non-irrigation and drip-irrigation conditions. For dry bean at non-irrigation condition, the mean values of the length, width, and thickness varied from 14.92 mm, 7.03 mm and 5.76 mm, respectively. For dry bean at drip-irrigation condition the mean values of the length, width, and thickness varied from 15.40 mm, 7.26 mm and 5.91 mm, respectively. The t test showed that non-irrigation and drip-irrigation length, width, and thickness showed be significant differences ($p < 0.01$).

The plot of scatter diagram dependent on L, W, T in non irrigation and drip-irrigation conditions were presented in Figures 3 and 4. The scatter diagram of non irrigation and drip-irrigation showed that there was a significant level of differences among L, W, T dimensions.

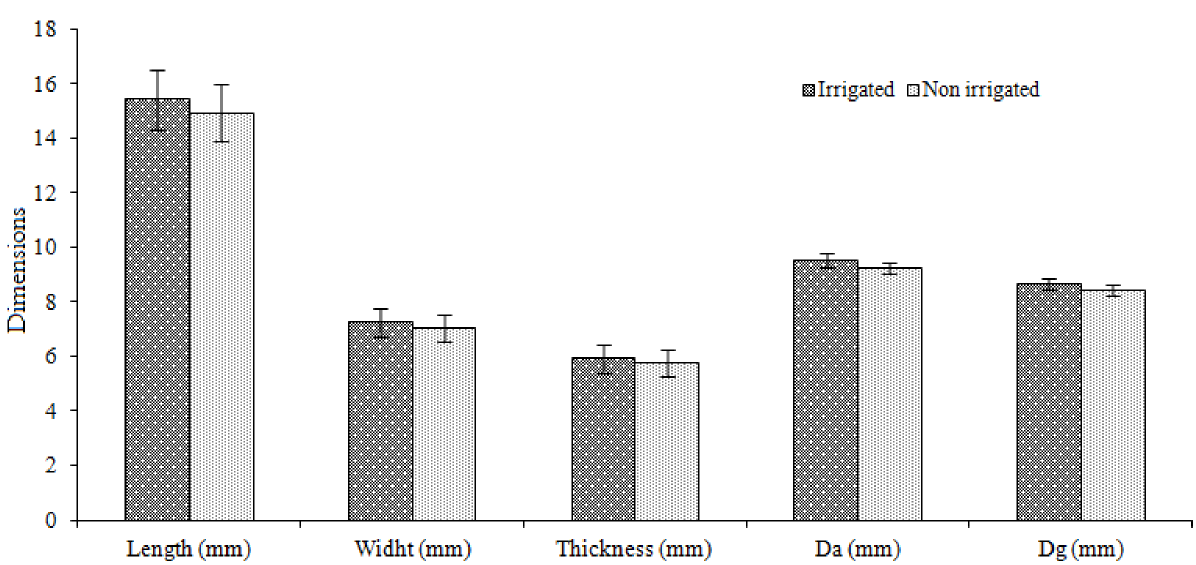

Figure 2. The axial dimensions of dry bean depending upon non-irrigation and drip-irrigation conditions.

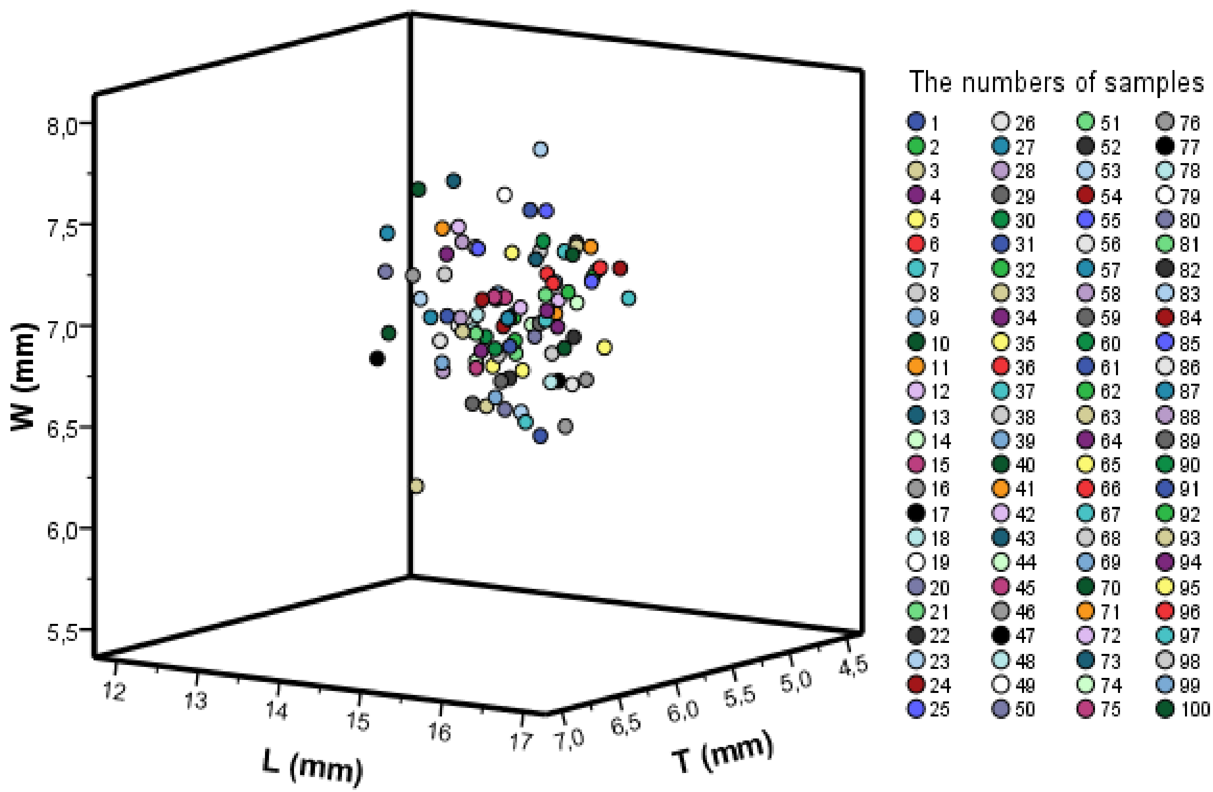

Figure 3. Scatter diagram depending upon L, W, T in non-irrigation conditions.

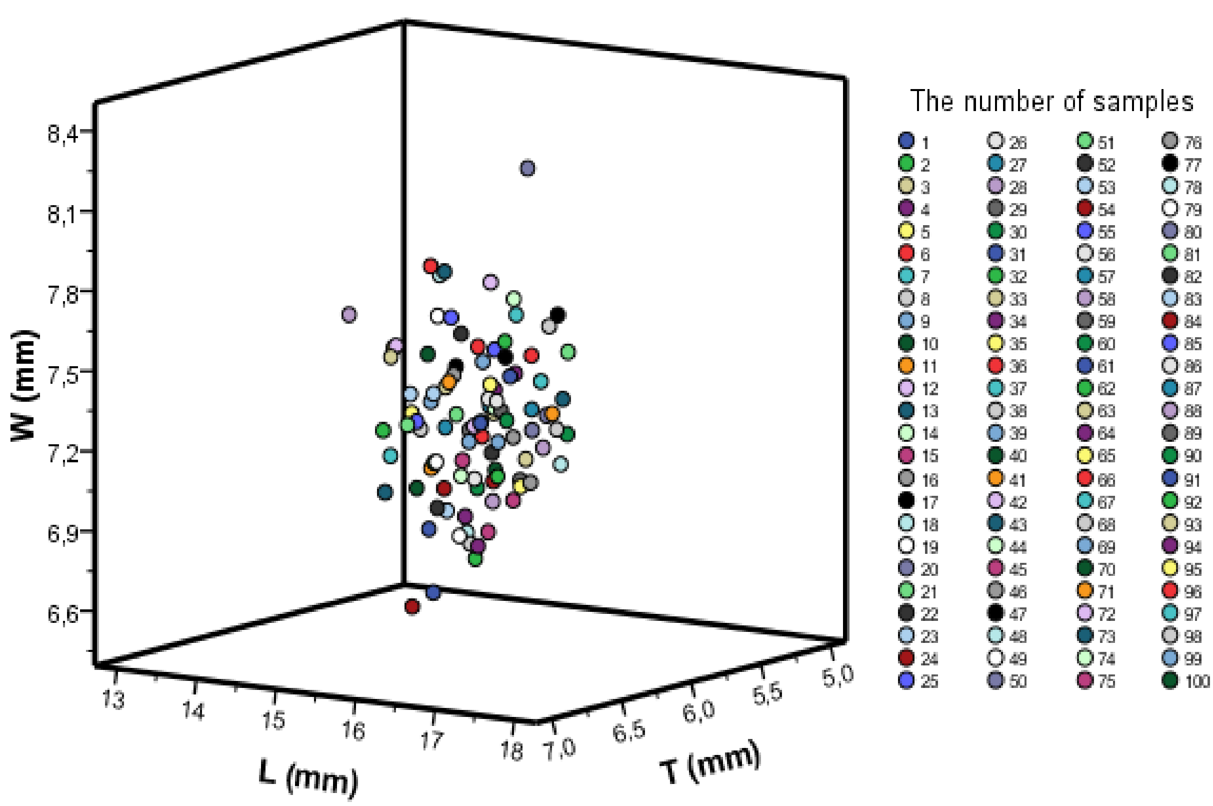

Figure 4. Scatter diagram depending upon L, W, T in drip-irrigation conditions.

Raw materials often occur in sizes that are too large to be used and, therefore, they must be reduced in size. This size-reduction operation can be divided into two major categories depending on whether the material is a solid or a liquid. If it is solid, the operations are called grinding and cutting, if it is liquid, emulsification or atomization. All depend on the reaction to shearing forces within solids and liquids (EARLE; EARLE, 2010). Size reduction is a unit operation widely used in a number of processing industries. Many types of equipment are used in size reduction operations. In a broad sense, size reduction machines may be classified as crushers used mainly for coarse reduction, grinders employed principally in intermediate and fine reduction, ultra-fine grinders utilized in ultra-fine reduction, and cutting machines used for exact reduction (MACCABE et al., 1986). The coefficients of correlation for non-irrigation showed that the dimension ratios of dry bean were not statistically significant. Whereas, it can be seen from the Table 1 dimension ratios of dry bean at drip-irrigation were statistically significant (L/W and L/T $p < 0.05$; L/D_g and L/D_a $p < 0.01$). Regarding this subject, a similar result was reported by Valverde et al. (2006).

Table 1. Ratio of dimensions of dry bean depending upon non-irrigation and drip-irrigation conditions.

Parametres	Non-irrigation					Drip-irrigation				
	Mean	Min.	Max.	SD	Correlation	Mean	Min.	Max.	SD	Correlation
L/W	2.12	1.81	2.38	0.11	0.118^{ns}	2.12	1.80	2.31	0.10	0.228^{*}
L/T	2.59	2.11	2.95	0.12	0.044^{ns}	2.61	2.38	2.89	0.12	0.229^{*}
L/D_g	1.76	1.67	1.87	0.51	0.102^{ns}	1.77	1.69	1.89	0.47	0.267^{**}
L/D_a	1.61	1.50	1.71	0.33	0.105^{ns}	1.63	1.52	1.65	0.29	0.271^{**}

*Significant at 0.05 level, **Significant at 0.01 level, ^{ns}Non-significant; SD: Standard deviation.

As given in Table 2, the sphericity (ϕ) of dry bean for irrigation systems (non-irrigation, drip-irrigation) was found to range from 0.53 to 0.63 and 0.54 to 0.64, respectively.

Table 2. Physical properties of dry bean depending upon non-irrigation and drip-irrigation conditions.

Properties	Non-irrigation				Drip-irrigation			
	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD
ϕ (%)	56	53	63	0.18	56	54	64	0.01
S (mm^2)	223.18	218.55	224.66	4.10	236.99	231.79	240.94	4.70
V (mm^3)	200.62	194.65	204.73	5.29	213.97	199.78	224.72	12.82
M_{1000} (g)	439.8	434.70	450.10	7.84	480.50	466.50	494.20	13.85
ρ_b (kg m^{-3})	804.69	801.12	808.56	3.73	820.00	815.23	818.77	5.49
ρ_t (kg m^{-3})	987.02	980.45	995.41	7.65	1164.44	1000.55	1025.43	12.53
P(%)	18.47	17.53	19.53	1.00	19.00	18.52	19.45	0.46

SD: Standard deviation.

The sphericity values given by drip-irrigation achivied higher values compared with the one by non-irrigation. Differences between the values were not statistically significant at $p > 0.05$ (Table 3). Similar results have been reported by Olajide and Ade-Omowaye (1999). for locust bean seed, Asoegwu et al. (2006) for African oil bean seed and Cetin (2007) for barbunia bean. Sphericity is an important parameter used in fluid flow and heat and mass transfer calculations (SAHIN; SUMNU, 2006).

Table 3. Results of the statistical analysis of physical properties in the dry bean according to the irrigation regimes.

Parametres	Between both irrigation regimes	
	t	Sig.
ϕ	-0.661	0.510^{ns}
S	5.853	0.0005^{***}
V	5.816	0.0002^{***}
M_{1000}	4.100	0.015^{*}
ρ_b	4.533	0.011^{*}
ρ_t	6.518	0.003^{**}
P	-6.601	0.003^{**}

*Significant at 0.05 level ** Significant at 0.01 level *** Significant at 0.001 level ^{ns} Non-significant.

As seen from the Table 2 according to Equation 2, the surface area of dry bean for non-irrigation and drip-irrigation between 218.55-224.66 mm^2 and 231.79-240.94 mm^2 were determined. It was determined that surface area of dry beans harvested from irrigated plots was higher than in the dry beans harvested from non-irrigation plots, because both grain moisture content of dry beans harvested from irrigated plots were higher and has better quality than in the dry beans harvested from non-irrigation plots. Similar trends have been reported by Asoegwu et al. (2006) for African oil bean seed. Differences between both irrigation systems were statistically significant at $p < 0.001$ (Table 3). Surface area is important in all applications where the process is surface dependent. Examples of such applications are mass and heat transfer, flow through packed beds, or fluidization. In food process engineering, combined heat and mass transfer is critical in quality control of many materials where moisture has to be removed to the lowest possible level, but the use of excessive heat may impair sensory attributes (BARBOSA-C´ANOVAS et al., 2005). Abrasiveness and flowability of granular materials is their ability to damage surfaces of equipment with which they are in contact as a result of movement over the surfaces. The degree of abrasiveness and classification of flowability is related to the hardness, shape and size of the grains (MOLENDA; HORABIK, 2005). In this context, the sphericity and surface area of agro-granular materials comes to the fore. The sphericity increases, porosity between the grains decreases and the grains are better compressed. Thus, less energy is consumed for the compression process.

The volume (V) of dry bean under non-irrigation and drip-irrigation ranged from 194.65 to 204.73 mm^3 and 199.78 to 224.72 mm^3 respectively (Table 2). It was determined that volume of dry beans harvested from irrigated plots was higher than in the dry beans harvested from non-irrigation plots, because both moisture content of dry beans harvested from irrigated plots were higher and have higher dimensions (length, width and thickness) than that of the dry beans harvested from non-irrigation plots. Olajide and Ade-Omowaye (1999), also reported the same results for locust bean seed. In this context, differences between both irrigation systems were statistically significant at $p < 0.001$ (Table 3).

The M_{1000} of dry bean under non-irrigation and drip-irrigation were ranged from 434.70 to 450.10 g, and 446.50 to 494.20 g, respectively (Table 2). It was determined that M_{1000} of dry beans harvested from irrigated plots was higher than in the dry beans harvested from non-irrigation plots, because both grain moisture content of dry beans harvested from irrigated plots were higher and have a heavier mass than in the dry beans harvested from non-irrigation plots. A similar trend has been reported for guna seeds (AVIARA et al., 1999). The t test showed that between both irrigation systems significant differences were found, according to $p < 0.05$ (Table 3). This parameter is useful in determining the equivalent diameter which can be used in the theoretical estimation of dry bean volume and in cleaning using aerodynamic forces (TABAK; WOLL, 1998; KHOSHTAGHAZA; MEHDIZADEH, 2006; SOLOMON; ZEWDU, 2009).

The bulk density (ρ_b) of dry bean under non-irrigation and drip-irrigation were ranged from 801.12 to 808.56 kg m^{-3} and 815.23 to 818.77 kg m^{-3} respectively (Table 2). This was due to the fact that an linear increasing in mass owing due to moisture gain in the sample was higher than accompanying volumetric expansion of the bulk. Most of researchers reported linear increasing trends for faba, barbunia bean and African yam beans (ALTUNTAŞ; YILDIZ, 2007; CETIN, 2007; ASOIRO; ANI, 2011). Differences between both irrigation systems were statistically significant at $p < 0.05$ (Table 3). The reported that stress-strain behavior of granular material depends on the bulk density of the sample (MOLENDA; HORABIK, 2005). Dense samples dilate during shear test while loose samples decrease in volume. In dense samples shear stress attains a peak value, and with continuing shear displacement it drops back to a lower ultimate value and remains at that constant level during further shear. In the loose state most granular materials tend to decrease in volume when subjected to shear under constant normal load. Measurement of bulk density is of fundamental use by the industry to adjust storage, processing, packaging and distribution conditions. Chang et al. (1983) reported that distributed filling of silo increases the density of granular material from 5.1 to 9.2% as compared to filling from centrally located spout of conveyor. Stephens and Foster (1976) observed increases in density of the order of 3 to 5% above the bulk density values in condensed filling from spout of a conveyor, and 7% in the case of distributed filling.

For dry bean, depending upon non-irrigation and drip-irrigation conditions the true density (ρ_t) ranges from 980.45 to 995.41 kg m^{-3} and 1000.55 to 1025.43 kg m^{-3}, respectively (Table 2). The increase in true density with increase in moisture content of grain with irrigation might be attributed to the relatively lower true volume as compared to the corresponding mass of dry bean attained due to adsorption of water Pradhan et al. (2009). The same results for grainy products were given by Kibar and Öztürk (2008) and Pradhan et al. (2009). Differences between both irrigation systems were statistically significant at $p < 0.01$ (Table 3).

Porosity (P) was evaluated using mean values of bulk density and true density in Equation 6. The variation of porosity for non-irrigation and drip-irrigation conditions was shown in Table 2. Since the porosity depends on the bulk density as well as densities, the magnitude of variation in porosity depends on these factors only. The reason of low porosity is little of difference between the bulk density and true density of dry beans. In addition, low porosity may be related to the nutritional composition of the product. The same results for grainy products were given by Kibar and Öztürk (2008) and Unal et al. (2009). Differences between both irrigation systems were statistically significant at $p < 0.001$ (Table 3). Porosity is an important physical property characterizing the texture and the quality of dry and intermediate moisture foods. Porosity data is required in modelling and design of various heat and mass transfer processes such as drying, frying, baking, heating, cooling, and extrusion (SAHIN; SUMNU, 2006).

The experimental results for the angle of internal friction (φ) with respect to non-irrigation and drip-irrigation was shown in Table 4.

Table 4. Mechanical properties of dry bean depending upon non-irrigation and drip-irrigation conditions.

Properties	Non-irrigation				Drip-irrigation			
	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD
φ (degree)	21.60	20.70	22.40	0.85	25.60	24.50	27.20	1.40
μ_s								
Wood	0.354	0.346	0.370	0.014	0.430	0.418	0.448	0.016
Galvanized steel	0.303	0.292	0.320	0.015	0.331	0.315	0.342	0.014
Concrete (C30)	0.466	0.456	0.482	0.014	0.588	0.566	0.615	0.025
υ	0.39	0.38	0.39	0.05	0.36	0.35	0.37	0.01
k								
k_K	0.63	0.62	0.65	0.13	0.57	0.54	0.59	0.25
k_L	0.58	0.56	0.58	0.16	0.51	0.49	0.53	0.22
k_E	0.69	0.68	0.71	0.15	0.62	0.60	0.64	0.24

SD: Standard deviation.

The angle of internal friction of dry bean under non-irrigation and drip-irrigation were from 20.70° to 22.40° and 24.50° to 27.20°, respectively. This increasing trend of angle of internal friction with moisture content in drip-irrigation occurs because surface layer of moisture surrounding the particle hold the aggregate of kernel together by the surface tension. Differences between both irrigation systems were statistically significant at $p < 0.01$ (Table 5).

Table 5. Results of the statistical analysis of mechanical properties in the dry bean according to the irrigation regimes.

Parametres	Between both irrigation regimes	
	t	Sig.
φ	4.855	0.008**
μ_s		
Wood	7.200	0.002**
Galvanized steel	2.962	0.041*
Concrete (C30)	8.281	0.00***
υ	-4.000	0.016*
k		
k_K	-4.118	0.015*
k_L	-4.588	0.010**
k_E	-5.277	0.006**

*Significant at 0.05 level **Significant at 0.01 level ***Significant at 0.001 level.

Researches also found in their study that the angle of internal friction increased linearly with increase of moisture content (MOLENDA et al., 1998; MOYA et al., 2002). The angle of internal friction and the angle of friction on the wall material increase with an increase in the moisture content of grain, while the bulk density decreases or increases depending on the pressure level. The angle of friction at the interface of grain and the wall material depends strongly on the roughness of the wall surface. All those three properties of bulk of grain influence the pressure ratio. Consequently, the angle of internal friction is of paramount importance in designing hoper openings, side wall slopes of storage bins and design of wall pressures in storage structures (MOLENDA; HORABIK, 1998).

The static coefficient of friction for dry bean was determined against surfaces of wood, galvanized steel and concrete surfaces. The experimental results related to the static coefficient of friction were given in Table 4. As seen from the Table 4 the value of the static coefficient of friction for non-irrigation conditions was ranged from 0.346 to 0.370 on wood, 0.292 to 0.320 on galvanized steel and 0.456-0.482 on concrete surface. The value of the static coefficient of friction for drip-irrigation conditions was ranged from 0.418 to 0.448 on wood, 0.315 to 0.342 on galvanized steel and 0.566 to 0.615 on concrete surface. The relationships between these coefficients against various surfaces and irrigation systems of dry bean were shown in Table 5. The between both irrigation systems with each of surface were found to be significantly different (Table 5). The coefficient of friction of granular materials of plant origin depends on numerous factors, among which the following are regarded as the most important: moisture content, normal pressure, sliding velocity, surface state and ambient conditions. According to some authors, increase in moisture content caused a decrease in the resulting coefficient of friction, from the presence of liquid water in the contact area (LAWTON, 1980; MOLENDA; HORABIK, 1998). The static coefficient of friction is important for designing of storage bins, hoppers, pneumatic conveying system, screw conveyors, forage harvesters, threshers, etc. (SAHAY; SINGH, 1996; PRADHAN et al., 2008).

The Poisson ratio of dry bean depending upon non-irrigation and drip-irrigation were between 0.38 to 0.39, and 0.35 to 0.37, respectively (Table 4). Poisson ratio of African nutmeg was researched at different moisture content in the range of 8.0-28.7%. In their studies it was found that the Poisson ratio decreased linearly with the increase of moisture content (BURUBAI et al., 2008). Differences between both irrigation systems were statistically significant at $p < 0.05$ (Table 5). Poisson ratio is necessary in design with finite element analysis of wall pressures in storage structures.

The pressure ratio is one of the three most important physical properties of bulk solids, commonly used for calculation of pressure in a silo. Almost all design codes use a Janssen-type pressure distribution to predict silo pressures (WILMS, 1991; MOLENDA; HORABIK, 2005). The variation of pressure ratios for non-irrigation and drip-irrigation conditions was shown in Table 4. Today they are used in calculation of the wall pressures equation proposed by Eurocode 1 (2003). Here the comparison is made between the other methods with Eurocode 1 (2003). The highest value for pressure ratio was determined in k_E (0.71) at non-irrigation and the lowest value in k_L (0.49) at drip-irrigation. Similar results have been reported for some cereal grains (HORABIK; RUSINEK, 2002).

Differences between both irrigation systems with each of the methods (k_K, k_L and k_E) were statistically significant (Table 5). Pressure ratio is necessary in the design of wall pressures (standards such as 30, 55-57) in storage structures. Because postharvest moisture content has higher (7.2%) at products obtained from drip-irrigated plots, moisture content brings about more pressure increases in the design of storage structures. These results were found for different products in the studies related to pressure equations developed by Janssen, Rankine, Reimbert and Eurocode1 (ÖZTÜRK; KIBAR, 2008; ÖZTÜRK et al., 2008). The effect of engineering properties such as bulk density, angle of internal friction, static coefficient of friction, pressure ratio and Poisson ratio in this increase are very important.

At the end of PCA, factor coefficients of identifying qualities were evaluated and the attributes scoring a coefficient value higher than 0.7 in the first three PCA were determined. The plot of the physical and mechanical properties on the first two PCs obtained from analysis of irrigation conditions were presented in Figure 5.

The first two principal components (PCs) accounted for 100% of the total variability among the physical and mechanical properties for drip-irrigation. The first principal component (PC1), which is the most important component, explained 70.162% of the total variability. The second principal component (PC2) had 29.838% of the total variation. PC1 explained 73.249%, while PC2 explained 26.751% of the total variability.

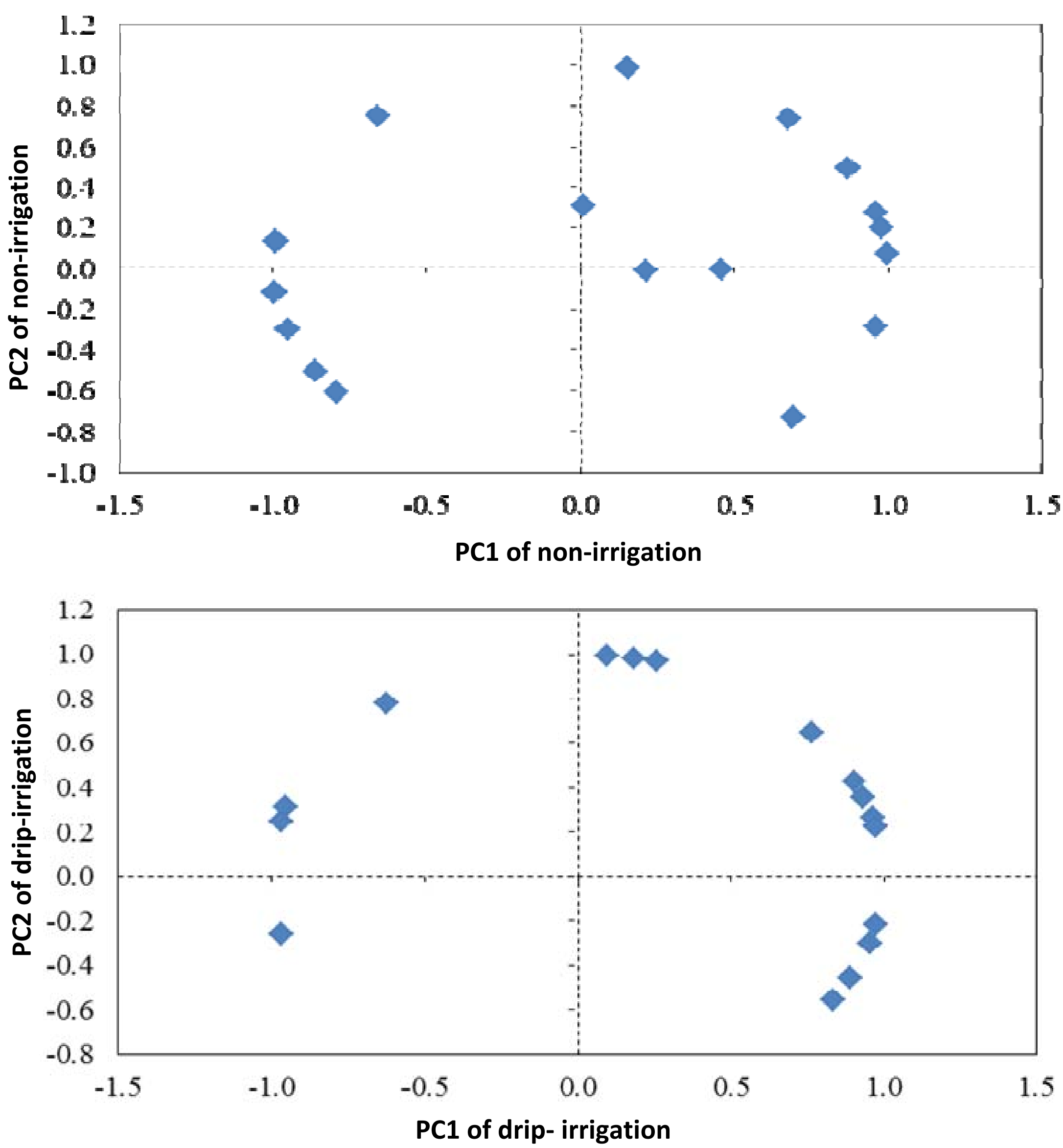

Figure 5. First (PC1) versus second (PC2) principal component according to the method of irrigation.

Conclusion

1. The surface area and the volume of dry beans from irrigated plots are higher than non-irrigation plots.
2. The bulk and true density values in drip-irrigation conditions are higher than non-irrigation conditions.
3. The angle of internal friction is importance in designing hoper openings and wall pressures in storage structures. The significant differences between both irrigation systems were observed.
4. The static coefficient of friction values on three test surfaces in drip-irrigation conditions are higher than non-irrigation conditions.
5. Poisson ratio is necessary in the design with finite element analysis of wall pressures in storage structures. The differences between both irrigation systems were statistically significant.
6. The mean highest value for pressure ratio was determined in k_E (0.68) at non-irrigation and the mean lowest value in k_L (0.48) at drip-irrigation.

Nomenclature

L	Length, mm
W	Witdh, mm
T	Thickness, mm
ϕ	Sphericty, %
D_g	Geometric average diameter, mm
D_a	Arithmetic average diameter, mm
V	Volume, mm^3
S	Surface area,mm^2
ρ_b	Bulk density, kg m^{-3}
G_1	Free weight of bulk density bucket, kg
G_2	Weight of bulk density bucket with rice, kg
V_b	Volume of bulk density bucket, m^3
ρ_t	True density, kg m^{-3}
m_s	Weight of liquid, kg
m_w	Weight of air dry sample, kg
V_s	Volume of liquid, m^3
V_w	Volume of sample, m^3
P	Porosity, %
φ	Angle of internal friction, degrees
σ	Normal stress, kPa
N	Load applied on the sample, kg
A	Cellular area, cm^2
τ	Shear stress, pressure on cutting edge, kPa
T_s	Shear force, load on cutting edge, kg
C	Coefficient of cohesion
μ_s	Static coefficient of friction
F_s	Force starting movement at surface interface, kg m^{-2}
W_s	Force applied to surface interface, kg m^{-2}
ν	Poisson ratio
k_K	Pressure ratio according to Kézdi
k_L	Pressure ratio according to Lohnes
k_E	Pressure ratio according to Eurocode 1

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