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# Some technical properties of dried *Terminalia chebula* (kara halile*)* for use in harvest and post-harvest processing

**Elçin Yeşiloğlu Cevher**

*Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Ondokuz Mayıs University, Samsun, Turkey*

**Corresponding Author:** Elçin Yeşiloğlu Cevher, Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Ondokuz Mayıs University, Samsun, Turkey. Email: elciny@omu.edu.tr

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**PAPER**

## Abstract

Depending on humidity, some technical properties of *T. chebula* (black halile) dried fruit were investigated. It was observed that various properties, such as dimension, geometric mean diameter, and arithmetic mean diameter, increased linearly with increasing moisture content. With the increase in moisture content, sphericity increased from 57.2% to 67.7%, surface area increased from 487.65 mm$^2$ to 805.03 mm$^2$, porosity increased from 0.49 to 0.59, and the angle of repose increased from 22.77° to 27.86°. However, moisture content, true density, and bulk density decreased from 1.85% to 3.27%, 1469.54 kg/m$^3$ to 1740.22 kg/m$^3$, and 735.64 kg/m$^3$ to 705.99 kg/m$^3$, respectively. When the moisture content increased from 1.85% to 3.27%, the static and dynamic friction coefficient increased from 0.231 to 0.495 and 0.311 to 0.637, respectively. The lowest static and dynamic friction force values were obtained for stainless steel and the highest for rubber surface. When moisture content increased from 1.85% to 3.27%, tensile strength decreased from 446.46 N to 257.59 N. Rupture energy and deformation increased with an increase in the moisture content of the fruit. When the moisture content increased from 1.85% to 3.27%, the rupture energy and deformation increased from 0.09 J to 0.27 J and 0.83 mm to 1.76 mm, respectively.

*Keywords*: deformation; friction coefficients; rupture energy; rupture force; *Terminalia chebula*

## Introduction

*Terminalia chebula* (*T. chebula*) belongs to the Combretaceae family. The fruit is a yellowish-green oval drupe, 3–6-cm long and 1.3–1.5-cm wide, containing an oval seed. *T. chebula* can grow in various soils, including clay and shady soils. The trees can be grown at altitudes of about 2000 m above sea level and in regions where the annual precipitation is 100–150 cm and the temperature is 0–17°C. Although *T. chebula* is a native of Asia, it is also found in Nepal, Sri Lanka, Myanmar, Bangladesh, Egypt, Iran, Turkey, Pakistan, Yunnan, Tibet, and Guangdong, Guangxi province of China. In India, it grows in the deciduous forests of Himachal Pradesh, Tamil Nadu, Kerala, Karnataka, Uttar Pradesh, Andhra Pradesh, and West Bengal (Gupta, 2012). Famous as *kara halile* in Turkey, worldwide *T. chebula* is known as myrobalan, mapki, harad, harada, karkchettu, kadukkaya, king of medicine, halile, harde, harar, and sa mao tchet. *T. chebula* is rich in organic acids, flavonoid substances, ascorbic acid, protein, amino acids, and minerals (Murathan *et al.*, 2020). It is called the "king of medicines" in Tibet and ranks first as an Ayurvedic medicine for its extraordinary wound-healing power and wide range of medicinal properties. *T. chebula* has antibacterial, antifungal, antiviral, antidiabetic, antimutagenic, antioxidant, antiulcer, and wound-healing properties. It also prevents heart damage, and is used to treat kidney disease. It is a mild, safe, and effective laxative in traditional medicine. *T. chebula* and its photo components have therapeutic effects without toxicity. It is an active ingredient in the well-known herbal preparation *triphala*, which is used to treat liver enlargement, stomach ailments, and eye inflictions (Gupta, 2012). Triphala's main component is a seed coat powder of dried *T. chebula* fruit. Therefore, removing the seed from the seed coat must be carried out carefully. It is necessary to design suitable equipment to perform this separation process (Pathak *et al.*, 2020). It is essential to know the engineering properties of the material for designing and developing equipment and for processing, transportation, classification, separation, and storage of agricultural products. This includes engineering features such as shape, size, mass, bulk density, true density, porosity, coefficient of static-dynamic friction against various surfaces, and rupture characteristics of the product. The engineering information obtained could be used to determine the efficiency and operation of crop machinery (Gharibzahedi *et al.*, 2010; Sangamithra *et al.*, 2016).

The moisture content of the product is one of the critical parameters in the designing of suitable equipment. Moisture-related properties of agricultural products are essential for process design, determination of product quality, processing, and packaging (Rao *et al.*, 2005). The physical properties of agricultural products are used in the designing of processing units, such as cleaning, separation, storage, transport, and drying systems. Sphericity is used to understand heat and mass transfer. The stagnation angle is an indicator of the flowing ability of a food product. Porosity is the property used to characterize and process food products (Bajpai *et al.*, 2019). Many researchers have conducted research to determine agricultural products' physical and mechanical properties depending on their moisture content. For example, Bajpai *et al.* (2019), Gharibzahedi *et al.* (2010), Pathak *et al.* (2020), and Putri *et al.* (2015) conducted studies to determine the physical and mechanical properties of jamun seeds, black cumin, myrobalan fruits, and rice, respectively, depending on their moisture content. Studies have been conducted using seeds and nuts to determine engineering properties of *Jatropha curcas L.* seeds (Herak *et al.*, 2013), raw cashews (Balasubramanian, 2001), mahogany seeds and kernels (Aviara *et al.*, 2014), almond seeds (Atteh *et al.*, 2021), charoli nut (Shelare *et al.*, 2021), bambara groundnut seed (Aremu *et al.*, 2022), arugula seed (Mirzabe *et al.*, 2021), tamaring seed (Mohite *et al.*, 2019), and date nut (Ola *et al.*, 2020). Investigation into physical and mechanical properties of agricultural products has an essential role in the designing aspects of harvesting and post-harvest machinery as well as sorting, packaging, and transport equipment (Bajpai *et al.*, 2019).

The literature review assessed the physical properties of *T chebula* and discovered that engineering features are not determined by their moisture content. The study to assess the engineering properties was carried out by considering the moisture content and the mechanical properties of the product obtained under the compression load which have not been studied before. This was obtained from the mechanical properties of rupture force, rupture energy, and deformation. Mechanical effects can damage harvest or post-harvest crops. Damage to the outer layers of the product causes faster deterioration. These factors negatively affect the storability and shelf life of products.

For this reason, it is essential to know the mechanical properties of agricultural products (Yıldız and Cevher, 2022). The study was carried out with three different moisture contents, and the relationship between engineering properties was explained through mathematical equations. Physical properties of *T. chebula* dried fruit such as length, width, thickness, geometric-arithmetic mean diameter, sphericity, surface area, bulk density, true density, porosity, and inclination angle were investigated as engineering properties. At the same time, mechanical properties such as fracture force, fracture energy, deformation, and static and dynamic friction coefficients were determined. Thus, engineering properties for improving the quality of *T. chebula* dried fruit have been demonstrated.

## Material and Methods

### Material

*T. chebula* dried fruit used in the study was obtained from the local market in Samsun, Turkey. Before starting the experiments, all foreign material in the samples, such as dirt, stones, dust, and cracked dried fruit were cleaned manually. Then, the initial and conditioned moisture content values were determined by keeping the dried fruit in a standard hot air oven at 105°C for 24 h. In the study, the samples were conditioned by adding a calculated amount of water according to the following equation to reach different humidity levels (Balasubramanian, 2001; Pathak *et al.*, 2019; Yurtlu *et al.*, 2010):

$$Q = \frac{Wi(M_f - M_i)}{100 - M_f}, \tag{1}$$

where

Q: mass of water to be added (kg),
$W_i$: initial mass (kg),
$M_i$: initial moisture content of the sample in percent (% wet basis [wb]), and
$M_f$: final moisture content of the sample in percent (% wb).

In order to ensure a homogeneous moisture distribution, the samples were placed in polyethylene bags and kept

**Figure 1. Dried *Termınalıa chebula* fruit.**

in a refrigerator at 5°C for 1 week. Humidity control was conducted before starting the experiments. The study was conducted with kara halile dried fruit with a moisture content of 1.85%, 2.59%, and 3.27% wb (Figure 1).

## Measurement of physical properties

Randomly selected 30 samples of *T. chebula* dried fruit were used. Dimensions of dried fruit were measured with a digital caliper with an accuracy of 0.01 mm (Mitutoyo, Absolute Digimatic, Japan) (Figure 2).

Mass measurements were conducted with a Kern electronic precision balance with a sensitivity of 0.01 g and a maximum measurement capacity of 2500 g. The arithmetic mean diameter ($D_a$), geometric mean diameter ($D_g$), and sphericity ($\phi$) values were calculated with the following equations (Bulan *et al.*, 2020; Mohsenin, 1970, 1980) (Figure 3):

$$D_a = \frac{L + W + T}{3}, \tag{2}$$

$$D_g = (LWT)^{1/3}, \tag{3}$$

**Figure 2. Size measurement of *T. chebula* dried fruit.**

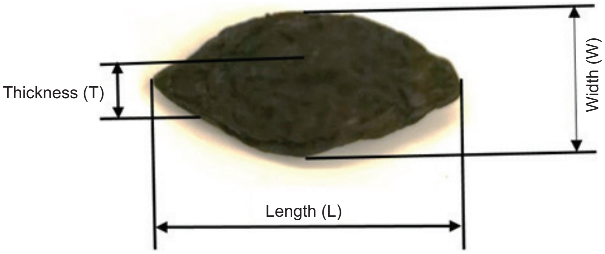

**Figure 3. Dimensions of *T. chebula* dried fruit.**

$$\phi = \frac{(LWT)^{1/3}}{L}, \tag{4}$$

where $L$ is the length (mm), $W$ is the width (mm), $T$ is the thickness (mm), and $\phi$ is the sphericity.

Following equation was used to calculate the surface area (Mohsenin, 1980):

$$S = \pi D_g^2, \tag{5}$$

where S: surface area (mm$^2$) and
$D_g$: geometric mean diameter (mm).

The bulk density ($P_b$) was determined by filling *T. chebula* dried fruit to a height of 150 mm into a 500-mL cylindrical carton and weighing it. The true density ($P_t$) was obtained by displacement method using the container with known mass and volume of the samples. While applying this method, toluene ($C_7H_8$), which is less absorbed by the samples, was used instead of water (Yurtlu and Yeşiloglu, 2011).

The porosity (ε, %) was determined using bulk density and true density values (Mohsenin, 1980; Selvi *et al.*, 2020).

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} \times 100, \tag{6}$$

where $P_b$: bulk density (kg m$^{-3}$), and $P_t$: true density (kg m$^{-3}$) (Mohsenin, 1980):

A 200 mm in diameter and 150 mm in height conical cylinder with two open sides was used to determine the angle of repose ($Q$). The conical cylinder filled with *T. chebula* dried fruit was lifted slowly, and its height and diameter consisting of fruit samples were measured. The angle of repose ($Q$, degree) is determined by the following equation (Pathak *et al.*, 2019):

$$Q = \tan^{-1}\left(\frac{2H}{D}\right), \tag{7}$$

where
H: height of cone (mm) and
D: diameter of the cone (mm).

For *T. chebula* dried fruit, this was determined by connecting a wooden box to the load cell of the universal tester. The wooden box (60 × 120 × 100 mm) had an opening at the bottom and was connected to the load cell (Lloyd Biologicals Tester; Figure 4) with a pulley mechanism. The test was carried out by moving the box filled with dried fruit horizontally at a speed of 100 mm/min so that the contents were in contact with the friction surface.

The opening at the bottom of the box allowed the fruit to touch the friction surface. A 10-mm gap was left between the opening and the surface of the fruit-filled box. Horizontal pull (friction force) was recorded with the software of the Lloyd device. The friction test was conducted at a sliding speed of 100 mm/min. Stainless steel, court fabric galvanized sheet and rubber surfaces were used in the test carried out with 10 replications (Yurtlu and Yeşiloğlu, 2011).

### Measurement of mechanical properties

A universal biological material test device (Lloyd Instrument LRX Plus; Lloyd Instruments Ltd, Bognor Regis, United Kingdom) was used to determine rupture force, rupture energy, and deformation values of *T. chebula* dried fruit (Selvi *et al.*, 2020; Yurtlu and Yeşiloğlu 2011). The experiments were carried out with a load cell having a capacity of 1000 Newton (N) by applying load to the cross-section axis of dried fruit at a compression speed of 10 mm/min. The coordinate system describing the compression position of dried fruit is given in Figure 5.

Data obtained from the compression test experiments were processed using the NEXYGEN Plus software (Figure 6).

Statistical analysis of the data was performed with the IBM SPSS Statistics 21 software. *T. chebula* dried fruit were tested at three different moisture contents (1.85, 2.89, and 3.27% wb) for all traits. Each test was performed in triplicate and mean ± standard deviation values were obtained and examined for variance using one-way ANOVA and Duncan's test. In addition, linear regression analysis was performed to obtain regression equation and coefficient of determination ($R^2$) for all parameters.

## Results and discussion

### Dimensions of dried fruit

Dimensions of *T. chebula* dried fruit are given in Table 1. With increase in moisture content, the three axial dimensions of the fruit also increased. This could be due to expansion in fruit size with moisture filled in the cell spaces of dried fruit. As the moisture content increased from 1% to 3.27%, the length, width, and thickness of dried fruit increased from 21.34 mm to 25.70 mm, 10.57

**Figure 4. Wooden box used in friction tests.**

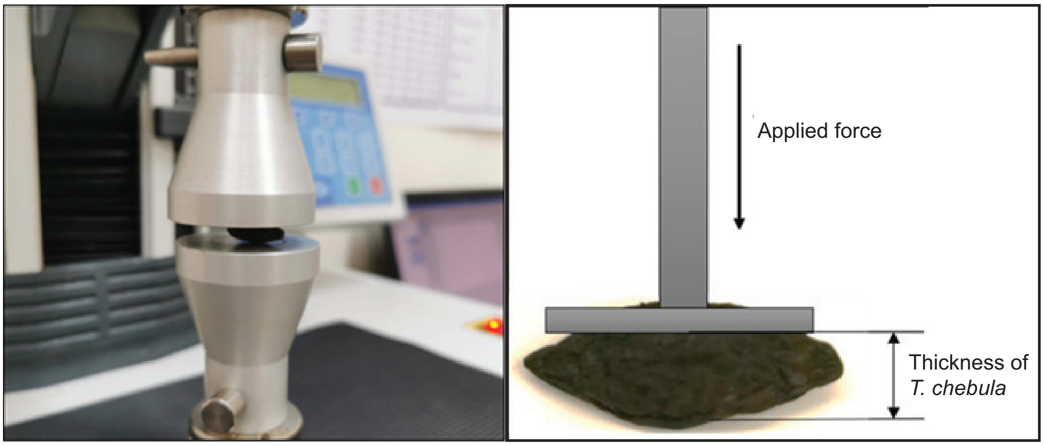

**Figure 5. Axis of *T. chebula* dried fruit under compression load.**

mm to 14.16 mm, and 8.55 mm to 11.27 mm, respectively. In addition, the average diameter of the fruit increased with the moisture content. With increase in the moisture content from 1.85% to 3.27%, the arithmetic and geometric mean diameters increased from 13.49 mm to 17.05 mm and 12.41–15.99 mm, respectively.

*T. chebula* dried fruit was statistically significantly related to humidity. Therefore, depending on the moisture content, the geometric mean diameter ($D_g$) of *T. chebula* dried fruit is presented graphically in Figure 7.

The given equation in Figure 7 establishes a relationship between the geometric mean diameter and the moisture content. The size and diameter values of *T. chebula* dried fruit were significantly affected by the moisture content ($p \leq 0.01$).

## Sphericity

Globality, which primarily refers to a social condition, potentially the end-point of globalization, and reveals the degree of global definition of the product, is an important parameter used in bringing products together. The sphericity of *T. chebula* dried fruit was significantly affected by the moisture content and increased from 57.2% to 67.7% ($p \leq 0.01$) (Figure 8). This indicates that relatively proportional changes occur in the size of the dried fruit because of sphericity. The linear equation for sphericity can be formulated as given in Figure 8.

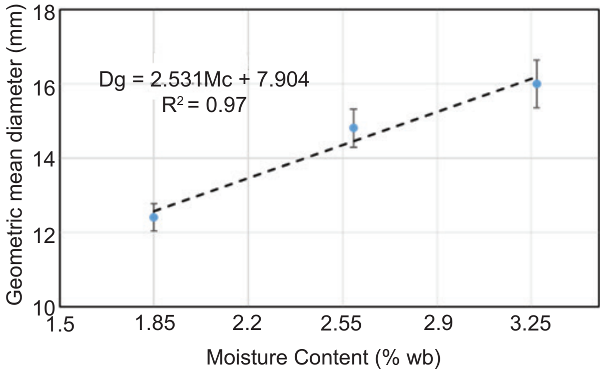

**Figure 7. Effect of moisture content on the geometric mean diameter of *T. chebula* dried fruit.**

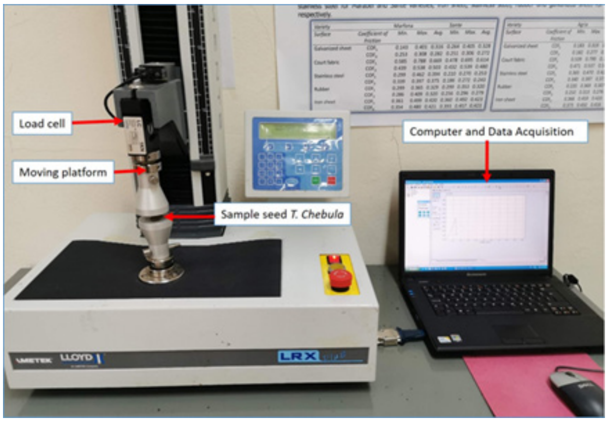

**Figure 6. Lloyd Instrument universal testing machine.**

Trends similar to the effect of moisture content on the sphericity of *T. chebula* dried fruit were reported by Vashishth *et al.* (2020) for horse gram, Gharibaahedi *et al.* (2010) for black cumin seed, Su *et al.* (2021) for maize kernel, and Yurtlu *et al.* (2010) for laurel seed.

## Surface area

In the study, the moisture content of *T. chebula* dried fruit increased from 1.85% to 3.27% and the surface area increased from 487.65 mm$^2$ to 805.03 mm$^2$. Figure 9 shows the linear relationship between moisture content and surface area and the regression equation of relationship between the moisture content and the surface area of the dried fruit of *T. chebula*. The surface area was significantly ($p \leq 0.01$) affected by the moisture content.

## Density

In the study, the bulk density of *T. chebula* dried fruit decreased from 735.64 kg/ m$^3$ to 705.99 kg/m$^3$. This

**Table 1. Means and standard deviation of the axial dimensions of dried *T. chebula* fruit.**

| Moisture content (%) wb | Axial dimension (mm) | | | Average diameter (mm) | |
|---|---|---|---|---|---|
| | Length (L) | Width (W) | Thickness (T) | Arithmetic mean ($D_a$) | *p*-value |
| 1.85 ± 2 | 21.34 ± 2.98$^{a}$ | 10.57 ± 0.96$^{a}$ | 8.55 ± 0.86$^{a}$ | 13.49 ± 0.41$^{a}$ | 0.000 |
| 2.59 ± 2 | 24.31 ± 0.53$^{a,b}$ | 13.38 ± 0.26$^{b}$ | 10.29 ± 0.54$^{b}$ | 15.90 ± 0.53$^{b}$ | 0.000 |
| 3.27 ± 2 | 25.70 ± 0.90$^{a,b}$ | 14.16 ± 0.96$^{c}$ | 11.27 ± 0.75$^{c}$ | 17.05 ± 0.62$^{c}$ | 0.000 |

*Note: Different letters in superscript indicate the import differences.*

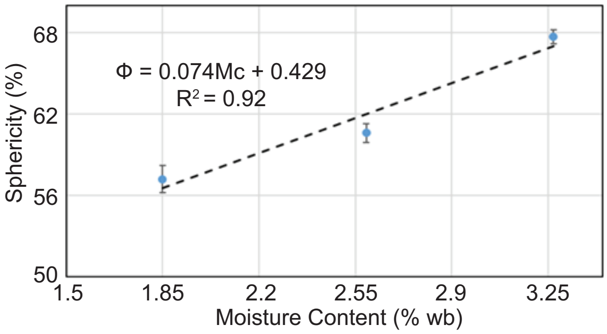

**Figure 8. Effect of moisture content on the sphericity of *T. chebula* dried fruit.**

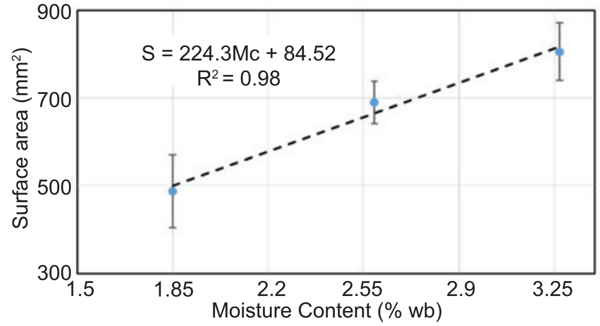

**Figure 9. Effect of moisture content on the surface area of *T. chebula* dried fruit.**

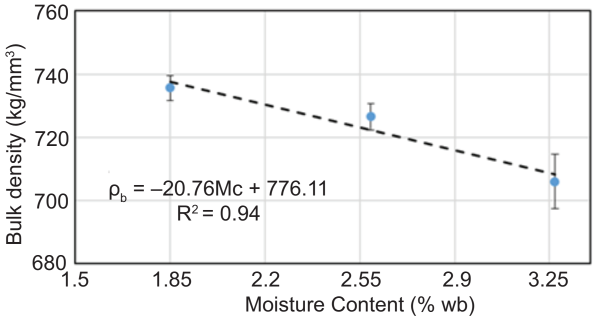

**Figure 10. Effect of moisture content on the bulk density of *T. chebula* dried fruit.**

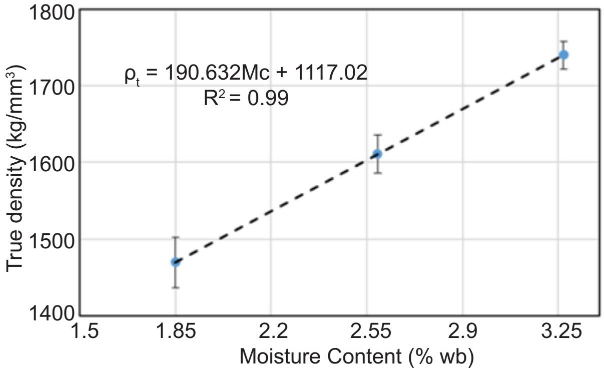

**Figure 11. Effect of moisture content on the true density of *T. chebula* dried fruit.**

showed that the product's mass increased due to lower moisture absorption than the volumetric expansion. The relationship between moisture content and bulk density and the regression equation is shown in Figure 10. The bulk density of *T. chebula* dried fruit was significantly affected by the moisture content ($p \leq 0.01$).

A negative correlation was observed between the moisture content and bulk density of *T. chebula* dried fruit. Similar results were observed in the studies conducted by Bhushan and Raigar (2020) for rice bean, Malik and Saini (2016) for sunflower seed, and Selvi *et al.* (2006) for linseed.

True density of any product is a physical property that can be used in aerodynamic handling and separation processes. In case of *T. chebula* dried fruit, this feature refers to its true mass, excluding all its cavities and pores (Bhushan and Raigar, 2020).

The true density of *T. chebula* dried fruit increased from 1469.54 kg/m$^3$ to 1740.22 kg/m$^3$ and was significantly ($p \leq 0.01$) affected by its moisture content. The relationship between moisture content and true density, and regression equation, is given in Figure 11. The overall increase in the true density of *T. chebula* dried fruit could be due to the higher increase in weight than fruit volume. The true density results of *T. chebula* dried fruit agreed with the results of the studies conducted by Singh and Meghwal (2019) for ajwain seed and Bhushan and Raigar (2020) for rice beans.

## Porosity

Porosity is an essential feature for applying airflow to agricultural grain products, and their packaging and cooling processes. With increase in the moisture content of *T. chebula* dried fruit from 1.85% to 3.27%, the porosity increased from 0.49 to 0.5. The porosity value of *T. chebula* dried fruit was significantly ($p \leq 0.00$) affected by moisture content. The relation between moisture content and porosity along with the regression equation is given in Figure 12.

The results obtained for the porosity of *T. chebula* dried fruit, depending on the moisture content, were consistent with the results obtained by Kumar *et al.* (2016) for chironji nut (Buchanania lanzan).

## Angle of repose

The angle of repose is the maximum angle at which a granular agricultural product can stand without

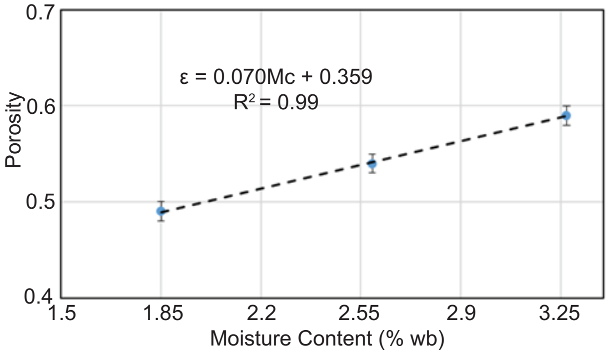

**Figure 12. Effect of moisture content on the porosity of *T. chebula* dried fruit.**

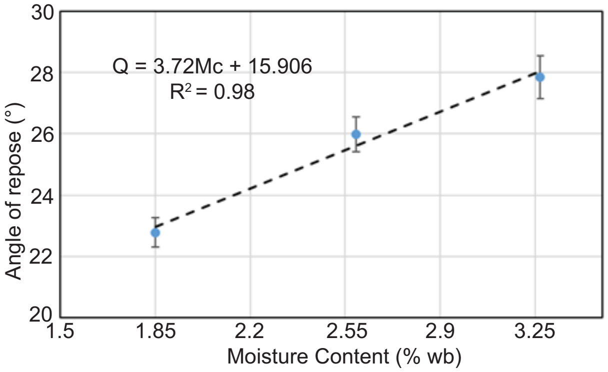

**Figure 13. Effect of moisture content on angle of repose of *T. chebula* dried fruit.**

scattering as a heap. This angle value can be used to design equipment and warehouse structure where mass flow of product is confronted. The angle of repose of *T. chebula* dried fruit was significantly ($p \leq 0.01$) affected by its moisture content. The effect of moisture content on the angle of repose of *T. chebula* dried fruit and the regression equation are given in Figure 13.

An increase in the natural agglomeration angle of *T. chebula* dried fruit was observed. The increased moisture of *T. chebula* dried fruit decreased its flow ability, which increased fruit's stickiness. The natural agglomeration angle of *T. chebula* dried fruit increased from 22.77° to 27.86°. The result obtained agreed with the result of the study conducted by Bajpai *et al.* (2019) for jamun seed (*Syzgium cuminii*).

### Static coefficient and dynamic of friction

It is necessary to know the friction coefficient of an agricultural product, mainly when it is transported by a conveyor. The friction coefficient of an agricultural product varies with the used surface. The following four surfaces were used in the study to compute static and dynamic friction coefficient values: the most commonly used stainless steel, court fabric, galvanized sheet, and rubber. The static and dynamic friction coefficient results of *T. chebula* dried fruit are summarized in Table 2.

It was observed that static friction coefficients were higher than dynamic friction coefficients for all moisture contents. In addition, static and dynamic friction coefficient values for the tire's surface were much higher than for other surfaces. This could be explained by the fact that the tire's surface was rougher than other test surfaces used. A lower adhesion force between smoother stainless-steel surface and *T. chebula* dried fruit resulted in lower coefficients of static and dynamic friction (Shafaei and Kamgar, 2017; Visvanathan *et al.*, 1996).

The coefficient of friction depends on roughness of the material used and frictional forces, which causes an increase in energy consumption. Similar results were obtained for the coefficient of friction in other studies (Kaliniewicz *et al.*, 2013; Shafaei and Kamgar, 2017; Visvanathan *et al.*, 1996).

According to the results presented in Table 2, the highest value of dynamic friction coefficient was obtained for rubber surface (0.448), followed by court fabric (0.387), galvanized sheet (0.338), and stainless steel (0.252). Similar results were obtained for static friction coefficient.

The increase in moisture content of *T. chebula* dried fruit caused an increase in both dynamic and static friction coefficients. This could be attributed to the increase in adhesion forces between the fruit and the surfaces used, because a rise in humidity increased the stickiness of dried fruit (Esgici *et al.*, 2018; Ghodki and Goswami., 2016). The lowest value of the dynamic friction coefficient was obtained for stainless steel surface (0.361), and the highest value was for rubber surface (0.632). The same results were observed for static friction coefficient.

Table 2 also includes the results of Duncan's multiple range tests to identify significant differences between average moisture content and the examined surfaces. Significant differences were observed between static and dynamic friction coefficients and moisture content. One-way ANOVA demonstrated that variations in moisture content, surfaces used, and interaction between moisture content and surface were significant for both static and dynamic friction coefficients ($p \leq 0.01$). Both static and dynamic friction coefficients for *T. chebula* dried fruit increased linearly with moisture content and varied with used structural surfaces. This trend was consistent with the findings of the previous studies (Aviara *et al.*, 2014, 2015; Shafaei *et al.*, 2016).

At higher moisture content, increased roughness was observed in *T. chebula* dried fruit, resulting in its

**Table 2. Average static and dynamic friction coefficient values for different moisture content and surfaces used for *T. chebula* dried fruit.**

| Moisture content | Surface | Dynamic coefficient of friction | Static coefficient of friction |
|---|---|---|---|
| 1.85 ± 2 | Stainless steel | 0.174 ± 0.011 | 0.249 ± 0.012 |
| | Court fabric | 0.259 ± 0.005 | 0.359 ± 0.009 |
| | Galvanized sheet | 0.218 ± 0.012 | 0.261 ± 0.017 |
| | Rubber | 0.274 ± 0.021 | 0.374 ± 0.037 |
| 2.59 ± 2 | Stainless steel | 0.220 ± 0.021 | 0.360 ± 0.044 |
| | Court fabric | 0.359 ± 0.021 | 0.471 ± 0.049 |
| | Galvanized sheet | 0.344 ± 0.024 | 0.434 ± 0.035 |
| | Rubber | 0.446 ± 0.035 | 0.664 ± 0.013 |
| 3.27 ± 2 | Stainless steel | 0.362 ± 0.028 | 0.472 ± 0.028 |
| | Court fabric | 0.543 ± 0.017 | 0.650 ± 0.021 |
| | Galvanized sheet | 0.451 ± 0.023 | 0.568 ± 0.014 |
| | Rubber | 0.623 ± 0.016 | 0.858 ± 0.021 |
| Mean values | | | |
| Stainless steel | | $0.252^a$ ± 0.084 | $0.361^a$ ± 0.098 |
| Court fabric | | $0.387^c$ ± 0.120 | $0.481^c$ ± 0.127 |
| Galvanized sheet | | $0.338^b$ ± 0.099 | $0.433^b$ ± 0.134 |
| Rubber | | $0.448^d$ ± 0.147 | $0.632^d$ ± 0.204 |
| 1.85 ± 2 | | $0.231^a$ ± 0.041 | $0.311^a$ ± 0.061 |
| 2.59 ± 2 | | $0.342^b$ ± 0.086 | $0.482^b$ ± 0.119 |
| 3.27 ± 2 | | $0.495^c$ ± 0.101 | $0.637^c$ ± 0.146 |
| p-values | | | |
| Moisture content | | 0.000 | 0.000 |
| Surface | | 0.000 | 0.000 |
| Moisture content × surface | | 0.000 | 0.000 |

decreased sliding properties and increased coefficient of static friction. In addition, an increase in static friction coefficient was observed due to increased stickiness and adhesion forces between *T. chebula* dried fruit and material surfaces used at higher moisture content.

## Mechanical properties

*T. chebula* dried fruit with moisture contents of 1.85%, 2.59%, and 3.27% was tested in the cross-section direction. The mechanical properties of *T. chebula* dried fruit, such as rupture force, rupture energy, and deformation values, were determined. It was observed that moisture content had a statistically significant ($p \leq 0.01$) effect on the mechanical properties of the fruit.

### *Rupture force*

The study determined that the force required for rupturing *T. chebula* dried fruit decreased with increasing moisture content. This was due to increased flexibility of the dry fruit because of increased moisture content; increase in elasticity decreased the rupture force of the fruit. It was concluded that rupture force was minimum when moisture content was maximum. This established that more loading force was required when the moisture content of *T. chebula* dried fruit was low and *vice versa*.

In *T. chebula* dried fruit, for a moisture content of 1.85%, the minimum rupture force determined was 405.24 N and the maximum was 487.20 N. For a moisture content of 2.59%, the minimum rupture force was 296.79 N and the maximum was 397.72 N. Finally, for a moisture content of 3.27%, the minimum rupture force determined was 214.29 N and the maximum was 309.33 N. One-way ANOVA demonstrated a significant relation between moisture content and rupture force of *T. chebula* dried fruit ($p \leq 0.01$); this along with regression equation is given in Figure 14.

The results obtained in the present study were compatible with the previous studies (Amoah *et al.*, 2017; Pathak *et al.*, 2020; Putri *et al.*, 2015).

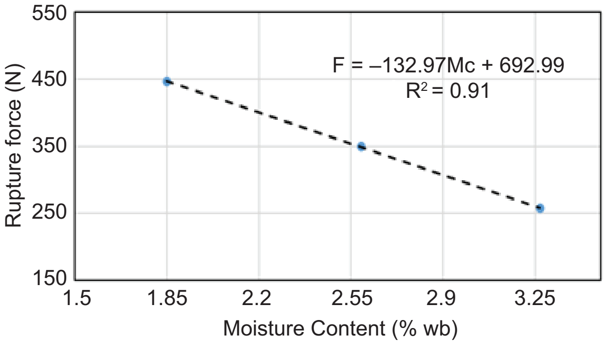

**Figure 14. Effect of moisture content on the rupture force of *T. chebula* dried fruit.**

*Rupture energy*

Depending on the size of the fruit or seed, increase in rupture energy was observed in *T. chebula* dried fruit (Pathak *et al.*, 2020). Increase in size of the fruit or seed increased its rupture energy. At a moisture content of 1.85%, the maximum rupture energy determined was 0.11 J and the minimum was 0.07 J. At a moisture content of 2.59%, the maximum rupture energy determined was 0.18 J and the minimum was 0.13 J. Finally, at a moisture content of 3.27%, the maximum rupture energy was 0.31 J and the minimum was 0.22 J. The relationship between moisture content and rupture energy was significant ($p \leq 0.01$), which along with the regression equation is given in Figure 15.

The results obtained for rupture energy in the present study were compatible with the previous studies (Olaniyan and Oje, 2002; Shashikumar *et al.*, 2018; Swain and Gupta, 2013).

*Deformation*

Deformation in *T. chebula* dried fruit also increased with the moisture content. At a moisture content of 1.85%, the maximum deformation determined was 0.94 mm whereas the minimum was 0.73 mm. At a moisture content of 2.59%, the maximum deformation determined was 1.64 mm whereas the minimum was minimum 1.22 mm. Finally, at a moisture content of 3.27%, the maximum deformation determined was 1.61 mm whereas the minimum was 0.65 J. According to one-way ANOVA, the effect of moisture content on the deformation of *T. chebula* dried fruit was significant ($p \leq 0.01$). The relationship between moisture content and deformation, along with the regression equation, is given in Figure 16.

It was observed that deformation and rupture energy increased whereas rupture force decreased with increased moisture content of *T. chebula* dried fruit. Similar results were obtained for faba bean (Altuntaş and Yıldız, 2007), beechwood seed (Nyorere and Uguru, 2018), walnut (Sharifian and Derafshi, 2008), and Lima bean (Aghkhani *et al.*, 2012). Further, if the moisture content of *T. chebula* dried fruit was low, it was less susceptible to breakage during harvest and post-harvest processing.

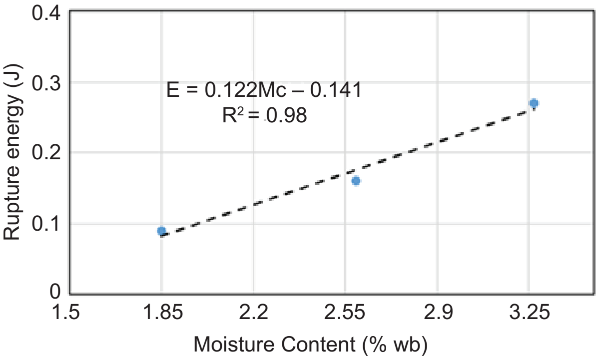

**Figure 15. Effect of moisture content on the rupture energy of *T. chebula* dried fruit.**

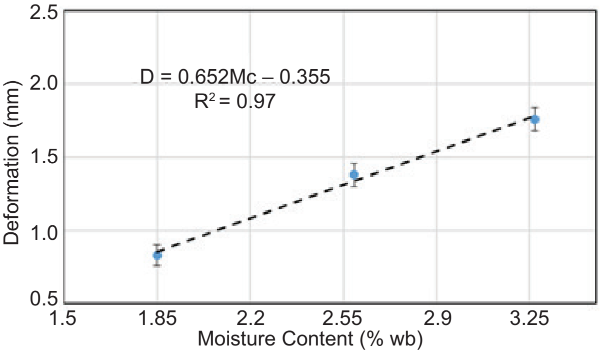

**Figure 16. Effect of moisture content on the deformation of *T. chebula* dried fruit.**

The effect of moisture content on the crushing resistance of *T. cheb*ula dried fruit was also investigated in the present study. The results depicted that the crushing resistance of the dried fruit was a function of fruit's moisture content, because breaking force of the seed decreased whereas its breaking energy and deformation increased with increase in the moisture content of the fruit. Therefore, the crushing resistance of the fruit was found to be useful for designing and development of processing machinery.

## Conclusion

The study obtained the following results, including the physical and mechanical properties of *T. chebula* dried fruit at a moisture content of 1.85%, 2.59%, and 3.27% wb. The moisture content significantly affected dried fruit's physical and mechanical properties ($p \leq 0.01$).

1. Physical properties of *T. chebula* dried fruit increased with increasing moisture content, except for bulk density.

2. Maximum static and dynamic friction coefficient values were observed for the rubber surface, followed by court fabric, galvanized sheet, and stainless steel.

3. Rupture force decreased with an increase in the moisture content of the fruit.

4. Deformation and rupture energy increased with an increase in the moisture content of the fruit.

The results and regression equations of physical and mechanical properties of *T. chebula* fruit obtained in the study, depending on the moisture content, would provide technical and functional information for designing harvest and post-harvest machinery and classification, separation, packaging, and transportation of the product.

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