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Influence of Controlled Moisture Levels on the Dimensional, Gravimetric, Frictional, and Mechanical characteristics of Grape (*Vitis vinifera* L.) Seeds for Optimized Processing and Storage: An Attempt Towards Circular Economy

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Abstract

This study evaluates the effects of varying moisture levels on the physicochemical, dimensional, gravimetric, frictional, and mechanical properties of grape seeds, essential for optimizing processing and handling. Results revealed that seed dimensions, including length, width, and thickness, significantly (P<0.05) expanded by 4.55%, 5.37%, and 5.47%, respectively, as moisture increased. Mean diameters (arithmetic and geometric), sphericity, and volumetric properties such as volume and surface area also increased, indicating structural changes in response to moisture. The volumetric expansion coefficient rose accordingly, the aspect ratio remained stable, while the elongation ratio decreased slightly. As moisture content increased, rupture force, deformation at the rupture point, energy absorption at the rupture point, hardness, and toughness of grape seeds decreased significantly (P<0.05). Understanding the connection between hardness and moisture content, as well as loading in the processing of grape seed, could be crucial to energy conservation. Furthermore, the nutritional composition analysis revealed that grape seeds contain 8.74% ± 0.21 moisture, 12.03% ± 0.11 crude protein, 19.27% ± 0.19 fat, 3.02% ± 0.05 ash, and 42.66% ± 0.25 total carbohydrates. These findings will contribute to a better understanding of how moisture affects grape seed properties, which could apprise strategies for optimizing processing and handling.

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Introduction

Grape (*Vitis vinifera* L.) is a commonly grown fruit crop throughout the world. Subtropical and tropical regions, with typical climatic conditions of warm summers and mild winters, are ideal for grape harvesting. Grapes have a high economic value and are in high demand in both the processed as well as fresh fruit markets.[1] Grapes generally consist of about 25% (weight by weight, w/w) dry pomace and also contain seed with 38% (w/w) approximately.[2] Grape seed is categorized as oilseed, which is widely recognized for its expensive oil when compared to several other vegetable oils.[2] Furthermore, grape seeds are becoming increasingly popular these days due to their potential value as a source of various other nutrients such as protein, carbohydrates, antioxidants, etc. Grape seeds have indeed been produced in large quantities as a waste material by the wine industry. Besides being an authentically valuable waste resource, grape seeds also cause major disposal issues if not utilized appropriately.[3] Since, the physical properties have a direct impact on the effectiveness of critical processes like drying, milling, as well as storage, studying them at different moisture levels is essential for dealing with issues concerning grape seed disposal and processing. Developing an understanding of these properties makes it possible to develop processes that are optimised to use less energy and better material handling. Moreover, this knowledge promotes the valorisation of grape seeds by transforming these seeds, from a waste product into useful raw materials for sectors like food and bioenergy. Properties such as bulk density, size, and shape influence the design of equipment as well as processes for sorting, processing, and handling of seeds. Efficient processing reduces waste during collection and processing, making these operations more sustainable.

Therefore, the investigation of moisture-influenced physical properties of grape seed becomes a priority for designing the handling machinery. Mechanical and physical properties must be comprehended in order to effectively conserve, reduce costs, and use other post-harvest processes.

The designing of the metering device used in seeders and planter machines is quite dependent on the dimensions of the seed, which is used for designing the sorter and separator and for calculating aerodynamic properties.[4] The thousand seed mass has been an important parameter in the case of aerodynamic cleaners.[5] Bulk density has been used to determine the pressure exerted on storage structures, material handling machine design, and thermal processes.[6] Another important parameter is particle density, which could be helpful in aerodynamic and hydrodynamic separations and transportation systems as well. Porosity is used to design aeration and dryer machinery for the stored material.[7] The angle of repose is critical in determining the belt conveyor width and storage shape design.[7] A better understanding of seed aerodynamic properties is required to construct post-harvest machinery, including cleaners, dryers, pneumatic elevators, pneumatic planters, and pneumatic conveyors.[8] According to the literature available on grape seed, there has been no comprehensive study on the frictional, gravimetric, and mechanical properties of grape seed at varying moisture content levels. The purpose of the present investigation was to evaluate mechanical, dimensional, gravimetric as well as frictional properties related to grape seeds affected by variations in moisture levels.

Materials and Methods

Preparation of the Sample

Twenty kilograms (kg) of grape seeds of the Bangalore blue variety (*Vitis vinifera* L.) were obtained from Elite Vintage Winery in Karnataka, India. The collected grape seeds were separated from residue pomace, which consists of fruit pulp, dirt, and stems obtained as waste material from the winery. The collected grape seeds were washed with clean water and dried at 40 ^{o}C for 36 h. Grape seeds were stored in plastic bags and kept under refrigeration at 5 ^{o}C until further analysis. The grape seed moisture content was found to be 8.74% (wb). For adjustment of the controlled moisture level of grape seeds, drying was done in a tray dryer (cabinet dryer) at 40 ^{o}C and distilled water was added as per the following Eq. (1) as described by Altuntas and Demirtola.[9]

$$Q = W_i(M_f - M_i)/(100 - M_f) \quad ...(1)$$

wherein,

Q is the water mass (kg)

Wi is the initial sample mass (kg)

Mf is the final level of moisture in the sample (%)
Mi is the initial level of moisture in the sample (%)

The moisture level of grape seeds (250 g each) was adjusted accordingly to 8.74%, 12.35%, 16.13%, 20.18%, and 24.10% (wb) since most seed processing takes place between these moisture contents.[10,9] The grape seeds were then kept inside individual plastic bags under sealed conditions. Mechanical and physical parameters of grape seeds were determined with three replications.

Proximate Analysis

Determination of the protein content of grape seed samples was performed by using the Kjeldahl method (N×5.75). The crude fat and moisture content of grape seeds samples were estimated according to the methodology mentioned by Ubaid *et al*.[11] Total carbohydrate content was determined by differences among all the constituents.

Dimensional Properties Calculations

Volume (Vu)

Grape seed volume (mm^3) was measured on the assumption that the grape seed dimensions are in the following order: L>W>T as described by Munder *et al*.[12]

$$Vu=(L\times W\times T\times \Phi) \qquad ...(2)$$

wherein,

L is the grape seed length (mm)
W is the grape seed width (mm)
T is the grape seed thickness (mm)
Φ is the grape seed sphericity

Geometric Mean Diameter (Dg) and Arithmetic Mean Diameter (Da)

A sample size containing 100 grape seeds was randomly collected for the estimation of the average size of dimensions: thickness (T), width (W), and length (L) by using a 0.01 mm accuracy with the help of a digital vernier calliper (Corceptive, India). Calculation of Dg and Da was done following Mirzabe *et al*,[13] with following equation:

$$Dg=\sqrt[3]{(L\times W\times T)} \qquad ...(3)$$

$$Da=\frac{(L+W+T)}{3} \qquad ...(4)$$

Sphericity (Φ)

The roundness of the seed is measured by its sphericity. It is the measure of the sphericity of an object. The sphere’s isoperimetric aspect was used in its calculation as follows in according to Izli.[14]

$$\Phi=\frac{\sqrt[3]{(L\times W\times T)}}{L} \qquad ...(5)$$

Elongation Ratio (Er) and Aspect Ratio (Ar)

The determination of parameters linked to shape, such as elongation as well as aspect ratio related to grape seed, was done according to the methodology followed by Mansouri *et al*.[15] The elongation ratio reflects the tendency of the grape seed to shape, whereas the aspect ratio indicates if the grape seeds will roll or slide down flat surfaces with the following equation

$$Ar= W/L\times 100 \qquad ...(6)$$

$$Er=L/W \qquad ...(7)$$

Volumetric Expansion Coefficient (ψ)

ψ calculates how much grape seed will expand or contract in response to changing the level of moisture content. ψ of grape seed mass, which was measured after drying at 100 °C for 8 h under the vacuum.

$$\Psi= Vu/(V°g) \qquad ...(8)$$

wherein,

V°g is the grape seed volume subjected to vacuum drying for 8 h at 100 °C.

Projected Area (Pa)

For the determination of aerodynamic characteristics of grape seed, one of the crucial parameters is the projected area, which reflects the surface area that is perpendicular with respect to force. It is used in the designing of grape seed cleaners. Given below is the equation that follows Mansouri *et al*.[15]

$$Pa=((\pi\times L\times W))/4 \qquad ...(9)$$

Surface Area (Sa)

Sa of grape seed (mm^2) was calculated using the methodology described by Izli.[14] It is an extent to the overall area occupied by an object's surface.

$$Sa = \pi(Dg)^2 \quad ...(10)$$

wherein,

Dg is the grape seed geometric mean diameter (mm)
Gravimetric Properties Calculations

Bulk Density (ρ*b*)
ρ*b* (kg/cm^3) is determined by grape seed mass divided by its volume. It reveals how much material weight can be stuffed per unit area as suggested by Kate *et al*.[16]

$$\rho b = M/Vc \quad ...(11)$$

wherein,

M is the grape seed mass (g)
Vc is the volume occupied by grape seeds of a measuring cylinder (mm^3)

True Density (ρt)
ρt (kg/m^3) is determined by the mass of the grape seeds divided by its actual volume. Its mass was calculated with a digital balance (Sartorius Göttingen, Germany). The formula was following Karaj and Muller.[17]

$$\rho t = M/(n \times Vc) \quad ...(12)$$

wherein,

n is the grape seed numbers

Porosity (ε)
ε (%) suggested how many pores are present in a bulk material. The relationship between the true and bulk density was used in the calculation of porosity (%) as suggested by Mirzabe *et al*.[13]

$$\varepsilon = (1 - \rho b/\rho t) \times 100 \quad ...(13)$$

wherein,

ρb is the grape seed's bulk density (kg/m^3)
ρt is the grape seed's true density (kg/m^3)

The Mass of the Seed
Calculation of thousand mass (g) and unit mass (g) of grape seeds was performed with a digital balance (Sartorius, Göttingen, Germany).

Frictional Properties Calculations
Angle of Static Friction (μ)
μ is defined as the proportion of the normal force and the force needed to start an object to slide over a surface. μ changed for the grape seeds with varying moisture content and was subjected to four kinds of surfaces of contact, namely perpendicular as well as parallel plywood, galvanized iron, and glass. These are frequently employed in handling operations, storage, and transportation purposes as noted by Izli.[14]

$$\mu = \tan \tau \quad ...(14)$$

wherein,

τ is the tilt angle

Angle of Repose (Ɵ)
Ɵ is an angle generated between the pile's surface and the horizontally flat surface when granular material in the bulk is poured onto a flat surface. It provides insight into the cohesiveness of the various material units and serves as a reliable gauge of the product's flowability. Ɵ calculated with a cylinder (an open-ended) having dimensions height (13 cm) and diameter (8 cm). Placed a hollow cylinder on the flat surface table, after which grape seeds were put into it. When the cylinder filled with grape seeds slowly raised, a cone was formed. Both the height and the diameter of the cone were estimated as given by Izli.[14]

$$\theta = \tan^{-1} 2h/D \quad ...(15)$$

wherein,

h is the grape seeds pile height (mm)
D is the grape seeds pile diameter (mm)

Mechanical Properties Calculations
The textural analyzer was used to measure compression behavior (TA-XT2i, Stable Micro Systems, Surrey, United Kingdom). The experimental conditions were as follows: 75 mm compression platen probe was used to estimate the deformation at the rupture point (DrP), rupture force (RF), energy absorbed at rupture (Ea), toughness (T), and hardness (H). The test parameters included a test speed of 2.0 m/s, a pre and post-test speed of 1.5 m/s, and 10 m/s, a target distance of 5 mm, and

a trigger force of 10 g. Grape seed was put onto a static platform, and then to compress them, a flatten probe was used as suggested by Karaj and Muller.[17]

Deformation at Rupture Point (DrP)

The alteration to the initial dimensions of grape seed at the rupture point, when it undergoes compression, is known as deformation at the rupture point (mm). A continuous force drop showed in a force-deformation curve 'or' the point wherein the sample exhibits an apparent or undetectable disintegration in the shape of fractures indicates the rupture point as noted by Manuwa and Muhammad.[18]

Hardness (H)

Hardness is the result of the deformation-to-rupture force ratio at the rupture point. It is measured in N/mm. It is also considered a vital factor influencing seed strength. It was estimated by the following equation given by Izli.[14]

$$H = RF/DrP \quad ...(16)$$

wherein,

RF is the rupture force (Newton)
DrP is the deformation at the rupture point (millimeter)

Rupture Force (RF)

RF is the least amount of force necessary to cause a break or other type of fracture in the microscopic structure of grape seed and can be calculated directly with the help of a force-deformation curve plot as suggested by Gezer *et al.*[10]

Toughness (T)

The absorption of energy by grape seed till the rupture point of grape seed per unit volume is known as toughness (mJ/mm^3) and is calculated by following the equation shown by Gezer *et al.*[10]

$$T = Ea/Vu \quad ...(17)$$

wherein,

$$Ea = 1/2\ RF \times DrP$$

Energy (Ea)

At the rupture point, the absorption of energy (Nmm) by the grape seed was calculated by using a force-deformation curve as proposed by Vursavus and Ozguven.[19]

$$Ea = 1/2\ RF \times DrP \quad ...(18)$$

wherein,

RF is the rupture force
DrP is the deformation at the rupture point (mm)

Statistical Analysis

Results are presented as the mean of three observations and their standard deviation (±). Statistical analysis was performed at a significant (5%) level with the help of ANOVA. Duncan's test was used for the estimation of significant differences between different types of samples performed with SPSS software, version 16.0 (SPSS Corp, Chicago, USA).

Results

Compositional Analysis of Grape Seeds

The proximate analysis of grape seeds is mentioned in the Table 1. Grape seeds contain moisture (8.34%), crude protein (12.03%), crude fat (19.27%), Ash (3.02%), and carbohydrates (42.66%) respectively.

Table 1: Chemical composition of Grape seeds

Nutrients	Percentage (%)
Moisture	8.34±0.21[d]
Crude Protein	12.03±0.11[c]
Crude Fat	19.27±0.19[b]
Ash	3.02±0.05[e]
Total carbohydrate	42.66±0.25[a]

Note: Values are means± SD of triplicate determinations. Different letters in superscript within the same column indicate significant differences (P≤0.05) among the moisture content treatments tested.

Dimensional Properties

The dimensional properties of grape seeds at different moisture content level are presented in the Table 2. As far as length, thickness, and width are concerned there was an increasing trend observed as the moisture content increased from 8.74% to 24.10%. Dimensional properties of grape seeds at different moisture content. Arithmetic mean diameter and geometric mean diameter inclined from 5.05 to 5.30 mm and 4.77 to 5.01 mm as the moisture content rise from 8.74 to 24.10%. Sphericity increased from 0.650 to 0.673. Moreover, volume increased from 0.071 to 0.083 mm3 as the moisture content increased 8.74 to 24.10% respectively. Surface area and projected area showed increasing trend from 71.72 to 79.10 mm2 and 27.07 to 29.81 mm2 with the increase in the moisture content., respectively. Aspect ratio increased from 65.51 to 66.09 %. Table 3. showed the regression equation, as well as the coefficient of determination (R2), demonstrate the link between moisture content and the dimensional properties. Higher "R2" values indicate that an equation's fit to experimental values is optimal. The accurate measurement of the dimensional characteristics of grape seeds is crucial due to its main role in determining the size of the aperture for the seed handling machines in order to estimate how many seeds are being engaged at once in processing.

Table 2: Dimensional properties of grape seeds at different moisture content

Parameters	Moisture content (% wb)				
	8.74	12.35	16.13	20.18	24.10
Length (mm)	7.25 ± 0.05^{e}	7.34 ± 0.02^{d}	7.41 ± 0.04^{c}	7.50 ± 0.04^{b}	7.58 ± 0.06^{a}
Width (mm)	4.75 ± 0.05^{e}	4.83 ± 0.04^{d}	4.89 ± 0.02^{c}	4.95 ± 0.01^{b}	5.01 ± 0.02^{a}
Thickness (mm)	3.16 ± 0.01^{e}	3.22 ± 0.01^{d}	3.27 ± 0.02^{c}	3.29 ± 0.02^{b}	3.33 ± 0.01^{a}
Arithmetic mean diameter (mm)	5.05 ± 0.03^{e}	5.13 ± 0.04^{d}	5.19 ± 0.05^{c}	5.24 ± 0.02^{b}	5.30 ± 0.08^{a}
Geometric mean diameter (mm)	4.77 ± 0.09^{e}	4.85 ± 0.10^{d}	4.91 ± 0.11^{c}	4.96 ± 0.04^{b}	5.01 ± 0.15^{a}
Sphericity	0.650 ± 0.01^{e}	0.657 ± 0.04^{d}	0.663 ± 0.01^{c}	0.667 ± 0.01^{b}	0.673 ± 0.01^{a}
Volume (mm^3)	0.071 ± 1.21^{e}	0.075 ± 2.76^{d}	0.078 ± 1.32^{c}	0.080 ± 2.01^{b}	0.083 ± 2.87^{a}
Volumetric expansion coefficient	0.38 ± 0.04^{e}	0.40 ± 0.02^{d}	0.42 ± 0.06^{c}	0.43 ± 0.03^{b}	0.45 ± 0.05^{a}
Surface area (mm^2)	71.72 ± 0.12^{e}	73.89 ± 0.18^{d}	75.74 ± 0.84^{c}	77.29 ± 0.66^{b}	79.10 ± 0.98^{a}
Projected area (mm^2)	27.07 ± 0.7^{d}	27.82 ± 0.23^{c}	28.04 ± 0.13^{c}	29.14 ± 0.11^{b}	29.81 ± 0.18^{a}
Aspect ratio (%)	65.51 ± 0.13^{c}	65.80 ± 0.06^{ab}	65.99 ± 0.12^{a}	66.00 ± 0.15^{a}	66.09 ± 0.12^{a}
Elongation ratio	1.527 ± 0.03^{a}	1.519 ± 0.002^{b}	1.516 ± 0.05^{c}	1.515 ± 0.003^{d}	1.512 ± 0.004^{e}

Note: Values are means ± standard deviation (SD) of triplicate determinations. Different letters in superscript within the same row indicate significant differences ($P \leq 0.05$) among the moisture content

Table 3: Equations representing the relationship between engineering properties and moisture content of grape seeds

Parameters	Regression equation	Coefficient of determination
Length (mm)	$y = 0.0213x + 7.0694$	$R^2 = 0.998$
Width (mm)	$y = 0.0166x + 4.6158$	$R^2 = 0.993$
Thickness (mm)	$y = 0.0106x + 3.0814$	$R^2 = 0.962$
Arithmetic mean diameter(mm)	$y = 0.0158x + 4.9247$	$R^2 = 0.988$
Geometric mean diameter(mm)	$y = 0.0153x + 4.6512$	$R^2 = 0.984$
Unit Mass (g)	$y = 921.32x - 28.439$	$R^2 = 0.993$
Thousand seed mass (g)	$y = 0.6149x + 39.626$	$R^2 = 0.992$
Sphericity	$y = 0.0014x + 0.6384$	$R^2 = 0.988$
Volume (mm^3)	$y = 0.0008x + 0.0652$	$R^2 = 0.982$
Volumetric expansion coefficient	$y = 0.0044x + 0.3443$	$R^2 = 0.985$
Elongation Ratio	$y = -0.0009x + 1.5321$	$R^2 = 0.870$
Surface area (mm^2)	$y = 0.4703x + 67.882$	$R^2 = 0.993$

Projected area (mm^2)	y = 0.1767x + 25.495	R^2 = 0.974
Aspect ratio	y = 0.035x + 65.308	R^2 = 0.849
Bulk density (kg/cm^3)	y = 3.8488x + 573.79	R^2 = 0.949
True density (kg/cm^3)	y = 2.7243x + 1632.4	R^2 = 0.976
Porosity (%)	y = -0.1681x + 64.786	R^2 = 0.896
Angle of repose	y = 0.6169x + 20.983	R^2 = 0.997
Glass	y = 0.0098x + 0.1338	R^2 = 0.976
Parallel plywood	y = 0.0067x + 0.2022	R^2 = 0.979
Perpendicular plywood	y = 0.0094x + 0.2115	R^2 = 0.991
Galvanized iron	y = 0.0109x + 0.1508	R^2 = 0.971

Determination of Gravimetric Properties

Table 4. showed the gravimetric properties of grape seeds as a function of moisture content. Unit mass and thousand seeds mass increased from 0.0409 to 0.0576 g and 44.671 to 54.471 g as the level of moisture increased from 8.74% to 24.10%, respectively. Whereas bulk density and true density also increased from 609.40 to 673.12 kg/m^3 and 1665.71 to 1696.56 kg/m^3, with the variation in moisture content. Grape seeds porosity decreased from 63.19 to 60.32%, respectively.

Table 4: Gravimetric properties of grape seeds as a function of moisture content

Parameters	Moisture content (% wb)				
	8.74	12.35	16.13	20.18	24.10
Unit mass (g)	0.0409 ± 0.001^{a}	0.0442 ± 0.001^{a}	0.0478 ± 0.003^{a}	0.0523 ± 0.015^{a}	0.0576 ± 0.016^{a}
Thousand seed mass (g)	44.671 ± 0.09^{e}	47.540 ± 0.08^{d}	49.877 ± 0.07^{c}	51.680 ± 0.07^{b}	54.471 ± 0.08^{a}
Bulk density (kg/m3)	609.40 ± 0.11^{e}	623.69 ± 0.19^{d}	632.11± 0.61^{c}	644.33 ± 0.55^{b}	673.12 ± 0.43^{a}
True density (kg/m3)	1655.71 ± 0.61^{d}	1663.73 ± 1.01^{c}	1680.65 ± 1.32^{c}	1687.24 ± 0.73^{b}	1696.56 ± 1.62^{a}
Porosity (%)	63.19 ± 0.15^{a}	62.53 ± 0.09^{b}	62.38 ± 0.12^{c}	61.81 ± 0.25^{c}	60.32 ± 0.84^{c}

Note: Values are means ± SD of triplicate determinations. Different letters in superscript within the same row indicate significant differences (P ≤ 0.05) among the moisture content

Determination of Frictional Properties

With the increase in moisture content in grape seeds, the angle of repose values also increased from 26.32 to 35.71. The coefficient of friction of grape seeds at different surfaces changes with the variation in the moisture content of grape seeds. The coefficient of friction of grape seeds for glass, perpendicular plywood, parallel plywood, and galvanized iron surfaces increased from 0.21 to 0.36, 0.30 to 0.44, 0.26 to 0.36, and 0.24 to 0.40, respectively.

Table 5: Variation of frictional properties of grape seeds with moisture content

Parameters	Moisture content (% wb)				
	8.74	12.35	16.13	20.18	24.10
Angle of repose	26.32 ± 0.55^{e}	28.69 ± 0.45^{d}	30.78 ± 0.27^{c}	33.69 ± 0.23^{b}	35.71 ± 0.17^{a}
Coefficient of friction Glass	0.21 ± 0.02^{e}	0.26 ± 0.02^{d}	0.30 ± 0.02^{c}	0.34 ± 0.01^{b}	0.36 ± 0.03^{a}
Perpendicular plywood	0.30 ± 0.01^{e}	0.32 ± 0.02^{d}	0.36 ± 0.02^{c}	0.40 ± 0.3^{c}	0.44 ± 0.04^{a}
Parallel plywood	0.26 ± 0.01^{e}	0.28 ± 0.01^{d}	0.32 ± 0.01^{c}	0.34 ± 0.01^{b}	0.36 ± 0.01^{a}
Galvanized iron	0.24 ± 0.02^{e}	0.28 ± 0.01^{d}	0.34 ± 0.01^{c}	0.38 ± 0.06^{b}	0.40 ± 0.02^{a}

Note: Values are means± SD of triplicate determinations. Different letters in superscript within the same row indicate significant differences (P≤0.05) among the moisture content treatments tested.

Determination of Mechanical Properties

As shown in Table 6. The mechanical behavior of grape seeds upon compression has been observed. The rupture force decreased from 64.33 to 41.97 N as the moisture content increased from 8.74 to 24.10%. Deformation of grape seeds decreased from 0.789 to 0.626 mm with the change in moisture content. Hardness of grape seeds declined from 81.53 to 67.04 N/mm as the level of moisture content increased from 8.74 to 24.10%. Energy values obtained for grape seeds showed a decreasing trend with the increase in moisture content. Toughness of grape seeds decreased from 357.32 to 158.19 mJ/mm^3 with varying moisture content level.

Table 6: Effect of moisture content and compression axis on the mechanical behavior of grape seeds

Moisture content (%)	Rupture force (N)	Deformation (mm)	Hardness (N/mm)	Energy (Nmm)	Toughness (mJ/mm^3)
8.74	64.33 ± 0.32[a]	0.789 ± 0.001[a]	81.53 ± 0.87[a]	25.37 ± 0.18[a]	357.32 ± 2.06[a]
12.35	60.97 ± 0.27[b]	0.778 ± 0.006[ab]	78.36 ± 1.01[b]	23.71 ± 0.12[b]	316.13 ± 1.07[b]
16.13	54.69 ± 0.43[c]	0.721 ± 0.005[bc]	75.43 ± 1.21[c]	19.82 ± 013[c]	254.10 ± 1.05[c]
20.18	49.17 ± 0.22[d]	0.698 ± 0.003[cd]	70.44 ± 1.30[d]	17.16 ± 0.21[d]	214.50 ± 1.03[d]
24.10	41.97 ± 0.31[e]	0.626 ± 0.008[d]	67.04 ± 1.19[e]	13.13 ± 0.32[e]	158.19 ± 1.07[e]

Note: Values are means± SD of triplicate determinations. Different letters in superscript within the same column indicate significant differences (P≤0.05) among the moisture content treatments tested.

Discussion

Compositional Analysis of Grape Seeds

The average chemical composition of grape seeds is presented in Table 1. Grape seeds contain 19.27% crude fat, 12.03% crude protein, 3.02% ash, 8.34% moisture, and 44.66% carbohydrates. Moisture content was measured as a function of the seed and was found to significantly influence all physical properties of the grape seeds. The results of this study align with previous findings by Owon,[20] who reported an ash content of 2.86% in grape seeds. Additionally, Baydar and Akkurt,[21] observed crude fat content ranging from 11.6% to 19.6%, consistent with the current findings. Mironeasa *et al.*[22] found the crude protein content in the range of 6.26-9.01% based on different cultivar which is lesser than the present work.

Dimensional Properties

Size and Shape

The moisture content was found to be linearly correlated with the majority of the dimensional characteristics. The grape seeds showed increased average values for the dimensions, i.e., length, thickness, and width, with the change in moisture content from 8.74% to 24.10%, correspondingly (Table 2). With varying moisture content, the primary dimensions increased uniformly without distorting the shape of the seed. The overall average increase of grape seed in terms of length, width, and thickness was 4.55%, 5.47%, and 5.37% as a result of increased moisture content, which shows that grape seeds have a greater ability to expand in thickness and width rather than length. All the main dimensions (width, thickness, and length) of grape seeds varied significantly (P≤0.05) with the increased moisture content. The grape seed contains tiny air voids, or intracellular spaces, from where absorption of moisture takes place, which leads to an increase in its dimensional characteristics. Sahu *et al.*[23] revealed comparable outcomes for the mahua seeds. The regression equation, as well as the coefficient of determination (R^2), demonstrate the link between moisture content and the dimensional properties. Higher "R^2" values indicate that an equation's fit to experimental values is optimal (Table 3). The accurate measurement of the dimensional characteristics of grape seeds is crucial due to its main role in determining the size of the aperture for the seed handling machines in order to estimate how many seeds are being engaged at once in processing.

Principle geometric dimensions, e.g., geometric as well as arithmetic mean diameter of grape seeds, provide information about their shape. These measurements are vital for grading and sizing equipment design. With the rise in the moisture level of grape seeds, there was an increased trend in the geometric and arithmetic mean diameter observed in grape seeds (Table 2). Table 3 shows the regression equation used to illustrate the correlation between moisture content and geometric dimensions, which shows the optimal equation fitted well in comparison to experimental values. Similar findings have been presented by Pradhan *et al*.[24] for jatropha seeds.

Sphericity (Φ)

Variation in the sphericity values within a range (0.65 to 0.67) was found with the increased moisture content (Table 2). The relative inclination of grape seed's principal dimensions may be the cause. A higher sphericity value shows that seeds have a tendency with regard to the sphere, which will be important for the estimation of grape seed's drying behaviour and in the conveyor design as well as chute discharge.[16] The regression equation illustrates the connection between moisture content and sphericity (Table 3). Similar findings were previously reported in the case of sunflower seeds.[12]

Volume (Vu)

A linearly increasing trend in grape seed volume was observed with increased moisture levels (Table 2). A variation of 16.90% was seen in the grape seed's volume, which might be due to the moisture content that was absorbed. The mathematical regression equation and coefficient of determination (R^2) showed the connection between moisture content and grape seed volume (Table 3). Higher values of R^2 imply the best-fitted equation to the obtained experimental values.

It is indeed crucial to obtain an accurate approximation of the grape seed's volume in relation to its moisture content while considering parameters related to design, as in the case of machinery for sizing. Moreover, it paves the way for the calculation of other parameters, which could offer insight into the impacts of processing. Similar results were earlier observed in the case of apricot kernels.[25]

Volumetric Expansion Coefficient (ψ)

As illustrated in Table 2, ψ increased from 0.38 to 0.45 for the grape seeds with the moisture content variations. Grape seeds showed an 18.42% variation in their ψ with the changed moisture content, perhaps due to the fact that the grape seed's cellular structure changed as a result of the air spaces located among tissue decreasing.

Surface Area (Sa)

Sa gradually surged as the moisture content increased, and the maximum values were found at the moisture content of 24.10%, as shown in Table 2. The total change was found to be 10.29% in grape seed surface area, with the moisture content changing from 8.74 to 24.10%. At all the moisture content levels, grape seeds had a significant difference ($P \leq 0.05$) in the surface areas. A subsequent increase in grape seed surface area with an increase in the level of moisture may lead toward a shift observed in dimensional properties. It is crucial for the estimation of the drying rates of grape seeds. A similar trend was previously reported by Malik and Saini,[26] for sunflower seeds and Fathollahzadeh *et al*.[25] for apricot kernels, as the variations occurred in the moisture content.

Projected Area (Pa)

As the level of moisture increases, Pa also rises gradually in the range of 27.07 to 29.81 mm^2, individually. The grape seed's projected area showed a variation of 10.12% within the calculated moisture levels. The projected area showed a linear increase with the moisture content, following the regression analysis performed, and the higher R^2 value (Table 3) shows the equation is best fitted to experimental values. The findings are vital in the designing of separators, pneumatic conveyors, and kernel cleaners. Similar increased trends were earlier found by Aydin,[27] for almonds and Ehiem *et al*.[28] for Canarium schweinfurthii Engl fruit.

Aspect Ratio (Ar)

Ar values of the grape seeds varied in the range from 65.51 to 66.09 (Table 2). Aspect ratio plays a vital role in the determination of grape seeds' behaviour on a flat surface, as they will either slide or roll down. If the aspect ratio values of seeds were higher, it indicated that on the slopes, seeds would typically roll instead of slide because of the closeness of the aspect ratio towards seed sphericity. Similar inclined trends were reported earlier by Mansouri *et al*.[15] in the case of melon kernels as well as seeds.

Elongation Ratio (Er)

As the level of moisture increases, the elongation ratio of grape seeds changes to a smaller extent. Smaller values for the shape parameters demonstrate a seed had a greater tendency to have a flat, oblong shape. Mirzabe *et al.*[13] reported similar trends for cucumber seeds. A regression equation was used for the relationships (in mathematical terms) derived from experimental data with the change in moisture level illustrated in Table 2, which will be helpful in the designing of conveyor equipment and separator.

Determination of Gravimetric Properties

Unit Mass and Thousand Seed Mass (1000)

Grape seed unit mass as well as 1000 seed mass linearly rise with the rise in moisture level of grape seeds (Table 4). As moisture content increased, unit mass, as well as thousand seed mass, tended to rise in the range of 0.0409 to 0.0576 g and 44.671 to 54.471 g, respectively. The rise in water content (in terms of mass) caused by a surge in moisture content may be the reason behind it. A similar rising trend was reported earlier. In the case of Karanja kernels,[29] a similar upward trend was earlier reported. Grape seed unit mass and 1000 seed mass illustrated variations with significant differences ($P \leq 0.05$) as the moisture level rose, as indicated by the statistical analysis.

Bulk Density (ρb)

As shown in Table 4, the bulk density of grape seeds increased gradually with an increment in moisture content. ρb values differ significantly ($P \leq 0.05$) for grape seeds. ρb of grape seeds changed by 10.45% when the moisture content varied from 8.74% to 24.10%. ρb of grape seeds ranged from 609.40 to 673.12 kg/m^3, depending on the moisture content. This characteristic determines how seeds are distributed after shaking and how each particle is shaped. The higher the bulk density values, the more tightly packed and agitated the seeds are.30 Therefore, bulk density has practical applications in calculating Reynolds number in the pneumatic and hydraulic handling of seeds.[31]

True Density (ρt)

With the rising level of moisture from 8.74 to 24.10%, ρt values also rise. An increase in the percentage of about 2.46% was observed for true density. With the varied moisture level, the ρt values for grape seeds increased from 1655.71 to 1696.56 kg/m3. Similar findings were earlier documented for terebinth fruits.[32]

Porosity (ε)

As moisture content increased, the porosity of grape seeds reduced from 63.19 to 60.32%. Bulk density and true density have a direct relationship with porosity, and this dependence is not the same for every seed. The porosity (ε) of grape seed declined by 4.54% in the evaluated moisture level limit. The porosity, which reflects the seed's resistance to the flow of air, is a crucial parameter for the drying process. This knowledge is vital for designing seed hoppers.

Determination of Frictional Properties

Angle of Repose (Θ)

As the level of moisture increased in grape seeds, values of angle of repose also increased gradually. Θ showed a variation of 35.67% with a rise in the level of moisture (Table 5). A potential cause of this surging pattern in the angle of repose as moisture level increases might be because the surface of the seed is covered with a moisture layer that provides the required surface tension to keep the collection of grape seeds together. Higher levels of moisture cause grape seeds to adhere more tightly, improving stability and reducing flowability. It helps design the structural accessories and calculate belt conveyor width. This finding was also supported by similar studies.[15,33,34]

Angle of Static Friction (μ)

As shown in Table 5, In all these structural surfaces, μ gradually increased as the moisture content rose. The probable reason is due to the adhesive force at increased moisture levels, where the grape seed's surfaces became rougher, and their ability to slide consequently decreased.[14,35] It was also found that at each level of moisture content, perpendicular plywood showed higher μ than plywood (parallel), galvanized iron, and glass as well. The disparity among surface-related properties of various contacting surface materials could be the cause, and the results were supported by earlier studies.[33] The regression equation and R^2 derived from experimental data on the interconnection among μ and moisture level (Table 3) may be valuable in the designing of various post-harvest equipment, such as hoppers, forage harvesters, storage bins, etc.

The maximum angle of inclination of the conveyor systems is constrained through μ, and the findings may be crucial in determining the angle where chutes should be placed in order to ensure steady material flow.

Determination of Mechanical Properties

Rupture Force (RF)

As the level of moisture rose, the force needed to cause the rupture of the grape seeds decreased from 64.33 to 41.97 N respectively (Table 6). The results for the rupture force of grape seed showed an inverse relationship with the increased level of moisture. The potential cause behind rupture force drop with an increase in moisture level could be explained by the fact that at a higher level of moisture, water absorption causes modification in the cellular structure of the seed, which became softer and needed less force to crack.[19] Similar trends were previously reported for safflower seeds,[36] kenaf seeds,[14] and apricot kernels.[10] For handling agricultural products, extensive knowledge regarding the behaviour of grape seeds with respect to changed moisture content under the application of forces is crucial.

Deformation at Rupture Point (DrP)

With the increased moisture level of grape seeds, DrP decreased (Table 6). DrP significantly differs ($P \leq 0.05$) as the moisture content varied in grape seeds and this demonstrates the flexibility and resistance to deformation of grape seeds. A similar trend of inverse relationships was found for hazelnut.[37]

Hardness (H)

The grape seeds' hardness revealed a decreasing trend as the moisture level increased between 8.74 and 24.10%, as shown in Table 6. A potential reason may be related to the softening of the seed's structure because of the increased moisture content, which lowers the seed's resistance with regard to the compressive force.[38] Similar results were previously found in the case of kenaf seeds[14] as well as sunflower seeds.[39] Statistical analysis showed that compressive loading and moisture level produced a significant ($P \leq 0.05$) effect regarding the hardness of grape seeds. Thus, understanding the interconnection between hardness and moisture content, as well as loading in the processing of grape seed, could be crucial to energy conservation.

Energy (Ea)

The absorbed energy (Nmm) at the rupture point in relationship to variation in moisture content can be estimated by the area underneath the force-deformation curve. It was found that the energy values declined with the inclination in the level of moisture. The lowest value was 13.13 Nmm, obtained at a moisture content of 24.10% (Table 6). This suggests that compression of the grape seed would result in less energy required for cracking if the moisture level was high. A similar trend was earlier found in the case of apricot pits.[19]

Toughness

Grape seed toughness was revealed as the absorption of energy by grape seed till the point of rupture caused in the grape seed per unit volume. It was found that toughness values drop as the gain in moisture level. At a moisture level of 8.74%, the highest value of 357.32 (mJ/mm3) was found among all the moisture levels evaluated. The outcome illustrated that with the increased moisture content, the energy needed to rupture a compressed grape seed continued to decrease, which shows that at a higher level of moisture content, the grape seed rupture requires less energy for initiation. A similar result in relation to toughness was previously found in the case of apricot pits,[19] and shea nuts.[18]

Conclusion

The moisture-dependent properties of grape seeds were studied in the present research work. The grape seed exhibited a geometric shape that closely resembled an ovoid geometry. The findings showed that the dimensional, mechanical, and frictional properties of grape seed were significantly influenced by the level of moisture present in the seed. The level of moisture content showed a direct relationship to the angle of static friction and several other characteristic dimensions of grape seeds. With a rise in moisture content between 8.74% and 24.10%, bulk density and true density were also increased to 673.12 and 1696.56 kg/m3, whereas 1000 seed mass linearly rose between 44.671 to 54.471 g, respectively. Moisture content and DrP, energy, hardness, rupture force, and toughness were inversely interconnected. Moreover, porosity was found to be decreased from 63.19 to 60.32 with increased moisture level. In addition to that proximate analysis revealed that, grape seeds contain various macromolecules such as protein, lipid, and carbohydrates in significant amount, which can be exploited for the nutritional purposes of mankind. Consequently, understanding dimensional, mechanical, and frictional properties concerning changes in the level of moisture content may be vital in designing post-harvest related equipment as well as grape seed processing in order to conserve energy. Using a specific variety of grape seeds, i.e., Bangalore Blue, in the current study may limit the generalizability of the findings. However, this choice was intentional to ensure a detailed and focused investigation of the effects of moisture content on this particular variety. Future studies can expand on this work by exploring other grape seed varieties to provide a broader understanding of the phenomenon and other aspects like analysing the impact of various drying techniques or evaluating the potential of grape seeds as a source of bioactive compounds. The influence of harvesting season, variety and stage of maturity on the properties of grape seeds, which could be examined in the grape seed as a source of value-added products like nutraceuticals, food, or biofuels.

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- **Mohammad Ubaid:** Investigation, Visualization, Formal analysis, Data curation, Data analysis, Manuscript writing.
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