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Effect of Moisture Content on the Physical and Textural Properties of Fenugreek Seed

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ABSTRACT

The fenugreek seed (*Trigonella foenum-graecum*) exhibits marked unpredictability in major engineering properties (physical properties) owing to its varying moisture content (mc). Hence, fenugreek seeds were evaluated for changes in various physical properties viz. seed geometry (length, width, thickness and equivalent diameter), sphericity, roundness, specific surface area, surface area, seed volume, 1000-seed-mass, densities (true and bulk), porosity, angle of repose, specific gravity, coefficient of static friction on different surfaces, terminal velocity, aspect ratio as a function of mc. Some of the textural properties such as hardness, fracturability, cohesiveness and gumminess were also measured. The mc of the seeds was varied from 7.6-20.0% on dry weight basis (db). The physical dimensions i.e., seed length, width, thickness, equivalent diameter, sphericity, volume, seed roundness, specific gravity, surface area, true density, porosity, 1000 seed mass, angle of repose increased with increase in mc, while reverse was true for specific surface area and aspect ratio. Positive linear relationship was observed between terminal velocity and mc. Textural characteristics viz., seed hardness, fracturability and gumminess showed a declining trend with increasing mc, whereas cohesiveness increased with increase in the mc.

Keywords: cohesiveness, density, gumminess, hardness, porosity, roundness, terminal velocity

INTRODUCTION

Fenugreek (*Trigonella foenum-graecum*) is a shrub belonging to the family *Fabaceae*. It is popularly known as *Greek hay*. It is mainly grown worldwide in semi-arid region. Currently, India is the global leader in fenugreek production. Other major fenugreek-producing countries include Pakistan, Argentina, Egypt, Spain, Turkey, Morocco and China. In India, Rajasthan, Gujarat, Uttaranchal, Uttar Pradesh, Maharashtra, Haryana, and Punjab are the chief fenugreek-producing states. Rajasthan accounts for maximum production, contributing to more than 80% of the total fenugreek produced in India (Brar *et al.* 2012). In 2005-06, Rajasthan produced 29173 tons of fenugreek from 27292 ha of cultivated land (Bhatt 2008-09).

Fenugreek is used in various culinary preparations, with its leaf consumed as a herb (aromatic leaf) and its seed as a spice. Its seeds are cubical in shape ranging from yellow to amber in colour. The seeds are mainly employed in pastes, pickles and curry powder preparations. Besides, seeds are used as a conditioner and traditional remedy for hair fall when mixed with yogurt. In Egypt, seeds are used for tea preparation by boiling and then by sweetening, and served as a popular winter drink in shops. In the United States of America (USA), fenugreek is utilized as a flavouring agent in maple syrup (Abdel-Nabey and Damir 1990; Anon. 2011). Apart from these uses, fenugreek seeds are often used to increase milk supply during lactation since they have galactagogue content (Anon. 2011).

Fenugreek is a rich source of non-starch polysaccharide galactomannan. It also contains saponins such as diosgenin, yamogenin, gitogenin, tigonin, and neoteogens (Chatterjee *et al.* 2010). Other major bioactives present in fenugreek include mucilages, volatile oils, alkaloids (choline and trigonelline), etc. (Mebazaa *et al.* 2009). Its seeds are also rich in protein, minerals and vitamins. Proximate analyses have revealed that fenugreek seeds contain about 13.7 g moistures, 26.2 g proteins, 5.8 g fats, 3.0 g minerals, 7.2 g fibres and 44.1 g carbohydrates per 100 g of seeds (Gopalan *et al.* 1987; Goswami and Madhava 2001). In addition, 160 mg calcium, 370 mg phosphorus, 14.1 mg iron, 0.34 mg thiamine, 0.29 mg riboflavin, 96 µg carotene and 1.1 mg niacin were reported per 100 g of seeds (Gopalan *et al.* 1987). The energy value was calculated to be 333 Kcal per 100 g of seeds (Gopalan *et al.* 1987; Nasri and Tinay 2007).

Fig. 1 Fenugreek (AM-2) seed sample used for the study.

The design of processing equipments for handling, processing (Ogunjimi *et al.* 2002), aeration, storing, cleaning, grading, dehydrating (Kingsly *et al.* 2006), drying, harvesting, classification (Mohsenin 1986; Junior *et al.* 2007), packing (Karababa 2006) and filling of grains requires the fundamental knowledge of engineering properties of the material. Size, shape and density are important for separation of seed from undesirable foreign materials on oscillating chafers (Zewdu and Solomon 2007). The bulk density and porosity are useful properties in the development of aeration and drying systems as these properties affect the resistance to air-flow of stored mass (Coskuner and Karababa 2007). Angle of repose is very important in designing equipment for mass flow and storage structures (Singh and Goswami 1996). On the other hand, porosity and specific gravity of the agricultural products are useful for studying

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the heat transfer, mass transfer and air diffusion through the bulk seed and grain material (Correa *et al.* 2007). Friction between seed bulk and equipment surface has an influence on the flow of material on oscillating conveyors, in separation on oscillating sieves, in unloading and loading operations, grain movement on wall and on silo surfaces (Mohsenin 1986; Suthar and Das 1997). Terminal velocity in food processing and post-harvest operations is needed for designing air conveying systems and for designing and fabricating equipment and devices for separation (Gupta *et al.* 2007; Junior *et al.* 2007). In addition, physical properties are input parameters in heat transfer problems during heat processing of food material such as fenugreek seeds (Mohsenin 1986; Karababa 2006). Hardness and fracturability affects the palatability as well as sensory quality of value added products (Kingsly *et al.* 2006) cohesiveness, and gumminess are important engineering properties that must be known in order to design the equipment for grinding and dehydration of fenugreek as well as to assess the textural changes during handling and processing. Previous studies mentioned only a few physical properties of this commodity but there were no studies on the determination of seed geometry such as length, width, thickness and equivalent diameter; specific surface area, specific gravity, terminal velocity, aspect ratio, roundness, specific gravity; textural properties such as hardness, fracturability, cohesiveness and gumminess. On the other hand, this present study aims at evaluating all major engineering properties of *AM-2* variety of fenugreek seed. The objective of this study was to determine the major physical properties of fenugreek seeds as a function of varying mc such as seed geometry, seed equivalent diameter, sphericity, specific gravity, specific surface area, surface area, seed volume, 1000-seed mass, bulk density, true density, porosity, coefficient of static friction, aspect ratio, angle of repose, terminal velocity, hardness, fracturability, cohesiveness, gumminess.

MATERIALS AND METHODS

Sample preparation

Fenugreek was selected and procured from National Research Centre for Seed Spices (NRCSS) Ajmer, Rajasthan, India. The sample was selected from this place because Rajasthan is a major fenugreek producing state in India. The "*AM-2"* variety of fenugreek seed was selected for this study (**Fig. 1**). Samples were first sieved to remove dust, sand and smaller dirt particles and then cleaned manually to separate the stones, damaged seeds, foreign unwanted matter and immature seeds from the main sample of fenugreek seeds.

The initial moisture content (mc) of the fenugreek seed was determined by oven drying method at 72°C for 24 h until a constant weight was obtained (Singh and Goswami 1996; Pomeranz and Meloan 1996; Ranganna 1995). The mc dry basis (db) of the samples was maintained at 7.6, 12, 16 and 20% level. 16 and 20% mc levels were attained by adding a calculated amount of distilled water using following Eq. (1.1) (Ranganna 1995; Sahay and Singh 2001; Kingsly *et al.* 2006) whereas 7.6% level was obtained by controlled heating in vacuum oven. Observations were noted down at 15 min intervals. The normal mc of the fenugreek seed was 12%.

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \quad (1.1)$$

The prepared samples of fenugreek seeds were packed in polyethylene bags and stored in a refrigerator for one week to allow the water to uniformly distribute among the bulk seed (Singh and Goswami 1996; Kingsly *et al.* 2006). The experiments were replicated five times, and average values were reported.

Determination of physical properties

1. Seed shape, size and thickness

Data on dimensions of the fenugreek seed are required for the cleaning, separation, grading, sieving and carrying the seed over conveying belt, etc. The shape of fenugreek seed is almost cubical. Hundred seeds were selected randomly and their length (L), width (W) and thickness (T) were measured using the Grain measure (Grain Shape Tester, MK 100, Japan) having an accuracy of 0.01 mm at each moisture level. L, W and T are expressed in mm.

2. Equivalent diameter

Equivalent diameter is used as a general term for irregular shaped objects such as oblong, spherical and conical. Equivalent diameter gives us an idea about the geometry of the object. It is the most commonly used terminology for irregular shaped objects such as cumin, rice grain (Goswami and Madhava 2001) cardamom and black pepper seed. Equivalent diameter is denoted by 'D_g' and was calculated by using Eq. (2.1) (Mohsenin 1986).

$$D_g = [LWT]^{1/3} \quad (2.1)$$

3. Sphericity

Sphericity is denoted by 'Ψ'. It is the ratio of surface area of the sphere that has volume equal to the total volume of solid to the total surface area of the solid (Dutta *et al.* 1988; Lee *et al.* 2011). In other words, it is a measure of the degree by which an object is spherical in shape or it is the measure of compactness of an object. In this study, it was calculated by using the following relationship (Eq. 2.2) given by Mohsenin (1986).

$$\Psi = ([LWT]^{1/3})/L \quad (2.2)$$

4. Roundness

Roundness is the property of a surface that is curved or object which is round in shape. Here, in this investigation roundness is denoted by 'ω'. A zero value of roundness means that the object is having totally flat surface without any curves and a roundness value of one shows that the object is perfectly round like a sphere. When expressed as a fraction, it varies from 0 to 1; in per cent it varies from 0 to 100%. It was calculated by using the following relation Eq. (2.3) (Dutta *et al.* 1988).

$$\omega = \frac{A_p}{A_c} \quad (2.3)$$

where A_c is the area of the smallest circumscribing circle (mm^2), A_p is the largest projected area (mm^2).

5. Specific gravity

Specific gravity (SG) is the ratio of true density of fenugreek seed to the density of water, as density of water has been taken as the density of reference substance (Eq. 2.4), temperature (25°C) and pressure (101.32 kPa) of reference substance. If a substance has specific gravity less than one it means that the object will easily float on the surface of reference substance if the reference material is liquid and if the SG value is more than one it means the substance will easily sink in the reference material if reference substance is liquid.

$$SG = \frac{\rho_t}{\rho_w} \quad (2.4)$$

6. Specific surface area

The surface area per unit mass of the material is called as specific surface area. It is represented by 'S_{sa}' and is expressed in $mm^2\ g^{-1}$ or $m^2\ kg^{-1}$. A powder has higher specific surface area compared to whole solid block of material. In food processing such as in case of functional, nutraceutical and fortified food materials greater specific surface area helps in easy absorption and greater bioavailability of material in the human body. Specific surface area of fenugreek seed can be expressed by the following relationship (Eq. 2.5) (Geankoplis 1999; Das 2005).

$$S_{sa} = [6 / (\rho_t \psi D_g)] \quad (2.5)$$

7. Surface area

Surface area of an object is the sum total of all the surfaces of different shapes that covers an object; a cubical body has six surfaces and its total surface area is six times the area of one side. Here, it is represented by 'S_a' and is expressed in mm^2. The surface area of fenugreek seed was calculated by using following Eq. (2.6) (McCabe *et al.* 1993).

$$S_a = \pi D_g^{2} \tag{2.6}$$

8. Seed volume

Seed volume is the total space occupied by given unit mass of the fenugreek seeds. It is denoted as '*V'* and is expressed in mm^3 (cubic mm). Volume can be calculated from Eq. (2.7) and (2.8) as it was used by other researchers for studies on popcorn kernel (Karababa 2006):

$$V = \frac{3.14L^2C^2}{6(2L-C)} \tag{2.7}$$

$$C = (W\,T)^{0.5} \tag{2.8}$$

9. 1000-seed mass

To give best representation of weight of representative seed sample and its variation with varying mc; 1000 seeds were selected randomly and their mass was measured using an electronic balance (DC 170, Ohaus Corp., Teraoka Seiko Ltd., USA) having accuracy up to 0.001 g and the same was repeated for five times and average mass of the samples are reported. The thousand seed mass is denoted by 'M_{1000}' and is expressed in g (Altuntas *et al.* 2005).

10. Bulk density, true density and porosity

Bulk density is defined as mass of particulate matter to the total space or volume it occupies. It is denoted by 'ρ_b' and is expressed in kilogram per cubic metre (kg m^{-3}). The average bulk density of fenugreek seeds at four different mc levels was determined with the Ohaus apparatus (Ohaus Scale Corporation, Union NJ, USA) (Altuntas *et al.* 2005). True density is the ratio of mass of particulate matter to the total space or volume occupied by that matter excluding void spaces in the particulate matter. True density is denoted by the symbol 'ρ_t' and expressed in kilogram per cubic metre (kg m^{-3}). True density at various mc levels was determined by adopting liquid displacement method where toluene was used as liquid. Pre-defined mass of fenugreek seeds was taken and immersed in toluene and the volume displaced was noted (Pomeranz and Meloan 1996). Porosity is the degree or measure of the void or empty space of the volume within the substance over the total volume occupied by the substance. It is shown by symbol 'Θ' and expressed in percent. Generally, it varies from 0 to 1 (in fraction) and 0 to 100 (in percent). Porosity was calculated by the standard relationship of true and bulk density as follows (Mohsenin 1986).

$$\Theta = (1-[\rho_b/\rho_t]) \tag{2.9}$$

11. Angle of repose

When sliding or slippery particulate materials are kept on a flat surface, they form a hip and in this condition they form an angle with the horizontal and slanting plane of the material. It is shown by 'θ' symbol and is expressed in degrees .It varies from 0 to 90^o. Angle of repose was determined using a ply box of 255 mm × 255 mm × 260 mm, provided with a removable front panel. The box was filled with seed sample, front panel was quickly removed so that seeds could flow and assume a natural slope (Singh and Goswami 1996). The angle of repose was calculated from the measurement of depth of free surface of the sample at the centre and base diameter of the heap formed outside the container and with the help of following relationship (Mohsenin 1986).

$$\theta = tan^{-1}\,(h/r) \tag{2.10}$$

where, *h* is the height of the hip and *r* is the radius formed by the hip.

12. Coefficient of static friction

It simply indicates the force of friction between two bodies under stationary condition. It is represented by 'μ' and it does not have any dimensions as it is simply a ratio of two quantities and is shown in fractional values. It varies from 0 to 1. Static coefficient of friction of fenugreek seed was determined over five different surfaces those are made up of plywood, aluminium sheet, mild steel (MS) sheet, galvanised iron sheet and paper board (Altuntas *et al.* 2005). A polyvinyl-chloride cylindrical pipe of 50 mm diameter and 50 mm height was kept on adjustable tilting plate, faced with a surface, and filled with the seed.

$$\mu = tan\,\varphi \tag{2.11}$$

μ is the static coefficient of friction (dimension less quantity) and φ is the angle formed between horizontal surface and the sliding plane in degrees (^{o}).

13. Aspect ratio

In general, aspect ratio (AR) is the ratio of width to the height of the object or the ratio of longer dimension to the smaller dimensions. We have expressed it as the ratio of largest physical diameter to the smallest physical diameter or axis of the seed. Higher value of the aspect ratio means that object is not of regular shape. It is given by the following formula as:

$$AR = (\text{Largest seed diameter}/\text{Smallest seed diameter}) \tag{2.12}$$

AR = ratio of largest seed diameter with common reference to the smallest seed diameter with common reference.

14. Terminal velocity

The terminal velocities of fenugreek seeds at each moisture level were determined using an air column. This velocity is denoted by 'V_t' symbol and expressed in m s^{-1}. A sample was dropped into the air stream from the top of the air column, opposite to which air was blown to suspend the seed in the air stream. The air velocity in an air column at the moment and location when the seed reached a suspension condition was measured by an electronic anemometer (Almemo FVA915 S120, Ahlborn, Germany) connected with a multi meter (Almemo 2290–2, Ahlborn, Germany) having a least count of 0.1 m s^{-1} [Gezer *et al.* 2002; Junior *et al.* 2007).

Determination of textural properties

Textural properties are major components to be considered and analysed to assess the hardness, surface smoothness, etc. for judging acceptability or rejection of spice/food material (Bourne 1978). The whole fenugreek seed is also used as a spice and other uses of food preparation and therefore its textural property should be known.

1. Fraturability

It is the ability of any material to be fractured or broken. When force is applied to test the hardness of the material, a point is obtained at which the material starts to fracture. This first fracture force is termed as factorability (Kahyaoglu and Kaya 2006).

2. Hardness

It is the first fracture point on the plot of force-deformation curve during the first bite of compression where force falls off. Hardness is defined as the peak force during the first compression cycle under texture analyser. It is expressed in g or kg or N. reference?

3. Cohesiveness

Cohesiveness is how well the product withstands a second deformation relative to how it behaved under the first deformation. It is measured as the area of work during the second compression divided by the area of work force during the first compression. The following relationship was used to calculate the cohesiveness (Bourne 1978; Kahyaoglu and Kaya 2006).

$$\text{Cohesiveness} = \text{Area}_2/\text{Area}_1 \quad (2.13)$$

Area_1 and Area_2 are shown in **Fig. 2** as 1-2 and 2-3, respectively.

In the present investigation, a Stable Micro-system Texture Analyser (TA XT2i, Mlch city, USA) was used to obtain the relation between the force applied and hardness as a function of time and the force against distance at various mc levels ranging from 7.6 to 20%. These values were used to calculate various properties like fracturability, hardness, cohesiveness and gumminess.

4. Gumminess

Gumminess is a characteristic of solid materials. It is expressed by 'G_m'. To calculate the gumminess, the following relationship was used (Bourne 1978; Kahyaoglu and Kaya 2006).

$$G_m = \text{Hardness x Cohesiveness} = \text{Hardness} \times (\text{Length}_2 / \text{Length}_1) \quad (2.14)$$

where; Length_1 and Length_2 as shown in **Fig. 2**, are length from starting point to the peak line in the first and the second bite respectively on X-axis of the graph of seed compression.

RESULTS AND DISCUSSION

Seed size, shape and thickness

The average length, width, and thickness of fenugreek seed was found to vary between 4.05 to 4.12 mm, 2.92 to 3.08 mm, and 1.97 to 2.12 mm respectively at mc ranging from 7.6 to 20% and it is graphically represented as shown in **Fig. 3**.

$$L = 4.004 + 0.005M \ (R^2 = 0.993) \quad (3.1)$$

$$W = 2.807 + 0.012M(R^2 = 0.844) \quad (3.2)$$

$$T = 1.863 + 0.011M \ (R^2 = 0.957) \quad (3.3)$$

Eq. 3.1, 3.2 and 3.3 shows the regression coefficients and coefficients of determination of major, intermediate and minor axis of the fenugreek seed. As shown in **Fig. 3**, all the dimensions are found to increase with increase in mc and similar findings are also reported by earlier researchers such as Gezer *et al.* (2002) (apricot kernel), Al-Mahasneh and Rababah (2007) (green wheat).

Geometrical or equivalent seed diameter

The effect of rise in mc of fenugreek seed has been shown in **Fig. 3**. Diameter of seeds at various mc levels varied from 2.85 to 2.99 mm as the mc was raised. Equivalent seed diameter and mc bears the relationship as given in Eq. (3.4).

$$D_g = 2.757 + 0.011M(R^2 = 0.994) \quad (3.4)$$

It can be shown from **Fig. 3** that as the mc increased the diameter of the seed also increased and similar trends for equivalent diameter have been reported by Zewdu and Solomon (2007), Kingsly *et al.* (2006), Sahoo and Srivastva (2002) for tef, oomegranate and okra seed, respectively.

Sphericity

Sphericity of fenugreek seed was calculated using Eq. (2.2) and data on L, W, T and D_g of the fenugreek seed was obtained. It was observed that the sphericity increased from

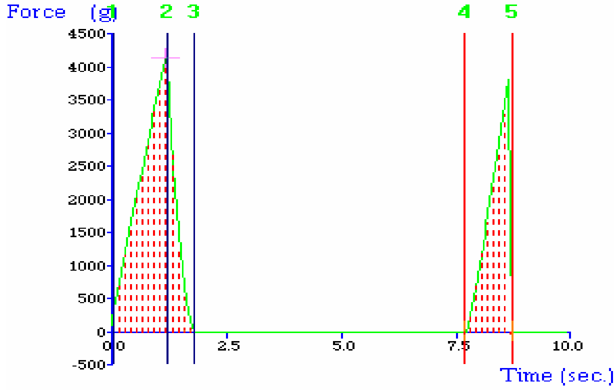

Fig. 2 The force deformation characteristics under compression of fenugreek seed as function of time.

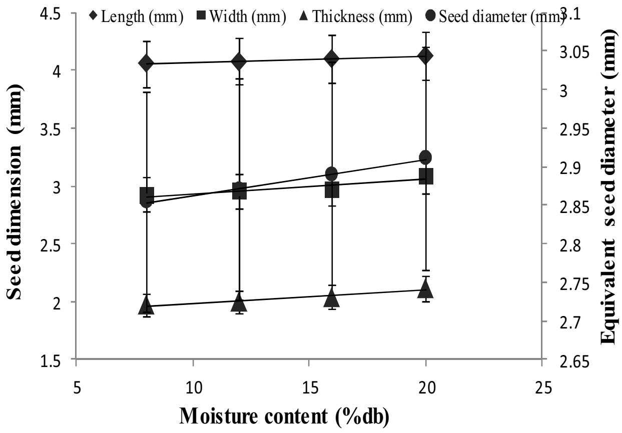

Fig. 3 Length, width, thickness and equivalent diameter of fenugreek seed.

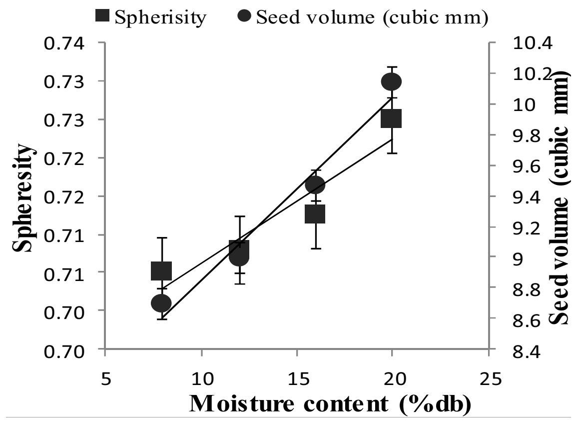

Fig. 4 Correlation between moisture content with sphericity and seed volume.

0.705 to 0.725 as mc increased as shown in **Fig. 4**.

A linear relationship between mc and sphericity can be represented as a regression Eq. (3.5) as shown below:

$$-\Psi = 0.716\text{-}0.002M \ (R^2\text{=}0.991) \quad (3.5)$$

A similar trend was obtained by Yalcin (2007a) for pea seed and black pepper. These results will help to have ideas of variation in shape characteristics of fenugreek having varying water content in it.

Roundness

Roundness varied linearly with increasing mc (**Fig. 5** and Eq. (3.6)). This is because of the fact that fenugreek seeds

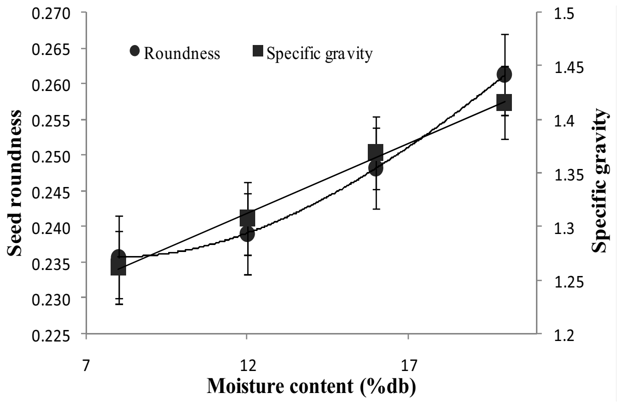

Fig. 5 Illustration of variation in roundness and specific gravity of fenugreek seed with varying moisture content.

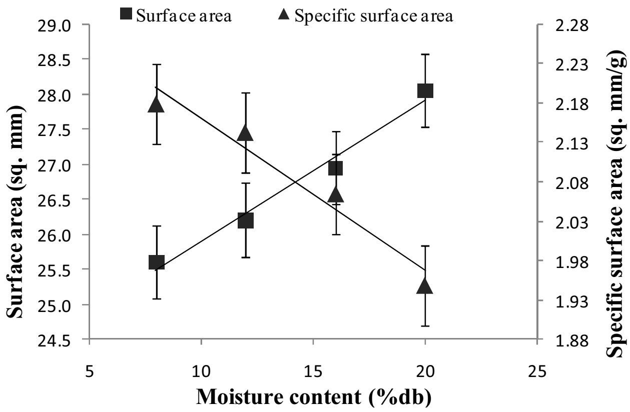

Fig. 6 The effect of varying moisture content on the surface area and specific surface area of fenugreek seed.

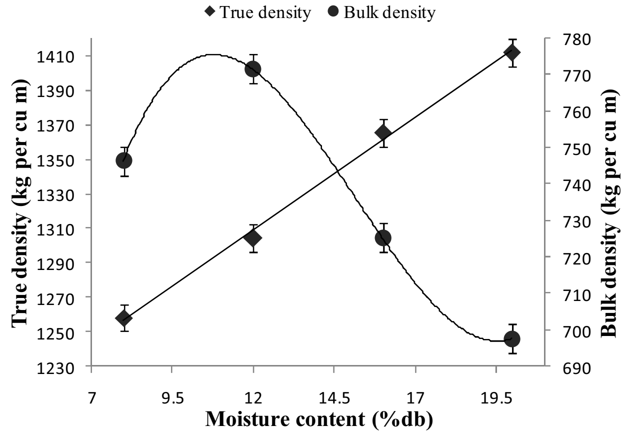

Fig. 7 Variation in bulk and true density with varying moisture content.

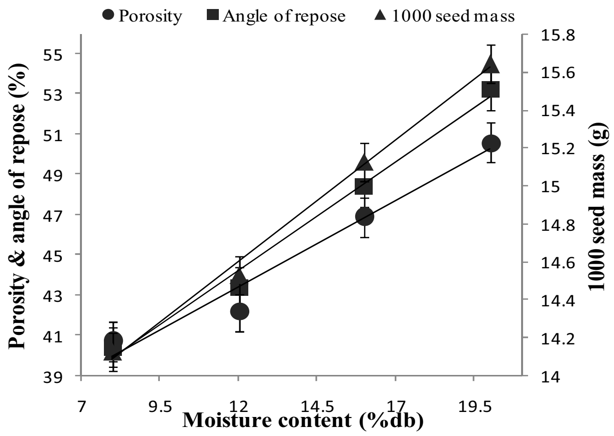

Fig. 8 Variation in 1000 seed mass, porosity and angle of repose with varying moisture content.

on absorption of moisture swell and become more round in physical shape.

$$\omega = 0.216 + 6.002M \ (R^2 = 0.938) \quad (3.6)$$

Specific gravity

Specific gravity increased continuously and sharply with increasing mc in the studied range of mc (**Fig. 5**) and a mathematical regression equation showing this relation is indicated below as Eq. (3.7).

$$SG = 1.155 + 0.013M \ (R^2 = 0.996) \quad (3.7)$$

The cause for increasing *SG* is that on increasing mc, ρ_t was increased continuously but reference ρ_w was constant at constant temperature (25°C) and pressure (101.32 kPa).

Seed volume

Seed volume was calculated using Eq. (2.7) and (2.8). **Fig. 4** shows the effect of mc on seed volume. Regression Eq. (3.8) represents the relationship between mc and seeds volume. It can be observed that seed volume increased with increasing mc. It is due to increased geometrical characteristics of the seed dimensions.

$$V = 8.643 – 0.039M + 0.005M^2 \quad (R^2 = 0.999) \ (3.8)$$

Similar trends of increasing seed volume with increased mc was reported by Altuntas and Yildiz (2007) (faba beans), Al-Mahasneh and Rababah (2007) (green wheat).

Specific surface area

Specific surface area of fenugreek seeds was calculated using Eq. 2.5. It was observed that as the mc increased from 7.6 to 20%, surface area decreased from 2.179 to 1.948 mm^2 as shown in **Fig. 6**.

Variation in specific surface area with mc of fenugreek seed can be represented by the following Eq. (3.9).

$$S_{sa} = 2.353 - 0.019M \ (R^2 = 0.950) \quad (3.9)$$

It can be concluded from **Fig. 6** that the specific surface area decreased as the mc increased. It is due to the increase in true density, equivalent diameter of seed and sphericity.

Surface area

Surface area was calculated using Eq. (2.6), and the graphical relationship between surface area and mc are shown in **Fig. 6**. The regression Eq. (3.10) describes the relationship between mc and surface area.

$$S_a = 25.24 - 0.017M + 0.007M^2 \quad (R^2 = 0.999) \ (3.10)$$

It can be depicted from **Fig. 6** that surface area increased as mc content was increased. This is due to the enlargement in seed diameter on increasing mc. Studies by Dursun and Dursun (2005) on caper seed; Saciliket *et al.* (2003) on hemp seed and Baryeh (2001) on bambara groundnuts show a similar trend of increasing surface area with increasing mc.

Thousand seed mass

The 1000-seed mass was observed to increase from 14.124 to 15.637 *g* as the mc was increased from 7.6 to 20% as shown in **Fig. 8**. A linear relationship between 1000-seed mass and mc can be represented by the following regression Eq. (3.11):

$$M_{1000} = 13.05 + 0.128M\ (R^2 = 0.994) \qquad (3.11)$$

The similar trend of rising of mass with raised mc for barbunia bean material was obtained by Cetin (2007).

Bulk density

Bulk density of the fenugreek seed material was found first increased from 746.4 to 771.6 kg m^{-3} then decreased to 697.6 kg m^{-3} as mc increased as is depicted in **Fig. 7**. A regression relationship between mc and bulk density can be represented by Eq. (3.12).

$$\rho_b = 122.6 + 148.2M - 10.65M^2 + 0.233M^3\ (R^2 = 1) \qquad (3.12)$$

A similar trend for cumin seed, pistachio nut and kernel was reported by Singh and Goswami (1996) and Kashaninejad *et al.* (2006), respectively.

True density (ρ_t)

An increase from 1258.4 kg m^{-3} to 1412 kg m^{-3} in true density of fenugreek seed was obtained as mc was increased as is graphically represented in **Fig. 7**.

Increasing trends of true density with increasing mc can be represented by the following regression Eq. (3.13).

$$\rho_t = 1152 + 13.05M\ (R^2 = 0.996) \qquad (3.13)$$

These results of increase in true density of seed with increasing mc are in line with the findings of true density of tef seed (Zewdu and Solomon 2007), cumin seed (Singh and Goswami 1996), vetch seed (Yalcin and Ozarslan 2004), and raw cashew nut (Balasubramanian 2001).

Porosity (ϵ)

Porosity was calculated by using the Eq. (2.9). The variation in porosity is shown in **Fig. 8**. The porosity increased from 40.7 to 50.6 on increasing mc within studied range.

The variation in porosity with respect to varying mc can be represented by the following polynomial regression Eq. (3.14)

$$\epsilon = 39.09 - 0.101M + 0.034M^2\ (R^2 = 0.986) \qquad (3.14)$$

Coskun *et al.* (2006) (sweet corn seed), Yalcin and Ozarslan (2004) (vetch seed), Yalcin (2007a) (cowpea seed) have reported an increasing nature of porosity with increasing mc which is similar in nature as depicted in **Fig. 8** for fenugreek seed. This is because of the greater increase in true density compared to bulk density.

Angle of repose

The results on angle of repose are shown in **Fig. 8**. It was reported that angle of repose linearly increased from 40.4 to 53.2° as the mc increased from 7.6 to 20%. The relationship between angle of repose and mc can be shown by the relationship given below as Eq. (3.15)

$$\theta = 31.16 + 1.085M\ (R^2 = 0.989) \qquad (3.15)$$

Similar results were reported by many researchers like Singh and Goswami (1996), Karbaba (2006), Zewdu and Solomon (2007) and Kingsly *et al.* (2006) for cumin, coriander, tef and pomegranate seed, respectively.

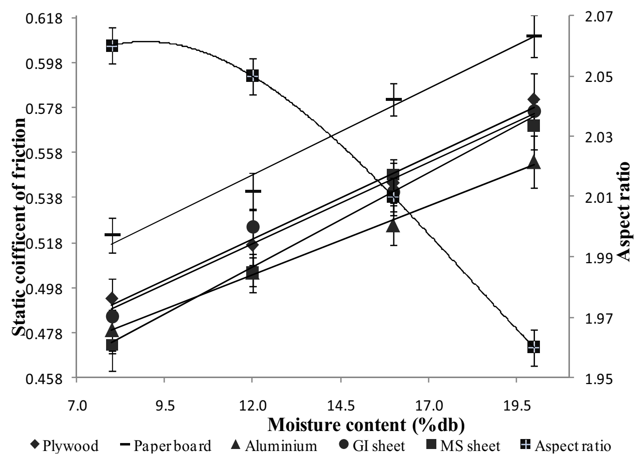

Fig. 9 Variation in static coefficient of friction with respect to moisture content.

Coefficient of static friction

The coefficient of static friction for fenugreek seeds was determined on five different surfaces as depicted in **Fig. 9**. For all five materials i.e., plywood, paper board, aluminium sheet, galvanized iron sheet and MS sheet, coefficient of static friction was observed to increase lowest for aluminium sheet and maximum for paper board.

$$\mu_{Paperboard} = 0.456 + 0.007MC\ (R^2 = 0.983) \qquad (3.16)$$

$$\mu_{Plywood} = 0.431 + 0.007MC\ (R^2 = 0.989) \qquad (3.17)$$

$$\mu_{Galvanized\_iron} = 0.430 + 0.007MC\ (R^2 = 0.975) \qquad (3.18)$$

$$\mu_{Mild\_steel\_sheet} = 0.406 + 0.008MC\ (R^2 = 0.986) \qquad (3.19)$$

$$\mu_{Aluminium\_sheet} = 0.429 + 0.006MC\ (R^2 = 0.997) \qquad (3.20)$$

Recent findings on barbunia bean seed (Cetin 2007), sugar beet seed (Dursun *et al.* 2007) and karingda seed (Suthar and Das 1996) shows similar trend of increasing static coefficient of friction with increasing mc. The main reason for the increase in these values is that as mc increased, surface roughness and friction between seed surfaces and material surfaces also increased (Altuntas *et al.* 2005).

Aspect ratio

As shown in the **Fig. 9**, it was found that *AR* decreased continuously and sharply as mc was increased and a mathematical linear relationship showing gradual decrease in AR with increasing mc is shown in Eq. (3.21).

$$AR = 2.139 - 0.008M\ (R^2 = 0.932) \qquad (3.21)$$

Terminal velocity

Eq. (3.22) represents relationship between terminal velocity and mc

$$V_t = 9.109 + 0.014M\ (R^2 = 0.969) \qquad (3.22)$$

It is revealed from **Fig. 10** that terminal velocity of fenugreek seed increased with increasing mc (it is because of increase in mass of an individual seed per unit frontal area presented to the air stream in the air column). Dursun *et al.* (2007), Baryeh (2001), Yalcin and Ozarslan (2004) and Calisir *et al.* (2005) have also reported an increase in terminal velocity with increasing mc for sugar beet seed, bambara groundnuts, vetch seed and okra seed, respectively.

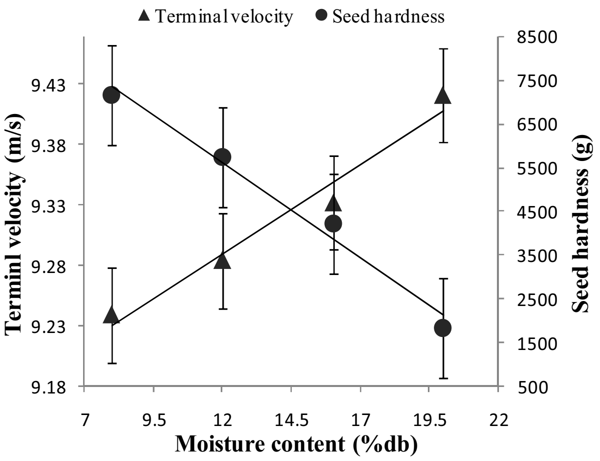

Fig. 10 Variation in terminal velocity and hardness with varying moisture content.

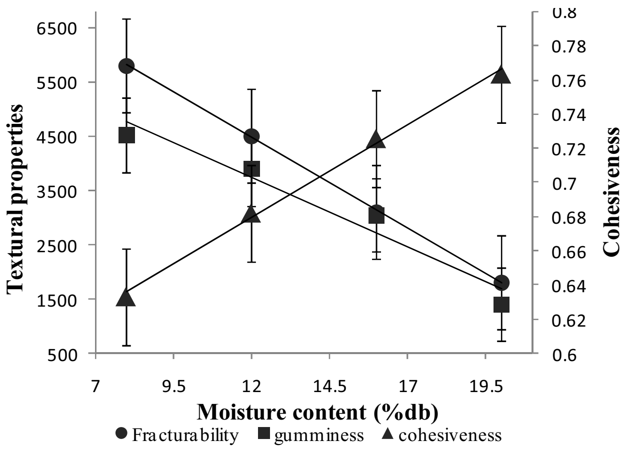

Fig. 11 Variation in fracturability, gumminess and cohesiveness with varying moisture content.

Fracturability

A decreasing trend in fracturability (5500 to 1000 g) with increasing mc was observed as shown in **Fig. 11**. A linearly falling nature with raised mc for fracturability is representted by the following regression Eq. (3.23).

$$F = 8490 - 335M \; (R^2 = 0.999) \qquad (3.23)$$

Hardness

A decreasing trend in hardness for fenugreek seeds with increased mc is shown in Eq. (3.24).

$$H = 10842 - 437.1M \; (R^2 = 0.983) \qquad (3.24)$$

The study on pomegranate seeds (Kingsley *et al*. 2006) revealed that hardness linearly decreased with increased mc. The decrease in hardness of the seed is because of increased softness of seed at higher moisture levels.

Cohesiveness

In the present study, it was observed that cohesiveness increased from 0.3444 to 0.6272 on increasing mc from 7.6 to 20% as it is shown in **Fig. 11**. A linearly increasing nature of cohesiveness with increasing mc can be represented by the regression Eq. (3.25)

$$C = 0.548 + 0.010M \; (R^2 = 0.996) \qquad (3.25)$$

Kaur *et al*. (2009) and Lee *et al*. (2009) studied kidney bean and oats and reported an increased cohesiveness at higher mc. This can be attributed to higher viscosity of the seed molecules at higher mc.

Gumminess

A decreasing trend in gumminess from 2600 to 1000 as the mc increased from 7.6 to 20% is shown in **Fig. 11**. Eq. (3.26) describes the linearly decreasing nature of gumminess with increased moisture levels.

$$G_m = 6800\text{-}256.1M \; (R^2 = 0.949) \qquad (3.26)$$

Similar results of declining trend in gumminess at higher mc are reported by Lee *et al*. (2009) and Kaur *et al*. (2009) for oats and kidney beans, respectively.

CONCLUSION

The physical dimensions of fenugreek seed viz. length, width, thickness, diameter, sphericity, seed volume, seed roundness, specific gravity, surface area, true density, porosity, 1000-seed mass, angle of repose were found to increase on increasing mc. while specific surface area and aspect ratio decreased. Bulk density was found to increase initially from 746.4 to 771.6 kg m^{-3} and then decreased to 697.6 kg m^{-3} as the moisture level was increased from 7.6 to 20%. Static coefficient of friction was found to be maximum for paper board (0.521 to 0.609) and minimum for aluminium sheet surface (0.479 to 0.554) within the studied range of the mc. Terminal velocity also increased from 9.23 to 9.42 m s^{-1} for 7.6 to 20% mc. With regards to textural properties, seed hardness, fracturability, and gumminess decreased whereas cohesiveness increased on increasing mc. The physical and textural properties evaluated in this study have practical application in industry as well as in academia.

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Nomenclature

A, B	regression coefficients
A_c	area of smallest circumscribing circle (mm^2)
A_p	largest projected area (mm^2)
db	dry basis (%)
D_g	equivalent diameter (mm)
g	gram
H	hardness (g or kg or N)
h	hour
h	height (mm)
kJ	kilojoule
L	litre
L, W, T	length, width, thickness
m	meter
M	moisture content
M_{1000}	thousands seed mass (g)
mc	moisture content (% db)
mg	milligram
mJ	millijoule
M_f	desired mc of sample
M_i	initial mc of sample
N	Newton
Q	quantity of water (ml)
r	radius
R^2	coefficients of determination
S_{sa}	specific surface area (mm^2)
S_a	surface area (mm^2)
V_t	Terminal velocity (ms^{-1})
W_i	initial mass of sample (g)
φ	angle of repose (^{o})
ρ_b	bulk density (kg m^{-3})
ϵ	porosity
ω	roundness
Ψ	sphericity
μ	static coefficient of friction
ρ_t	true density (kg m^{-3})

Subscripts

a	area
b	bulk
f	final
i	intial
sa	surface area