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Impact of Moisture Level on Engineering Characteristics of Different Indian Cultivars of Halim (*Lepidium sativum*) Seed

Nirbhay Kumar*, Sukhcharn Singh and DC Saxena

Department of Food Engineering and Technology, Sant Longowal Institute of Engineering and Technology (SLIET), Longowal, Punjab, India

***Correspondence to:**
Nirbhay Kumar
Department of Food Engineering and Technology,
Sant Longowal Institute of Engineering and Technology (SLIET),
Longowal, Punjab, India.
E-mail: nirbhaynir000@gmail.com

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Abstract

This study investigated the engineering properties of three cultivars of halim (*Lepidium sativum*) seeds across moisture levels ranging from 5% - 20%. These characteristics are crucial for designing and developing systems for handling, transport, processing, and storage, as well as for evaluating seed quality. Dimensional, gravimetric, frictional, and mechanical attributes were examined in relation to moisture content, and regression models were developed to describe these relationships. The findings indicated that all measured properties were significantly influenced by moisture variation. Among the cultivars, HS-2 exhibited the largest seed dimensions, followed by HS-3 and HS-1. At 5% moisture content, the HS-2 seeds had average length (L), width (W), thickness (T), and thousand seed weight values of 2.21 mm, 0.89 mm, 0.69 mm, and 1.95 g, respectively. With increasing moisture, the arithmetic mean diameters (D_a) and geometric mean diameters (D_g) of HS-2 increased from 1.26 - 1.35 mm and 1.10 - 1.19 mm, respectively, while sphericity ranged from 0.50 - 0.51. Over the same moisture range, bulk and true densities decreased from 762.52 - 678.76 kg/m^3 and 1235.62 - 1148.33 kg/m^3, respectively, while porosity increased from 38.29% - 40.89%. The angle of repose also rose from 18.75° - 25.38° as moisture content increased. Various parameters such as seed dimensions, volume (V_u), surface area (S_a), thousand seed weight, angle of repose, and static friction showed a linear increase with moisture, while bulk density (ρ_b), true density (ρ_t), and rupture force decreased linearly. Among the tested surfaces, the highest coefficient of static friction was recorded on plywood, followed by galvanized iron and glass. These engineering properties are fundamental for the design and optimization of equipment used in harvesting, processing, handling, sorting, and packaging of halim seeds.

Keywords

Halim seeds, Physical properties, Moisture content, Engineering properties, Regression equations

Introduction

Halim (*L. sativum* L.) is a rapidly growing annual herb from the Brassicaceae family, known for its peppery and tangy flavor [1, 2]. It is commonly referred to as "garden cress", "garden pepper cress", "pepper wort", "pepper grass", "poor man's pepper", "asaliyo", or "chandrasoor". It is both a medicinal and oilseed crop [2-5]. It is grown for its seeds globally, including the Mediterranean region, along with West and Central Asia, North America, and many Indian states. Although it thrives in various climates and soils year-round, it yields best in winter [3, 6]. Halim seeds are tiny, oval-shaped, with a pointed triangular end, and have a reddish-brown color [7]. These are rich in macro and micronutrients, including 30.7% carbohydrates, 24.2% proteins, 23.2% fats, 11.9% fibers, and 7.1% minerals, and vitamins. The oil extracted from these seeds is beneficial due to its

high content of polyunsaturated (46.8%) and monounsaturated (37.6%) fatty acids, which boost metabolism and lower the risk of diseases like cancer, obesity, asthma, and arthritis [8]. Halim seeds are nutrient-dense and effective against anemia, malnutrition, and other nutritional deficiencies. They have various health benefits and can fortify functional foods [1]. Although underutilized, their demand is rising due to their nutritional and pharmacological properties, classifying them as a "superfood" [9, 10]. Post COVID-19 pandemic, increased health awareness has boosted the production and consumption of halim seeds.

Moisture content significantly impacts the processing, nutritional quality, and safety of halim seeds. Higher moisture increases elasticity, reducing milling efficiency and producing coarser flour, while lower moisture improves milling but may cause breakage. It affects extrusion properties, influencing texture, and plays a crucial role in oil extraction, where excess moisture can cause emulsification issues, while drier seeds enhance oil yield but require careful handling. Moisture also impacts ρ_b, flow, and friction, affecting storage, sorting, and packaging. Nutritionally, high moisture levels can degrade bioactive compounds like glucosinolates and flavonoids, while controlled drying preserves them. Moisture influences protein stability, improving digestibility at optimal levels but leading to degradation if excessive. Proper hydration can also enhance nutrient bioavailability in sprouted seeds, whereas over-hydration promotes microbial growth. For food safety, high moisture (>12%) encourages mold, yeast, and bacterial growth, increasing risks of *Salmonella* and *E. coli* contamination. Maintaining moisture below 8 - 10% limits microbial activity and extends shelf life. Excess moisture accelerates lipid oxidation, causing rancidity, and fosters aflatoxin-producing fungi, which can be controlled through proper drying and packaging. Optimizing moisture content is essential for efficient processing, nutrient retention, and ensuring food safety in halim seed applications [11, 12].

Understanding the engineering properties of horticultural products is essential for designing handling, processing, and storage equipment to minimize post-harvest losses [13-15]. Optimizing processes and equipment design relies on assessing physical and mechanical properties at various moisture levels [15]. High moisture content in grains/seeds increases silo wall pressure, causing flow issues like arching, segregation, and irregular flows. Key axial dimensions of grains/seeds are crucial for determining milling power, sieve selection, kernel V_u, and S_a, impacting aeration, drying, heating, and cooling processes. Understanding bulk and true densities is vital for sizing storage facilities and hoppers and ensuring efficient heat and moisture transfer during aeration and drying. The angle of repose indicates the flow characteristics of grains/seeds, which are crucial for designing hoppers. Hopper walls should have an inclination angle exceeding the material's angle of repose to maintain a consistent flow through gravity. The friction coefficient is essential for conveyor design to prevent seed slippage. Seed hardness affects milling quality and end-use, while moisture content influences rupture force under quasi-static loading. These properties are fundamental for designing processing equipment and optimizing halim seed handling and processing [13].

Many studies have examined the physical and mechanical characteristics of various grains and seeds, including plum kernels [15], quinoa seeds [13], kenaf seeds [16], bitter gourd seeds [17], and sunflower seeds [18], in relation to moisture content. Determining physical and mechanical characteristics at various moisture levels is essential for optimizing equipment design and process parameters. Halim seeds are underutilized seeds which may have numerous potentials. A literature review indicates limited research on the engineering properties of halim seeds, with their physical and mechanical characteristics at different moisture levels yet to be explored. Moreover, factors like seed variety, geographical location, and environmental conditions significantly influence their dimensional, gravimetric, and mechanical attributes. Hence, this study seeks to investigate the specific engineering properties of halim seeds grown in India, considering the impact of seed variety and moisture content fluctuations. This research endeavor aims to enhance understanding of halim seeds and facilitate the development of efficient post-harvest handling and processing machinery.

Materials and Method

Sample preparation and moisture content determination

Three cultivars of good quality halim seeds were procured from different geographical locations of India: HS-1 from RR Agro Foods, Neemuch, Madhya Pradesh, HS-2 from Shri Ram Food International, Jodhpur, Rajasthan, and HS-3 from YSP University, Solan, Himachal Pradesh. The seeds were manually cleaned to eliminate foreign materials, including dirt, dust, stones, residual seeds, and broken or immature seeds. The refined seeds were then used for the study.

The moisture content of the halim seed sample was determined using the hot air oven technique. The initial moisture content of three cultivars of halim seed were found to be 7.65 ± 0.09%, 7.63 ± 0.15%, and 8.29 ± 0.02% (wet basis) respectively. Each cultivar of seeds was conditioned to four different moisture contents, ranges from 5% - 20% (with a gap of 5%), as seed processing is typically conducted within these moisture ranges. The desired moisture contents of the halim seed were adjusted by drying at 50 °C in convection air oven or adding pre-calculated amount of distilled water, following the specified equation [15].

$$Q = \frac{W_i(M_f - M_i)}{(100 - M_f)} \quad (1)$$

Where: Q = Mass of water to be added (kg); W_i = Initial sample mass (kg); M_i = Initial moisture content (%); and M_f = Desired final moisture content (%).

The samples were then sealed in separate polyethylene bags to maintain uniform moisture distribution and kept in a refrigerator at 5 °C for one week. Prior to analysis, the seeds were removed from refrigeration and left at an ambitious temperature for about an hour. The physical and mechanical characteristics of the seeds were evaluated at four moisture levels: 5%, 10%, 15%, and 20%. Three replications of each sample were examined to prevent errors.

Determination of dimensional properties

Axial dimensions (L, W, and T)

A random sample of 20 seeds was selected to measure the average axial dimensions, including L, W, and T. These measurements were taken using a digital vernier caliper with an accuracy of ±0.01 mm.

D_a and D_g

The D_a (mm) and D_g (mm) of the seeds were calculated as the averages of three dimensions using the following equations [15].

$$D_a = \frac{(L+W+T)}{3} \quad (2)$$

$$D_g = \sqrt[3]{L \times W \times T} \quad (3)$$

Sphericity (Ψ)

Sphericity is a metric that indicates how closely an object approximates a perfect sphere. It is determined as the ratio of the S_a of a sphere with the same V_u as the seed to the actual S_a of the seed. Sphericity is calculated using isoperimetric property of a sphere, as expressed in the following equation [15].

$$\Psi = \frac{\sqrt[3]{L \times W \times T}}{L} = \frac{D_g}{L} \quad (4)$$

V_u

The V_u (mm^3) of the halim seed was determined by employing an equation derived from the assumption that halim seeds share similarity with a scalene ellipsoid, with L > W > T [15].

$$V_u = (L \times W \times T \times \Psi) \quad (5)$$

Equivalent diameter (De)

The D_e (mm) of halim seed was described by following equation [19].

$$D_e = \sqrt[3]{\frac{6 \times V_u}{\pi}} \quad (6)$$

Elongation ratio (Er), Flakiness ratio (Fr), and Aspect ratio (Ar)

The parameters defining the shape of halim seeds, including E_r, F_r, and A_r (%), were calculated using specific equations. These parameters indicate the seed's propensity for certain shapes and their likelihood of sliding or rolling on flat surfaces [15].

$$E_r = \frac{L}{W} \quad (7)$$

$$F_r = \frac{T}{W} \quad (8)$$

$$A_r = \frac{W}{L} * 100 \quad (9)$$

S_a

The S_a (mm^2) of halim seeds were estimated by assuming their shape to be a sphere with an equivalent D_g. S_a represents the total area covered by the object's surface and is calculated using the equation below [15].

$$S_a = \pi \times (D_g)^2 \quad (10)$$

Projected area (Pa) and specific surface area (Ssa)

The P_a (mm^2) and S_{sa} (mm^{-1}) are essential factors in evaluating the aerodynamic properties of halim seeds. These parameters were calculated using the provided equation. The P_a refers to the S_a positioned perpendicular to the applied force and holds significance in the design of seed cleaners [15].

$$P_a = \frac{(\pi \times L \times W)}{4} \quad (11)$$

$$S_{sa} = \frac{S_a \times \rho_b}{M} \quad (12)$$

Where: ρ_b is in g/mm^3 and M is mass of one seed in g.

Determination of gravimetric properties

Thousand seed weight (M1000)

The thousand seed weight was determined by randomly selecting 100 halim seeds from each sample and weighing them using an electronic balance with a precision of 0.001 g. The resulting weight was then multiplied by 10 [13].

ρb

ρ_b (kg/m^3) is described as the ratio of a seed's mass to its overall V_u, indicating the material weight per unit V_u. It was evaluated by pouring seeds into a 25 ml measuring cylinder from 15 cm height, then weighing the contents using a digital electronic balance with an accuracy of ±0.001 g. The ρ_b for each replicate was determined using the given formula [13, 15].

$$\rho_b = \frac{M}{V} \quad (13)$$

Where, M = mass of seed (kg); V = V_u occupied by seed (m^3)

ρt

ρ_t (kg/m^3) measures the mass of seeds relative to their actual V_u. It was determined using the toluene ($C_6H_5CH_3$) displacement method, which is preferred over water because it is less readily absorbed by seeds and more effectively fills fine crevices due to its low surface tension. To calculate ρ_t, a specific number of seeds were submerged in measured toluene within a graduated cylinder, and the V_u of displaced toluene was noted. The ρ_t was subsequently measured using the following formula [13].

$$\rho_t = \frac{M}{V_d} \quad (14)$$

Where, M = mass of seed (kg); V_d = V_u of toluene displaced by the seed (m^3).

Porosity (ϕ)

Porosity (in %) represents the proportion of pores within a bulk material, denoting the V_u of air present in relation to the total V_u. It is calculated as the ratio of pore V_u to total V_u. The porosity of halim seeds at varying moisture levels was

determined using ρ_b and ρ_t, following the given equation [15].

$$\phi = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \quad (15)$$

Determination of frictional properties

Angle of repose (θ)

The angle of repose (degrees) was measured using an open-ended cylinder placed on a circular plate, which was filled with seeds. The cylinder gradually lifted, allowing the seeds to form a conical pile. The cone's height and diameter were then measured with a vernier calliper, and the angle of repose was computed using the given equation [15].

$$\theta = \tan^{-1}\left(\frac{2H}{D}\right) \quad (16)$$

Where, H = height of conical heap and D = diameter of conical heap.

Coefficient of static friction (μ)

The coefficient of static friction was measured on three surfaces-plywood, glass, and galvanized iron-commonly used in transportation, storage, and handling. To determine this coefficient, a hollow cylinder filled with seeds was positioned on each surface, and the surface inclination was slowly increased until the cylinder, loaded with seeds, initiated to slide. The static coefficient of friction was then computed using the given formula [13, 15, 20].

$$\mu = \tan(\alpha) = \frac{h}{b} \quad (17)$$

Where, α = angle of tilt (degree); h = height raised (cm); and b = base distance (cm).

Determination of mechanical properties

The mechanical characteristics were assessed using a Texture Analyzer (TA-HDi, Stable Micro Systems) with minor adjustments [13]. Compression tests used a pre-test speed of 0.05 mm/s, test speed of 0.05 mm/s, post-test speed of 1 mm/s, test distance of 1 mm, auto trigger type, and a trigger force of 3 g with a P/5 probe (approx. 5 mm diameter). Individual halim seed was compressed between the P/5 probe and the base plate. Mechanical property such as peak rupture force (hardness) was determined, with three samples tested at each moisture level.

Statistical analysis

Statistical analysis was performed in triplicate, with results presented as mean ± standard deviation. Sample variance was evaluated using one-way analysis of variance (ANOVA) in SPSS (IBM SPSS Statistics 26). Duncan's multiple range test ($p \leq 0.05$) was applied to determine significant differences. Furthermore, linear regression analysis was performed using Origin (2017) software.

Results and Discussion

Effect of moisture content on dimensional properties

The changes in important dimensional characteristics of halim seeds at varying moisture contents are shown in table 1. The study's results show a strong positive correlation between moisture level and the L, W, and T of different halim seed cultivars. This suggests that as moisture content increases, halim seeds expand in all three axial dimensions. It was observed that the average primary dimensions (L, W, and T) of halim seeds expanded as the moisture level increased from 5% to 20%. But there is no significant difference ($p \leq 0.05$) among axial dimensions of halim seeds within the same variety. The expansion in halim seeds may be caused by the intracellular spaces absorbing moisture or by microscopic air holes that cause the seeds to become dimensionally larger. Comparable trends have been reported for plum kernels [15], quinoa seeds [13], African star apple seeds [20], and kenaf seeds [16], where dimensional size increases with moisture content.

The morphology of the halim seed remained unchanged despite variations in its moisture level. The mean value of L, W, and T of halim seed varied from 2.15 - 2.21 mm, 0.82 - 0.89 mm, and 0.62 - 0.68 mm for HS-1; from 2.21 - 2.37 mm, 0.89 - 0.96 mm, and 0.69 - 0.74 mm for HS-2; and from 2.16 - 2.37 mm, 0.84 - 0.96 mm, and 0.63 - 0.70 mm for HS-

Table 1: Some dimensional characteristics of halim seeds at varying moisture levels.

Moisture content (%)		L (mm)	W (mm)	T (mm)	D_a (mm)	D_g (mm)	Sphericity	V_u (mm³)	D_e (mm)
HS-1	5	2.15 ± 0.13^a	0.82 ± 0.05^a	0.62 ± 0.06^a	1.19 ± 0.08^a	1.03 ± 0.07^a	0.48 ± 0.01^b	0.53 ± 0.12^a	1.00 ± 0.07^a
	10	2.19 ± 0.19^a	0.87 ± 0.06^a	0.63 ± 0.07^a	1.23 ± 0.10^a	1.06 ± 0.09^a	0.48 ± 0.00^b	0.59 ± 0.15^a	1.03 ± 0.09^a
	15	2.20 ± 0.15^a	0.87 ± 0.10^a	0.65 ± 0.06^a	1.24 ± 0.10^a	1.07 ± 0.09^a	0.49 ± 0.01^{ab}	0.62 ± 0.18^a	1.05 ± 0.10^a
	20	2.21 ± 0.19^a	0.89 ± 0.09^a	0.68 ± 0.05^a	1.26 ± 0.11^a	1.10 ± 0.09^a	0.50 ± 0.00^a	0.67 ± 0.17^a	1.08 ± 0.09^a
HS-2	5	2.21 ± 0.14^a	0.89 ± 0.10^a	0.69 ± 0.09^a	1.26 ± 0.11^a	1.10 ± 0.11^a	0.50 ± 0.02^a	0.69 ± 0.23^a	1.09 ± 0.12^a
	10	2.28 ± 0.12^a	0.94 ± 0.07^a	0.73 ± 0.05^a	1.31 ± 0.08^a	1.16 ± 0.07^a	0.51 ± 0.01^a	0.80 ± 0.16^a	1.15 ± 0.08^a
	15	2.34 ± 0.18^a	0.94 ± 0.10^a	0.73 ± 0.08^a	1.33 ± 0.12^a	1.17 ± 0.11^a	0.50 ± 0.01^a	0.82 ± 0.25^a	1.15 ± 0.12^a
	20	2.37 ± 0.11^a	0.96 ± 0.09^a	0.74 ± 0.07^a	1.35 ± 0.09^a	1.19 ± 0.09^a	0.50 ± 0.02^a	0.85 ± 0.22^a	1.17 ± 0.10^a
HS-3	5	2.16 ± 0.15^a	0.84 ± 0.05^a	0.63 ± 0.09^a	1.21 ± 0.09^a	1.04 ± 0.09^a	0.48 ± 0.01^a	0.56 ± 0.16^a	1.01 ± 0.09^a
	10	2.28 ± 0.16^a	0.92 ± 0.08^a	0.67 ± 0.07^a	1.29 ± 0.10^a	1.12 ± 0.09^a	0.49 ± 0.01^a	0.70 ± 0.19^a	1.09 ± 0.10^a
	15	2.32 ± 0.15^a	0.94 ± 0.11^a	0.69 ± 0.09^a	1.31 ± 0.11^a	1.14 ± 0.12^a	0.49 ± 0.02^a	0.76 ± 0.26^a	1.12 ± 0.13^a
	20	2.37 ± 0.14^a	0.96 ± 0.12^a	0.70 ± 0.06^a	1.34 ± 0.10^a	1.16 ± 0.10^a	0.49 ± 0.02^a	0.80 ± 0.23^a	1.14 ± 0.11^a

Note: Values are means ± SD of triplicate determinations. Similar letters in superscript within the same variety and column did not differ significantly ($p \leq 0.05$).

3, respectively, as moisture levels increased from 5% to 20%. It was observed from the data that the dimensions of the halim seed variety HS-2 was comparatively larger, followed by HS-3 and HS-1. The axial dimensions of halim seeds follow the order: L > W > T. These dimensions are useful for determining the seed's shape and selecting the appropriate aperture size for seed handling equipment.

Basic geometric measurements like D_a, D_g, and D_e of halim seeds, are crucial for shaping and designing equipment for sorting and grading based on their shape. It was found that all average diameters of halim seeds, including the D_a, D_g, and D_e, increased as moisture content rose (Table 1). This is likely attributed to the growth in principal dimensions of the seeds. There is no significant difference ($p \leq 0.05$) in diameter related to moisture content within the same variety. The D_a, D_g, and D_e of halim seed ranged from 1.19 - 1.26 mm, 1.03 - 1.10 mm, and 1.00 - 1.08 mm for HS-1; from 1.26 - 1.35 mm, 1.10 - 1.19 mm, and 1.09 - 1.17 mm for HS-2; and from 1.21 - 1.34 mm, 1.04 - 1.16 mm, and 1.01 - 1.14 mm for HS-3, respectively, as the moisture level raised from 5% - 20%. The D_g could be used to determine sphericity of the seed theoretically. The results align with the increasing trend observed for plum kernels [15], quinoa seeds [13], African star apple seeds [20], and sunflower seed [21], with diameters increasing as moisture content rises. For two quinoa varieties, both the arithmetic and geometric were reported to increase with rising moisture content (5% - 25%), ranging from 1.47 - 1.71 mm and 1.58 - 1.80 mm (arithmetic), and 1.37 - 1.60 mm and 1.50 - 1.71 mm (geometric), respectively [13].

The sphericity of halim seeds indicates the measure of their roundness. It was observed that the value of sphericity of halim seed increased or varied very closely on moisture absorption (Table 1). The mean value of sphericity of halim seed varied from 0.48 - 0.50 for HS-1, 0.50 - 0.51 for HS-2, and 0.48 - 0.49 for HS-3, on elevating the moisture content from 5 - 20%. The sphericity of seeds depends on their principal dimensions. Greater sphericity values signify the inclination of seeds towards spheres, which is essential for the analytical forecasting of seed drying characteristics and the design of chute discharge and conveying systems [15]. The value of sphericity can be used to calculate the seed V_u theoretically. Comparable trends have been noted for plum kernels [15], quinoa seeds [13], bitter gourd seeds [17] and kenaf seeds [16] with increasing moisture content. For example, the sphericity of plum kernels was reported to range from 0.67 - 0.68 as moisture content increased from 2.64% - 16.85% [15].

The V_u of halim seeds expanded as moisture content increased, showing no significant variation within the same cultivar (Table 1). The average value of theoretical seed V_u ranged from 0.53 - 0.67 mm^3 for HS-1, 0.69 - 0.85 mm^3 for HS-2, and 0.56 - 0.80 mm^3 for HS-3, as moisture content rose from 5% - 20%. V_u of the seeds can also be used to determine its D_e. V_u can be considered a design parameter for equipment sizing. It also makes it possible to compute other factors, which may reveal information about the impacts of processing [15]. Similar patterns have been observed in plum kernels [15], and kenaf seeds [16], where V_u increases with rising moisture content.

The E_r, F_r, and A_r of halim seeds also varied with moisture content (Table 2). In most of these ratios, significant difference ($p \leq 0.05$) was not observed within same cultivar. The mean value of E_r, F_r, and A_r of halim seed ranged from 2.62 - 2.49, 0.75 - 0.77, and 38.14 - 40.23% for HS-1, from 2.49 - 2.48, 0.78 - 0.77, and 40.18 - 40.44% for HS-2, and from 2.57 - 2.48, 0.75 - 0.73, and 38.90 - 40.40% for HS-3, respectively, with increasing moisture content. A high E_r and low F_r of halim seeds indicate a tendency toward a flat, oblong shape, making them more likely to slide rather than roll on flat surfaces. This experimental data could be valuable for designing separators, hoppers, and conveying equipment. Similar trends have been observed for plum kernels [15], and sunflower seeds [22]. In plum kernels, the E_r, F_r, and A_r were reported to vary from 1.440 - 1.465, 0.657 - 0.670, and 68.08% - 69.31%, respectively, as the moisture content increased from 2.64% - 16.85% [15].

Table 2: Different shape ratios, S_a, and mechanical property of halim seeds at different moisture content levels.

Moisture content (%)		E_r	F_r	A_r (%)	S_a (mm^2)	P_a (mm^2)	S_{sa} (mm^{-1})	Rupture force (N)
HS-1	5	2.62 ± 0.00^a	0.75 ± 0.03^a	38.14 ± 0.02^b	3.34 ± 0.48^a	1.38 ± 0.17^a	1.49 ± 0.17^a	29.92 ± 6.67^a
	10	2.52 ± 0.04^{ab}	0.72 ± 0.03^a	39.76 ± 0.71^{ab}	3.56 ± 0.63^a	1.50 ± 0.23^a	1.44 ± 0.22^a	26.19 ± 5.49^a
	15	2.54 ± 0.12^{ab}	0.75 ± 0.02^a	39.46 ± 1.86^{ab}	3.65 ± 0.67^a	1.51 ± 0.27^a	1.38 ± 0.24^a	16.78 ± 2.15^b
	20	2.49 ± 0.04^b	0.77 ± 0.02^a	40.23 ± 0.61^a	3.82 ± 0.66^a	1.55 ± 0.29^a	1.39 ± 0.22^a	11.77 ± 2.26^b
HS-2	5	2.49 ± 0.12^a	0.77 ± 0.01^a	40.18 ± 1.98^a	3.87 ± 0.78^a	1.55 ± 0.27^a	1.50 ± 0.25^a	31.09 ± 3.92^a
	10	2.43 ± 0.05^a	0.78 ± 0.00^a	41.19 ± 0.90^a	4.24 ± 0.55^a	1.68 ± 0.21^a	1.46 ± 0.18^a	21.38 ± 6.47^b
	15	2.49 ± 0.07^a	0.78 ± 0.00^a	40.11 ± 1.19^a	4.33 ± 0.84^a	1.73 ± 0.31^a	1.42 ± 0.25^a	19.03 ± 5.30^b
	20	2.48 ± 0.12^a	0.77 ± 0.01^a	40.44 ± 1.92^a	4.46 ± 0.69^a	1.79 ± 0.25^a	1.40 ± 0.21^a	13.63 ± 2.16^b
HS-3	5	2.57 ± 0.03^a	0.75 ± 0.06^a	38.90 ± 0.38^a	3.44 ± 0.62^a	1.43 ± 0.18^a	1.45 ± 0.26^a	33.06 ± 5.10^a
	10	2.48 ± 0.04^a	0.73 ± 0.01^a	40.32 ± 0.68^a	3.95 ± 0.68^a	1.65 ± 0.26^a	1.51 ± 0.25^a	23.05 ± 4.31^b
	15	2.48 ± 0.13^a	0.73 ± 0.01^a	40.42 ± 2.13^a	4.15 ± 0.85^a	1.72 ± 0.31^a	1.48 ± 0.29^a	19.03 ± 6.37^{bc}
	20	2.48 ± 0.17^a	0.73 ± 0.03^a	40.40 ± 2.68^a	4.30 ± 0.77^a	1.79 ± 0.33^a	1.47 ± 0.24^a	12.95 ± 2.25^c

Note: Values are means ± SD of triplicate determinations. Similar letters in superscript within the same column and variety did not differ significantly ($p \leq 0.05$).

With increasing moisture level, the S_a and P_a of halim seeds expanded linearly, whereas the S_{sa} either declined or fluctuated within a limited range (Table 3). In most cases, significant difference ($p \leq 0.05$) was not observed within same variety. With moisture content increasing from 5% - 20%, the average S_a, P_a, and S_{sa} of halim seeds varied from 3.34 - 3.82 mm^2, 1.38 - 1.55 mm^2, and 1.49 - 1.39 mm^{-1} for HS-1; from 3.87 - 4.46 mm^2, 1.55 - 1.79 mm^2, and 1.50 - 1.40 mm^{-1} for HS-2; and from 3.44 - 4.30 mm^2, 1.43 - 1.79 mm^2, and 1.45 - 1.47 mm^{-1} for HS-3, respectively. The enhanced dimensional characteristics of halim seeds may explain the relative increase in S_a and P_a as moisture content rises. This information could be crucial for developing equipment like seed cleaners, separators, and pneumatic conveyors. Understanding S_{sa} is key for modelling processes such as seed drying, aeration, and cooling. It's also valuable for predicting how seeds will behave on moving surfaces during processing [15]. Similar patterns have been observed for plum kernels [15], quinoa seeds [13], kenaf seeds [16], sunflower seeds [21], and melon seeds [23]. For two quinoa varieties, the S_a was reported to increase with rising moisture content (5% - 25%), ranging from 5.90 - 8.08 mm^2 and 7.06 - 9.17 mm^2, respectively [13]. Similarly, the S_a, P_a, and S_{sa} of plum kernels were reported to vary from 141.37 - 153.20 mm^2, 53.23 - 56.95 mm^2, and 2.78 - 2.53 cm^2, respectively, as moisture content increased from 2.64% - 16.85% [15].

The mathematical correlations derived from experimental data are displayed in table 4. The linear regression equation and coefficient of determination (R^2) illustrate the connection between various dimensional parameters and moisture content. A higher R^2 value indicates a stronger correlation and suitable fit of the equations to the experimental results, while a lower R^2 value suggests a weaker correlation. Additionally, some dimensional property data of halim seeds in relation to moisture content are also presented graphically in figure 1.

Effect of moisture content on gravimetric properties

Gravimetric properties, including thousand seed weight, ρ_b, and ρ_t of halim seeds vary with moisture content, as presented in table 3. The thousand seed weight of halim seeds exhibited a linear increase with rising moisture content, ranging from 1.73 - 1.87 g for HS-1, 1.95 - 2.15 g for HS-2, and 1.80 - 2.03 g for HS-3 as moisture level increased from 5% - 20%. This can be attributed to the rise in water content by weight due to the higher moisture levels. It was observed that the thousand seed mass of HS-2 variety was comparatively greater, followed by HS-3 and HS-1. Similar patterns have been observed for plum kernels [15], quinoa seeds [13], and sunflower seeds [21]. For two quinoa varieties, the thousand seed weight was reported to increase with rising moisture content (5% - 25%), ranging from 2.54 - 3.03 g and 2.61 - 3.13 g, respectively [13].

The ρ_b of halim seeds showed a significant decrease as moisture level increased within the same cultivar, as shown in table 3. A decrease in ρ_b was observed from 772.24 - 680.96 kg/m^3 for HS-1, 762.52 - 678.76 kg/m^3 for HS-2, and 758.22 - 694.29 kg/m^3 for HS-3 as moisture content rose from 5% - 20%. This reduction in ρ_b is due to the volumetric expansion of the seeds caused by moisture absorption. Average seed size increases on moisture absorption, resulting in lesser number of seeds occupy the same V_u, and ultimately leads to reduction in density. Similar trends were reported for plum kernels [15], quinoa seeds [13], and kenaf seeds [16].

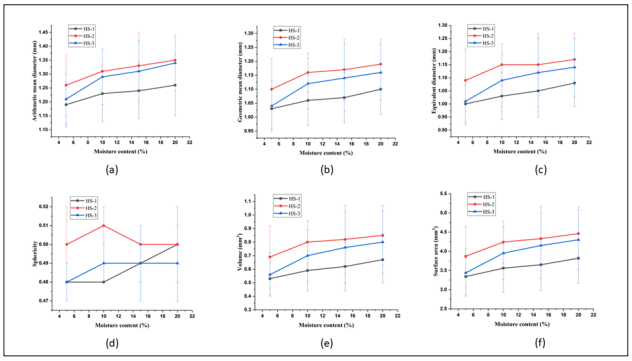

Figure 1: Impact of moisture level and variety on **(a)** D_a, **(b)** D_g, **(c)** D_e, **(d)** sphericity, **(e)** V_u, and **(f)** S_a of halim seeds.

Table 3: Variation of gravimetric and frictional properties of halim seeds at varied moisture levels.

Moisture content (%)		Thousand seed weight (g)	ρ_b (kg/m^3)	ρ_t (kg/m^3)	Porosity (%)	Angle of repose (degree)	Coefficient of static friction (Plywood)	Coefficient of static friction (Galvanized iron)	Coefficient of static friction (Glass)
HS-1	5	1.73 ± 0.05^b	772.24 ± 2.16^a	1252.50 ± 4.94^a	38.34 ± 0.07^d	17.08 ± 0.76^c	0.34 ± 0.01^d	0.34 ± 0.01^d	0.33 ± 0.01^d
	10	1.83 ± 0.06^a	745.66 ± 4.17^b	1215.32 ± 3.47^b	38.64 ± 0.17^c	17.65 ± 0.31^c	0.39 ± 0.01^c	0.38 ± 0.01^c	0.36 ± 0.01^c
	15	1.85 ± 0.03^a	701.48 ± 5.94^c	1183.52 ± 5.21^c	40.73 ± 0.24^b	21.14 ± 0.88^b	0.41 ± 0.01^b	0.40 ± 0.01^b	0.39 ± 0.01^b
	20	1.87 ± 0.03^a	680.96 ± 2.02^d	1157.77 ± 4.25^d	41.18 ± 0.04^a	24.97 ± 0.23^a	0.44 ± 0.01^a	0.42 ± 0.01^a	0.41 ± 0.01^a
HS-2	5	1.95 ± 0.08^b	762.52 ± 3.53^a	1235.62 ± 4.11^a	38.29 ± 0.08^d	18.75 ± 0.18^c	0.34 ± 0.01^d	0.33 ± 0.01^d	0.33 ± 0.01^d
	10	2.07 ± 0.02^a	713.45 ± 4.50^b	1181.47 ± 5.09^b	39.61 ± 0.12^c	21.39 ± 0.32^b	0.38 ± 0.01^c	0.37 ± 0.01^c	0.36 ± 0.01^c
	15	2.12 ± 0.05^a	695.84 ± 4.37^c	1165.55 ± 3.36^c	40.30 ± 0.20^b	22.05 ± 0.88^b	0.40 ± 0.01^b	0.39 ± 0.01^b	0.38 ± 0.01^b
	20	2.15 ± 0.02^a	678.76 ± 4.49^d	1148.33 ± 4.46^d	40.89 ± 0.16^a	25.38 ± 0.50^a	0.43 ± 0.01^a	0.41 ± 0.01^a	0.40 ± 0.01^a
HS-3	5	1.80 ± 0.01^c	758.22 ± 2.45^a	1252.62 ± 5.64^a	39.47 ± 0.07^a	17.50 ± 0.48^c	0.35 ± 0.01^d	0.34 ± 0.01^d	0.34 ± 0.01^c
	10	1.93 ± 0.02^b	737.01 ± 3.01^b	1220.58 ± 4.77^b	39.61 ± 0.01^a	18.38 ± 0.56^c	0.38 ± 0.01^c	0.37 ± 0.01^c	0.36 ± 0.01^b
	15	1.97 ± 0.03^b	706.28 ± 5.81^c	1165.12 ± 3.19^c	39.38 ± 0.33^{ab}	20.03 ± 0.84^b	0.41 ± 0.01^b	0.39 ± 0.01^b	0.39 ± 0.01^a
	20	2.03 ± 0.04^a	694.29 ± 6.02^d	1138.33 ± 4.05^d	39.01 ± 0.31^b	23.23 ± 0.47^a	0.43 ± 0.01^a	0.42 ± 0.01^a	0.40 ± 0.01^a

Note: Values are means ± SD of triplicate determinations. Different letters in superscript within the same column and variety indicate significant differences ($p \leq 0.05$).

The ρ_t of halim seeds also showed a significant reduction as moisture level increased, as indicated in table 3. ρ_t of halim seeds ranged from 1252.50 - 1157.77 kg/m^3 for HS-1, 1235.62 - 1148.33 kg/m^3 for HS-2, and 1252.62 - 1138.33 kg/m^3 for HS-3 as moisture content rose from 5% - 20%. This decrease in ρ_t can be attributed to the V_u increasing at a higher rate than the mass. Similar patterns for kenaf seeds [16] and plum kernels [15] have been documented. The porosity of halim seeds, derived from their bulk and true densities, either increased or fluctuated within a narrow range with rising moisture content (Table 3). The average porosity varied from 38.34 - 41.18% for HS-1, 38.29 - 40.89% for HS-2, and 39.47 - 39.01% for HS-3 with moisture content increasing from 5% - 20%. Similar trends were reported for plum kernels [15], quinoa seeds [13], and kenaf seeds [16]. The ρ_b, ρ_t, and porosity of plum kernels were found to range from 709.12 - 620.42 kg/m^3, 1533.31 - 1456.49 kg/m^3, and 53.61% - 57.45%, respectively, as moisture content increased from 2.64% - 16.85% [15].

Gravimetric properties, including ρ_b, ρ_t, thousand seed weight, and porosity, are essential for equipment design and understanding the behavior of halim seeds during handling. Seed density influences the required screening surface size. Moreover, density and specific gravity play a critical role in calculating thermal diffusivity for heat transfer processes, determining the Reynolds number, and enabling the pneumatic and hydraulic handling of seeds. These characteristics are valuable for designing silos, storage bins, and processing equipment, as well as for the separation and transportation of seeds [15, 20].

Table 4 presents the mathematical relationships derived from experimental data, showcasing the linear regression equations and R^2 elucidating the associations between different gravimetric properties and moisture content. A higher R^2 value denotes a stronger alignment of equations with experimental findings, indicating a robust correlation, while a lower R^2 value suggests a weaker correlation. The variations in gravimetric properties with moisture level are also depicted graphically in figure 2.

Effect of moisture content on frictional properties

Frictional characteristics, including angle of repose and coefficient of static friction of halim seeds, varied significantly with changes in moisture level, as presented in table 3. The angle of repose is defined as the angle formed between the surface of a conical seed pile and the horizontal plane. It is a key parameter for assessing the flow characteristics of the product and the cohesiveness of its components. The angle of repose of halim seeds exhibited a linear increase with rising moisture content, showing statistically significant differences ($p \leq 0.05$). The average angle of repose of halim seeds ranged from 17.08 - 24.97° for HS-1, 18.75 - 25.38° for HS-2, and 17.50 - 23.23° for HS-3 as moisture content increased from 5% - 20%. One potential explanation for the rising angle of repose as moisture content increases may stem from the presence of a surface layer of moisture enveloping the seed. This layer, influenced by surface tension, could bind the aggregate of halim seeds. With elevated moisture levels, seeds are more prone to adhere to one another, leading to heightened cohesion and consequently improved stability but reduced flowability. The angle of repose

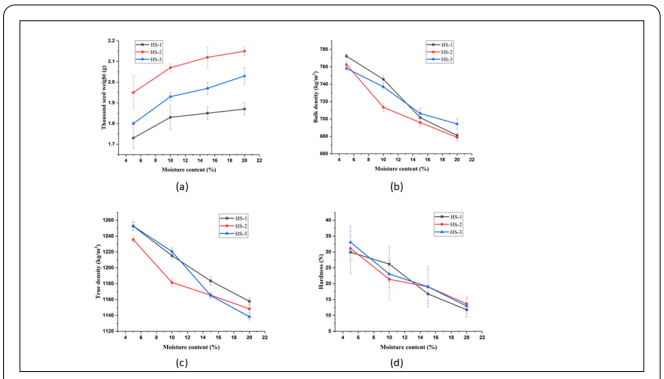

Figure 2: Effect of moisture level and variety on **(a)** thousand seed weight, **(b)** ρ_b, **(c)** ρ_t, and **(d)** hardness/rupture force of halim seeds.

is a crucial factor in designing mass flow equipment and storage structures [15, 23]. Similar increasing trends of angle of repose were also observed for plum kernels [15], quinoa seeds [13], kenaf seeds [16], sunflower seeds [21], and melon seeds [23]. For two quinoa varieties, the angle of repose was reported to increase with rising moisture content (5% - 25%), ranging from 19.07 - 26.57° and 15.05 - 23.86°, respectively [13].

The coefficient of static friction represents the maximum ratio of applied force to normal force at the point just before motion begins. When force is applied to initiate movement in an object initially at rest, there is a point at which the object opposes this motion. To set the body in motion, the applied force must exceed this resistance. This maximum resisting force, which the body offers against the applied force to maintain its state of rest, is termed the coefficient of static friction [24]. The coefficient of static friction of halim seeds on plywood, glass, and galvanized iron surfaces increased significantly as moisture level ranged from 5% - 20%, as shown in table 3. The cause may be due to either the seed's enhanced adhesive force at higher moisture contents or the fact that their rougher surface causes the seed's sliding characteristics to decline at higher moisture levels. These three contact surfaces - glass, plywood, and galvanized iron - are frequently used in the handling, storage, and transport of materials. Among three cultivars of halim seeds, the coefficient of static friction was highest on plywood (0.34 - 0.44), followed by galvanized iron (0.33 - 0.42), and then glass (0.33 - 0.41). At all moisture levels, plywood consistently exhibited a higher coefficient of static friction than both galvanized iron and glass. This experimental data could be beneficial in designing storage bins, conveying systems, hoppers, and other processing and handling equipment. This finding is supported by different studies done for quinoa seeds [13], kenaf seeds [16], sunflower seeds [21], and melon seeds [23], where the static coefficient of friction was found to increase with rising moisture content.

Table 4 displays the mathematical connections derived from experimental data, presenting the linear regression equation alongside the R^2. This elucidates how various frictional properties relate to moisture content. A higher R^2 indicates a more substantial agreement between the equations and experimental results, signifying a robust correlation. Conversely, a lower R^2 signifies a weaker correlation. Figure 3 illustrates the angle of repose and coefficient of static friction of halim seed cultivars as a function of varying moisture level.

Table 4: Linear regression equation and R^2 of engineering characteristics of halim seeds in relation to moisture level.

Parameter	HS-1		HS-2		HS-3	
	Linear regression equation	R^2	Linear regression equation	R^2	Linear regression equation	R^2
Dimensional properties						
L (mm)	y = 0.0042x + 2.1346	R^2 = 0.89	y = 0.0119x + 2.1499	R^2 = 0.99	y = 0.0147x + 2.0968	R^2 = 0.94
W (mm)	y = 0.0046x + 0.8044	R^2 = 0.83	y = 0.0046x + 0.8744	R^2 = 0.83	y = 0.0084x + 0.8092	R^2 = 0.89
T (mm)	y = 0.0043x + 0.5904	R^2 = 0.93	y = 0.0033x + 0.6808	R^2 = 0.77	y = 0.0051x + 0.6084	R^2 = 0.94
D_a (mm)	y = 0.0048x + 1.1692	R^2 = 0.93	y = 0.0064x + 1.2320	R^2 = 0.95	y = 0.0090x + 1.1738	R^2 = 0.92
D_g (mm)	y = 0.0048x + 1.0047	R^2 = 0.95	y = 0.0062x + 1.0773	R^2 = 0.88	y = 0.0084x + 1.0092	R^2 = 0.89
Sphericity	y = 0.0013x + 0.4701	R^2 = 0.93	y = -0.0001x + 0.5032	R^2 = 0.03	y = 0.0006x + 0.4805	R^2 = 0.71
V_u (mm^3)	y = 0.0098x + 0.4787	R^2 = 0.98	y = 0.0110x + 0.6509	R^2 = 0.87	y = 0.0172x + 0.4879	R^2 = 0.93
D_e (mm)	y = 0.0057x + 0.9685	R^2 = 0.99	y = 0.0053x + 1.0735	R^2 = 0.81	y = 0.0093x + 0.9730	R^2 = 0.92
E_r	y = -0.0084x + 2.6455	R^2 = 0.72	y = 0.0004x + 2.4668	R^2 = 0.01	y = -0.0059x + 2.5776	R^2 = 0.61
F_r	y = 0.0012x + 0.7317	R^2 = 0.16	y = -0.0002x + 0.7760	R^2 = 0.20	y = -0.0009x + 0.7463	R^2 = 0.42
A_r (%)	y = 0.1305x + 37.7565	R^2 = 0.73	y = -0.0076x + 40.5759	R^2 = 0.01	y = 0.1030x + 38.7142	R^2 = 0.67
S_a (mm^2)	y = 0.0335x + 3.1715	R^2 = 0.97	y = 0.0410x + 3.7088	R^2 = 0.91	y = 0.0615x + 3.1865	R^2 = 0.93
P_a (mm^2)	y = 0.0114x + 1.3408	R^2 = 0.85	y = 0.0169x + 1.4742	R^2 = 0.95	y = 0.0254x + 1.3279	R^2 = 0.92
S_{sa} (mm^{-1})	y = -0.0081x + 1.5265	R^2 = 0.88	y = -0.0075x + 1.5394	R^2 = 0.99	y = 0.0007x + 1.4683	R^2 = 0.03
Gravimetric properties						
Thousand seed weight (g)	y = 0.0097x + 1.6973	R^2 = 0.85	y = 0.0144x + 1.8914	R^2 = 0.93	y = 0.0160x + 1.7304	R^2 = 0.94
ρ_b (kg/m^3)	y = -7.0112x + 813.2506	R^2 = 0.99	y = -5.9387x + 787.3219	R^2 = 0.93	y = -4.9161x + 785.77	R^2 = 0.99
ρ_t (kg/m^3)	y = -6.9490x + 1289.6614	R^2 = 0.99	y = -6.1382x + 1259.9307	R^2 = 0.91	y = -8.7769x + 1304.5326	R^2 = 0.99
Porosity (%)	y = 0.2346x + 36.7720	R^2 = 0.92	y = 0.1872x + 37.4181	R^2 = 0.97	y = -0.0343x + 39.7993	R^2 = 0.62
Frictional properties						
Angle of repose (degree)	y = 0.5899x + 12.7918	R^2 = 0.91	y = 0.4454x + 16.2913	R^2 = 0.92	y = 0.4072x + 14.6642	R^2 = 0.90
Coefficient of static friction (Plywood)	y = 0.0070x + 0.3066	R^2 = 0.97	y = 0.0063x + 0.3076	R^2 = 0.98	y = 0.0059x + 0.3177	R^2 = 0.99
Coefficient of static friction (Galvanized iron)	y = 0.0057x + 0.3130	R^2 = 0.97	y = 0.0057x + 0.3030	R^2 = 0.97	y = 0.0057x + 0.3085	R^2 = 0.99
Coefficient of static friction (Glass)	y = 0.0059x + 0.2977	R^2 = 0.99	y = 0.0050x + 0.3039	R^2 = 0.99	y = 0.0046x + 0.3141	R^2 = 0.98
Mechanical properties						
Rupture force (N)	y = -1.4037x + 38.8173	R^2 = 0.98	y = -1.2010x + 36.3854	R^2 = 0.94	y = -1.4127x + 39.7871	R^2 = 0.97

Effect of moisture content on mechanical properties

Rupture force is an important mechanical property that can be related to the firmness or brittleness of the sample. It is the force required to produce a major break or rupture in the sample. Rupture force or hardness of halim seeds exhibited a linear decrease with rising moisture level and presented in table 2. The average rupture force of halim seeds varied significantly from 29.92 - 11.77 N for HS-1, 31.09 - 13.63 N for HS-2, and 33.06 - 12.95 N for HS-3 as moisture level raised from 5% - 20%. The value of rupture force is closely linked to the seed texture. At lower moisture levels, seeds are harder and thus have higher rupture forces, while with moisture absorption, seeds soften, resulting in lower rupture forces. The value of rupture force might be useful for design consideration of handling and processing equipment of agricultural commodities. Similar patterns have been reported for plum kernels [15], quinoa seeds [13], bitter gourd seed [17], and sunflower seeds [21], where rupture force decreases with increasing moisture content. Drying can cause shrinkage and changes in the structure of the food product. Finite element modelling can help predict these changes by modelling the mechanical behavior of the food material as it loses moisture [25, 26].

Table 4 presents the mathematical relationships derived from the experimental data, displaying both the linear regression equations and the R^2, which demonstrate the relationship between mechanical properties, such as rupture force,

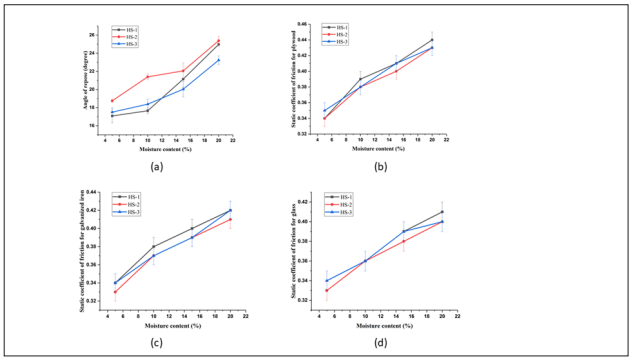

Figure 3: (a) Angle of repose, **(b)** coefficient of static friction for plywood, **(c)** galvanized iron, and **(d)** glass surfaces as a function of variety and moisture content of halim seeds.

and moisture content. A higher R^2 value suggests a stronger alignment between the equations and experimental outcomes, indicating a reliable correlation, while a lower R^2 indicates a weaker correlation. Variations in the hardness or rupture force of halim seeds with moisture level are shown in figure 2.

The variability in engineering properties of halim seeds with moisture content has significant implications for food processing applications. By understanding these properties, optimized processing equipment, such as conveyors, sorters, and dryers, can be developed, ensuring minimal loss, optimal flow, improved efficiency and quality control. Moisture content not only affects the physical properties of halim seeds but can also impact on the bioavailability of certain nutrients, potentially enhancing their health benefits when incorporate into functional foods. Furthermore, since higher moisture content can lead to structural changes that may promote microbial growth, maintaining optimal moisture levels is essential for ensuring food safety during storage and extended shelf life in consumer products.

Conclusion

The consumption and utilization of halim seeds are increasing worldwide because of their nutritional and therapeutic effects. Since handling and processing of agricultural material require appropriate equipment and machinery, engineering characteristics of halim seeds are crucial for its design consideration. This study investigated the impact of moisture level on the engineering characteristics of three cultivars of halim seed. Results showed that all engineering properties of halim seeds varied with moisture levels ranging from 5% - 20%. The HS-2 variety of halim seeds was the largest, followed by HS-3 and HS-1. Dimensional characteristics, including D_a, D_g, D_e, V_u, and S_a of halim seeds increased with rising moisture content. The HS-2 variety of halim seeds was also the heaviest. The thousand seed weight of halim seeds increased, whereas bulk and ρ_t decreased with higher moisture level, showing significant differences ($p \leq 0.05$). Frictional characteristics, such as angle of repose and coefficient of static friction of halim seeds, also increased with moisture content. The maximum coefficient of static friction was exhibited on plywood, followed by galvanized iron and then glass. Rupture force of halim seeds decreased as moisture content increased, with HS-2 and HS-3 varieties being more fracture resistant than HS-1. While most dimensional properties showed no significant differences ($p \leq 0.05$), gravimetric, frictional, and mechanical properties varied significantly within the same variety. These findings aid in designing machinery for industrial processing and postharvest handling, including sorters, graders, dryers, grinders, storage structures, and oil extraction equipment.

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Conflict of Interest

None.

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