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Effects of Moisture on Some Engineering Properties of Dried Date Fruits (Phoenix Dactylifera L.) Relevant To Its Handling, Processing and Storage

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ABSTRACT

Date fruits arrive in the high-humidity southern Nigerian market in a dried state and are highly hygroscopic. Some engineering properties (EP) relevant to the design of handling, processing, and storage equipment for this hygroscopic dried fruit were studied as a function of moisture content. The EP determined were: length, width, and thickness (L, W, T); geometric mean diameter (Dg); arithmetic mean diameter (Da); square mean diameter (Ds); equivalent mean diameter (De); surface area (S); aspect ratio (AR); specific surface area (Ss); sphericity (φ); mass (M); volume (V); density (D); porosity (ε); angle of repose (ζ); and coefficient of static friction (CoF) on three structural surfaces — glass (CoFg), plywood (CoFp), and galvanised steel (CoFgs) — at five moisture content levels (MCL) ranging from 6.08 to 16.23% (wet basis). Each EP was evaluated on 500 replicates, comprising 100 replicates per MCL. All measurements followed standard procedures reported in the literature. Mean values (±SD) were: L = 35.47 ± 3.40 mm; W = 17.53 ± 1.65 mm; T = 15.65 ± 1.53 mm; Dg = 21.32 ± 1.69 mm; Da = 22.88 ± 1.85 mm; Ds = 21.98 ± 1.75 mm; De = 22.06 ± 1.76 mm; S = 20257.69 ± 4864.71 mm²; AR = 0.496 ± 0.044; Ss = 6.03 ± 1.60 mm²/ml; M = 6.03 ± 1.60 g; V = 6.43 ± 1.60 cm³; D = 0.94 ± 0.06 g cm⁻³; ε = 40.42 ± 3.93%; ζ = 35.35 ± 2.82°; CoFg = 0.357 ± 0.047; CoFp = 0.338 ± 0.070; and CoFgs = 0.268 ± 0.034. All EP increased with increasing moisture content, with the exception of ζ, which showed an inverse relationship until the penultimate MCL before rising at 16.23%. Analysis of variance confirmed that the effect of moisture content was statistically significant ($p \leq 0.05$) for thickness, density, porosity, and CoF on all three surfaces. CoFp exhibited the highest values at all MCL studied. The results of this study are intended to support food engineers and processing equipment designers working with dried date fruits.

Keywords: Engineering properties; dried dates, Phoenix dactylifera L.; angle of repose; aspect ratio; coefficient of friction.

INTRODUCTION

Phoenix dactylifera, commonly known as the date palm, is a flowering plant species in the family Arecaceae, cultivated for its edible sweet fruit (Asiz et al., 2025). Botanically, the date fruit is a berry consisting of a single seed surrounded by a fibrous, parchment-like endocarp, a fleshy mesocarp, and the fruit skin (pericarp). The seed accounts for approximately 11–18% of the total fruit weight and is composed of carbohydrates, dietary fibre, fat, ash, and protein (Sayas-Barberá et al., 2024) . Date fruits are oval-cylindrical in shape, typically measuring 3 to 7 cm in length and about 2.5 cm in diameter, with colour ranging from bright red to bright yellow depending on the variety. When dried, they contain 61–68% sugar by mass and are valued as desserts and confectionery ingredients worldwide (Ghonimy et al., 2025). In addition, the antioxidant content of date seed oil (DSO) is comparable to that of olive oil, making it a good source of natural antioxidants. Oleic acid is the predominant fatty acid in DSO, followed by lauric, linoleic, palmitic, and myristic acids; however, fatty acid composition varies by variety. The fruit is attached to the spikelet by a perianth (calyx).

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The species is widely cultivated across northern Africa, the Middle East, and South Asia, and has been naturalised in many tropical and subtropical regions worldwide. Date palm is believed to have been introduced into Nigeria in the early 8th century by Arab traders from North Africa. Date fruits are a highly valued delicacy among many Nigerian communities, especially during ceremonies and festivals. The national consumption of dates in 2009 was estimated at 8,958 metric tons, placing the country among the top ten date consumers globally. Despite conducive soil and climatic conditions for date palm cultivation and the existence of local varieties with good fruit qualities, domestic production remains at a subsistence level, estimated at only 1,958 metric tons. Attempts to develop commercial date palm plantations have been hindered by the lack of adequate planting materials; however, recent evaluations of Nigerian date palm cultivars have demonstrated a high propensity for in vitro culture, with more than 50% embryogenic callus formation in tested genotypes.

For the right design of machinery for handling, transporting, separating, mechanically extracting oil, storing, and other activities, certain physical characteristics and mechanical behaviour of dried dates and dried date pit are thought to be required. The dried date fruit pit is mechanically processed in order to turn it into oil. The external pressures applied to each dried date fruit and pit are ultimately connected to this mechanical treatment. Knowing the material's physical characteristics and mechanical behaviour allows one to analyse the crushing and fracture brought on by forces applied to a dried date fruit and its pit.

The dimensions and physical characteristics of agricultural produce, including their length, width, thickness, arithmetic and geometric mean diameters, sphericity, volume, unit mass, bulk and true densities, porosity, projected area, and drag coefficient, are taken into account when designing handling, processing, and equipment. It is critical to have an accurate estimate of shape, size, volume, density, surface area, and other characteristics that may be taken into account as engineering parameters for that product when the properties of a material are studied by taking either bulk or individual units of the material into consideration (Mohsenin, 1980). Numerous issues related to the design of a particular machine or examination of the behaviour of the product in handling the material involve shape, size, volume, density, and porosity. Size and shape are most often used when describing grains, seeds, fruits and vegetables. Shape and physical dimensions are important in sorting and sizing of fruits, and determine how many fruits can be placed in shipping containers or plastic bags of a given size. Quality differences in fruits, vegetables, grain and seeds can often be detected by differences in density. When fruits and vegetables are transported hydraulically, the design fluid velocities are related to both density and shape. Volumes and surface areas of solids must be known for accurate modelling of heat and mass transfer during cooling and drying.

Porosity, which is the percentage of air space in particulate solids, affects the resistance to air flow through bulk solids. In addition to other uses, air flow and heat studies frequently need the porosity. Airflow resistance, in turn, affects the performance of systems designed for force convection drying of bulk solids and aeration systems used to control the temperature of stored bulk solids. Agricultural goods' bulk and real density are crucial for drying and storing them, designing silos and storage bins, separating them from unwanted items, and grading them (Mohsenin, 1980). Knowledge of frictional properties is needed for design of handling equipment. The most crucial characteristics for separation, hopper design while feeding the machine, and material cleaning are terminal velocity and drag coefficient.

Numerous researchers have investigated the physical properties of a wide variety of agricultural products Owolarafe & Shotonde, 2004, determined several physical properties of okra fruit at a moisture content of 11.42% (wet basis). Akar & Aydin, 2005, evaluated the physical properties of gumbo fruit varieties as functions of moisture content. Kashaninejad et al., 2006, characterised selected physical and aerodynamic properties of pistachio nut and its kernel as a function of moisture content to facilitate the design of processing equipment. Topuz et al., 2005 determined and compared the properties of four orange varieties. More recently, Bajpai et al. (2020) studied moisture-dependent engineering properties of Jamun (Syzygium cumini) seeds across a moisture content range of 11.54–26% (d.b.), confirming that geometric, gravimetric, and frictional properties responded significantly to increasing moisture. Peng et al. (2022) systematically characterised the physical, mechanical, and thermal engineering properties of Cassia tora L. seeds as a function of moisture content, demonstrating that such data are essential for the development of efficient processing machinery.

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Symbol	Parameter	Unit		Symbol	Parameter	Unit
L	Length	mm		**V_b**	Bulk Volume	cm^3
W	Width	mm		**ρ_b**	Bulk Density	g/ml
T	Thickness	mm		**ρ_t**	True Density	kg m^{-3}
M	Solid Mass	g		**S_s**	Specific surface area	mm^2/ml
D_A, AMD	Arithmetic Mean Diameter	mm		**φ**	Sphericity	%
D_G, GMD	Geometric Mean Diameter	mm		**AR**	Aspect ratio	%
D_S, SMD	Square Mean Diameter	mm		**ε**	Porosity	%
D_E, EMD	Equivalent Mean Diameter	mm		ζ (α)	Angle of repose	°
S	Surface Area	mm^2		CoFg (μg)	CoF on glass	—
V	Solid Volume	cm^3		CoFp (μp)	CoF on plywood	—
ρ_t	True Density	kg m^{-3}		CoFgs (μs)	CoF on galvanised steel	—
M_b	Bulk Mass	g		ε	Porosity	%

Also, Keramat-Jahromi et al., 2008 investigated selected physical properties of date fruit (cv. Dairi). Despite a thorough review of the literature, no published study was found on the systematic changes in the physical properties of dried date fruits and pits attributable to controlled changes in moisture content. The present study therefore aims to determine the effect of increasing moisture content on the physical, dimensional, and engineering properties of dried date fruits and their pits, with a view to providing data necessary for the industrial processing and technological development of this fruit.

MATERIALS AND METHODOLOGY

Material preparation

In this study, dried date fruits of high quality (Figure 1) were selected at random from a local vendor at Akpan Andem Market in Uyo, Akwa Ibom State. The fruits were transported to the Food Engineering Laboratory, Faculty of Engineering, University of Uyo, where all tests were conducted. Engineering properties determined included length, width, thickness, sphericity, volume, unit mass, bulk density, true density, porosity, terminal velocity, surface area, coefficient of friction, and moisture content. All determinations were made at five (5) varying moisture levels for the whole dried dates. To obtain these moisture levels, samples were divided into four groups of 100 each and conditioned to five different moisture levels. The first was the moisture content of

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the sample from the market and the other four moisture levels were accomplished by adding pre-determined quantities of distilled water, then sealed in airtight plastic containers and refrigerated at 5°C for 12 hours each time a new moisture level was required, to allow uniform moisture distribution throughout the sample.

Figure 1: The whole fruit of P. dactylifera fruit

Determination of Physical Properties

Physical properties

Physical properties — comprising the longitudinal axis (major dimension, length L), transverse axis containing the intermediate dimension (width W), and transverse axis containing the minimum dimension (thickness T), all measured in millimetres (mm) — were determined using a digital vernier calliper with a precision of 0.01 mm for external diameters, following the procedure described by Tscheuschner, 1987. The geometric mean diameter (D_g), arithmetic mean diameter (D_a), equivalent mean diameter (D_e), and square mean diameter (D_s) were calculated using the expressions given by Asoegwu et al., 2006 given in Equations (1) to (4)

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

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

$$D_s = \left[\frac{LW+TW+TL}{3}\right]^{1/2} \tag{3}$$

$$D_e = \frac{(D_g+D_a+D_s)}{3} \tag{4}$$

Where;

L, W and T are the longitudinal axis, intermediate dimension and the minimum dimension respectively. D_g is the Geometric mean diameter; D_a is arithmetic mean diameter; D_s is square mean diameter; and D_e is equivalent mean diameter all in millimetre (mm)

Sphericity, and Aspect Ratio

The sphericity (%) and aspect ratio (%) of 100 randomly selected samples were calculated using the following expressions (Tscheuschner, 1987; Sitkei, 1986; Güner, 2007):

$$\phi = \frac{(LWT)^{1/2}}{L} \tag{5}$$

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$$AR = \frac{W}{L} \quad (6)$$

Where;

Φ is sphericity, and AR is aspect ratio of the biomaterial product.

Surface Area and Specific Surface Area

Surface area and specific surface area were estimated using the relationships in Equations (7) and (8), given by Hacıseferoğulları et al., 2007, and Sobukola & Onwuka, 2011

$$S = \frac{\pi (WT)^{1/2} L^2}{2L - (WT)^{1/2}} \quad (7)$$

$$S_s = \frac{S \rho_b}{M_s} \quad (8)$$

where, S is surface area, S_s is specific surface area, ρ_b is bulk density and M_s is solid mass of the fruit and pit, given mm^2 and mm^2/ml, respectively.

Gravimetric properties

Mass, Volume and Density

The mass of individual fruit was determined using an electronic balance with a measurement sensitivity of 0.01 g. Solid volume (V_s) was determined by water displacement. Individual and bulk samples were weighed and immersed in a measuring cylinder containing a known volume of water, and the rise in water level was recorded as the respective volume. Solid volume was calculated using Equation (9) (Coşkuner & Karababa, 2007):

$$V_s = \frac{\pi B^2 L^2}{6(2L - B)} \quad (9)$$

Where;

$B = (WT)^{1/2}$; and V_s is the solid volume (mm),

True density (ρt) is defined as the ratio of the solid mass to its volume. Bulk density (ρb) is the ratio of the mass of the bulk fruit to its bulk volume. These were calculated using Equations (10) and (11) according to (Asoiro et al., 2017):

$$\rho_t = \frac{M}{V} \quad (10)$$

$$\rho_b = \frac{M_b}{V_b} \quad (11)$$

Where; ρ_t is the fruit density (g/ml); M and V are mass of date and volume displaced in water, respectively.

The bulk density was determined using the mass/volume relationship in Equation (11) by filling an empty graduated plastic container of predetermined volume and mass with the fruits dropped from a constant height, and weighed:

$$\rho_b = \frac{M}{V} \quad (12)$$

Where; ρ_b is the bulk density (g/cm^3), M and V are bulk mass of fruit (g), and the plastic container volume (cm^3), respectively. This method was based on the work of (Owolarafe et al., 2007), (Fraser et al., 1978) and (Suthar & Das, 1996).

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One Thousand Seed Weight

The weight of 1000 seed was determined by counting 250 seeds for the desired moisture content and weighed on an electronic balance weighing to 0.001 g accuracy and then multiplied by 4 to give the mass of 1000 seeds.

Moisture Content

Moisture content was determined using the ASAE standard method (ASAE, 1993) by drying the whole fruit in a ventilated oven at 105°C for 24 hours. Weight loss on drying to a constant final weight was recorded as moisture content, expressed on both a wet basis (w.b.) and a dry basis (d.b.) using Equations (13) and (14)::

$$MC_{wb} = \frac{M_i - M_f}{M_i} \times 100 \qquad (13)$$

$$MC_{db} = \frac{M_i - M_f}{M_f} \times 100 \qquad (14)$$

Where, MC_{wb} is moisture content, wet basis (%); MC_{db} is moisture content, dry basis (%); M_i is initial mass of fruit sample (g) and M_f is final mass of fruit sample (g).

Porosity (ε)

Porosity is the ratio of free space between fruit to that of the total bulk fruit. This was calculated as the ratio of the differences in the fruit and bulk densities to the fruit density value and expressed in percentage:

$$\varepsilon = \frac{\rho_s - \rho_b}{\rho_s} x100 \qquad (15)$$

Determination of frictional properties

Coefficient of Static Friction

The coefficient of static friction was determined for three structural surfaces — galvanised steel, plywood, and glass — using an inclined plane apparatus. The plane was gently raised and the angle of inclination at which the sample began to slide was read from a protractor with a sensitivity of one degree, following the procedure described by Shepherd & Bhardwaj, 1986, and Pliestic et al., 2006. The coefficient of static friction (μ) was calculated from the expression in Equation (16) according to (Asoiro et al., 2017):

$$\mu = \tan\theta \qquad (16)$$

Where; θ is the friction apparatus makes with the horizontal and θ is the tilt angle of the friction device. All the friction experiments were conducted in three replications for each surface.

Angle of Repose

The angle of repose is the angle with the horizontal at which the material will stand when piled (Paksoy & Aydin, 2004). The angle of repose for the dried dates and pits were determined practically by introducing the dates to a cylindrical container of determined volume and allowing the dates to fall with controlled speed and force. The dried dates formed a pyramid of relatively small height. The height and diameter the dried date makes with the horizontal were then recorded and used as height and diameter for the angle of repose calculation. It was calculated using the expression in Equation (17) according to (Heidarbeig et al., 2008):

$$\alpha = \tan^{-1}\left[\frac{2H}{D}\right] \qquad (17)$$

Where; α is the angle of repose (^{0}), H is height of the pile (mm) and D is diameter of the pile (mm).

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Statistical analyses were conducted using XLSTAT (version 2023.1.4, Addinsoft, Paris, France). A one-way analysis of variance (ANOVA) was performed with moisture content treatment (five levels: 6.08, 9.85, 12.39, 14.20, and 16.23% w.b.) as the fixed factor and each engineering property as the dependent variable, using 100 individual fruit measurements per treatment level (n = 500 in total). Where the overall F-test was significant at $\alpha = 0.05$, pairwise differences among treatment means were assessed using Duncan's multiple range test. Least-squares means and 95% confidence intervals were computed for all properties. Pearson product-moment correlation coefficients were calculated to quantify bivariate associations among all engineering properties. Linear dummy-variable regression models were fitted to quantify the directional effect of each moisture treatment relative to the highest moisture level (16.23% w.b.) as the reference category; goodness of fit was evaluated using the coefficient of determination (R^2).

RESULTS AND DISCUSSION

The date fruits prepared for this study were Five hundred (500) in number. The were conditioned to 5 moisture content level. The first was the moisture content of the product directly from the market – 6.08 %, then the conditioned moisture content levels were: 9.85 %, 12.39 %, 14.20 % and 16.23 % wb respectively.

Physical properties

Table 1 presents the summary statistics for the physical properties of dried date fruits, based on a total sample size of 500 observations, with 100 observations per moisture content treatment level. The geometric parameters studied all increased as moisture content increased. Specifically, length, width, thickness, and mass increased from 25 mm to 44.1 mm, 12.34 mm to 22.27 mm, 11.1 mm to 19.47 mm, and 2.478 g to 12.162 g, respectively, with corresponding mean and standard deviation values of 35.473 ± 3.396 mm, 17.526 ± 1.646 mm, 15.654 ± 1.526 mm, and 6.032 ± 1.601 g, as moisture content increased from 6.08% to 16.23% (w.b.). Figures 2, 3 and 4 show the

Table 1: summary statistics

Variable	Observations	Obs. With missing data	Obs. Without missing data	Minimum	Maximum	Mean	Std. Deviation
Length	500	0	500	25.000	44.100	35.473	3.396
Width	500	0	500	12.340	22.270	17.526	1.646
Thickness	500	0	500	11.100	19.470	15.654	1.526
Mass	500	0	500	2.478	12.162	6.032	1.601
GMD	500	0	500	16.100	26.067	21.319	1.691
AMD	500	0	500	17.010	28.020	22.884	1.846
SMD	500	0	500	16.490	26.880	21.979	1.747
EMD	500	0	500	16.530	26.990	22.061	1.756

Surface area	500	0	500	8780.020	36145.220	20257.691	4864.710
Volume	500	0	500	3.000	13.000	6.432	1.603
Density	500	0	500	0.701	1.165	0.936	0.062
Sphericity	500	0	500	49.740	69.240	60.276	3.212
Aspect ratio	500	0	500	0.370	0.650	0.496	0.044
Porosity	500	0	500	20.780	52.310	40.421	3.927
Angle of repose	500	0	500	32.29	38.78	35.35	
CoF - glass	500	0	500	0.249	0.499	0.357	0.047
Wood	500	0	500	0.176	0.554	0.338	0.070
Galvanized steel	500	0	500	0.158	0.344	0.268	0.034

A pairwise comparison between the average values of the properties (Table 3) reveals that there was no significant difference due to the changes in the level of moisture content at 5% level of significance for the length attribute, width, mass, geometric mean diameter, arithmetic mean diameter, equivalent mean diameter, square mean diameter, surface area, volume, sphericity, and the aspect ratio of the biological material. However, significant difference was observed in its other properties like thickness, density, porosity, as well as the coefficient of friction for glass surface, wood surface and steel surface.

The results from the Analysis of Variance shows that effect of the changes in the moisture content of the Dried date fruit on the average values of its physical properties is statistically significant at 5% level of significance.

Table 2: One-way ANOVA summary — effect of moisture content on all engineering properties of dried date fruit (Phoenix dactylifera; n = 500, df_h = 4, df_e = 495)

Parameter	**F-value**	**p-value**	**R^2**	**Significance**
Length (L)	0.377	0.825	0.003	ns
Width (W)	1.889	0.111	0.015	ns
Thickness (T)	3.066	0.016	0.024	*
Mass (M)	2.254	0.062	0.018	ns (trend)

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GMD	2.270	0.061	0.018	ns (trend)
AMD	1.556	0.185	0.012	ns
SMD	1.965	0.099	0.016	ns (trend)
EMD	1.920	0.106	0.015	ns (trend)
Surface Area	2.332	0.055	0.018	ns (trend)
Volume	1.559	0.184	0.012	ns
Density	4.077	0.003	0.032	**
Sphericity	1.430	0.223	0.011	ns
Aspect Ratio	0.813	0.517	0.007	ns
Porosity	4.302	0.002	0.034	**
CoF – Glass	2.890	0.022	0.023	*
CoF – Plywood	242.65	<0.0001	0.662	***
CoF – Galvanised Steel	6.165	<0.0001	0.047	***

Note: ns = not significant at $\alpha = 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. R^2 values reflect the proportion of total variance explained by the five moisture content treatment groups. Significance assessed using Duncan's multiple range test at 95% confidence.

Table 3: A pairwise comparison of the dried dates' average axial characteristics, mean diameters, mass, surface area, sphericity, density, porosity, aspect ratio, volume, and coefficients of static friction

Moisture Levels	**16.23**	**14.2**	**12.39**	**9.85**	**6.08**	**Pr > f(model)**	**Significant**
Length	35.697 a	35.543 a	35.598 a	35.355 a	35.173 a	0.825	No
Width	17.748 a	17.706 a	17.532 ab	17.463 ab	17.183 b	0.111	No
Thickness	15.883 a	15.841 a	15.751 a	15.560 ab	15.235 b	0.016	Yes
Mass	6.321 a	6.172 ab	6.063 ab	5.899 ab	5.705 b	0.062	No

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GMD	21.558 a	21.491 a	21.391 ab	21.229 ab	20.923 b	0.061	No
AMD	23.109 a	23.030 ab	22.960 ab	22.792 ab	22.531 b	0.185	No
SMD	22.213 a	22.142 a	22.052 ab	21.889 ab	21.600 b	0.099	No
EMD	22.294 a	22.220 a	22.135 ab	21.970 ab	21.685 b	0.106	No
S. Area	20961.814 a	20781.998 a	20435.833 ab	19997.200 ab	19111.610 b	0.055	No
Volume	6.690 a	6.540 ab	6.440 ab	6.320 ab	6.170 b	0.184	No
Density	0.948 a	0.945 a	0.941 a	0.930 ab	0.918 b	0.003	Yes
Sphericity	60.563 a	60.636 a	60.283 a	60.231 a	59.664 a	0.223	No
A. Ratio	0.499 a	0.500 a	0.494 a	0.496 a	0.490 a	0.517	No
Porosity	41.121 a	41.006 a	40.738 a	40.053 ab	39.189 b	0.002	Yes
Glass	0.362 a	0.362 a	0.360 a	0.355 ab	0.343 b	0.022	Yes
Wood	0.408 a	0.369 b	0.349 c	0.326 d	0.237 e	<0.0001	Yes
Gal. Steel	0.274 a	0.271 a	0.272 a	0.272 a	0.254 b	<0.0001	Yes

Effect of Moisture Content on the Physical properties

When determining the mean diameters, surface areas, volumes, densities, and other fruit qualities at varied moisture levels, the examined axial properties are crucial. Onwe et al., 2020, for the test involving two types of African star apples, Bamgboye & Adejumo, 2009, for the test using Roselle seeds, Tavakoli et al., 2009, for the test involving soybean grains, and Bamgboye & Adebayo, 2012, for the test involving Jatropha seeds, and more recently by Bajpai et al. (2020) for Jamun seed and Peng et al. (2022) for Cassia tora seeds, all noted a similar tendency.

The average values of the length, breadth, and thickness of the dried dates were examined using the Analysis of Variance (ANOVA) method, and the findings (Table 4) show that the effects of moisture content are statistically significant at the 5% level of significance.

Table 4: analysis of variance (length):

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Source	Df	Sum of squares	Mean squares	F	Pr > f	P-values signification codes
Model	4.000	17.496	4.374	0.377	0.825	°
Error	495.000	5736.030	11.588			
Corrected total	499.000	5753.526				
Computed against model y=mean(y)						
Signification codes: 0 < * < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1**						

The regression analysis for all geometric parameters revealed that moisture content accounted for a statistically discernible but modest proportion of the total variance in dimensional properties at the individual-parameter level (Table 4). Thickness (T) was the only axial dimension to attain formal significance at p = 0.016 ($F_{4,495}$ = 3.07), with an R^2 of 0.024, reflecting that 2.4% of the variance in thickness across the 500 observations was attributable to differences among the five moisture treatment groups. The remaining axial parameters — length (p = 0.825) and width (p = 0.111) — did not reach significance at the 5% level, though width exhibited a borderline tendency ($F_{4,495}$ = 1.89). This pattern is consistent with the biology of the dried fruit: the pericarp and mesocarp of

Phoenix dactylifera expand upon hydration, but the magnitude of dimensional change across the narrow moisture range studied (6.08–16.23% w.b.) is small relative to natural biological variability among individual fruits. Pairwise (Duncan) comparisons confirmed that, for thickness, the lowest moisture group (6.08%) was significantly different from the highest three groups (12.39%, 14.20%, and 16.23%), while intermediate groups shared membership in both homogeneous subsets (Table 3). Least-squares means and 95% confidence intervals for the four statistically significant parameters are provided in Table 5.

Table 5: Least-squares means and 95% confidence intervals for significantly affected engineering properties across moisture content levels (Duncan groupings indicated by shared letter; groups not sharing a letter differ at α = 0.05)

MC Level	LS Mean	Lower 95% CI	Upper 95% CI	Duncan Group
Thickness (mm)				
6.08%	15.235	14.937	15.532	B
9.85%	15.560	15.263	15.858	AB
12.39%	15.751	15.454	16.049	A
14.20%	15.841	15.543	16.138	A

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16.23%	15.883	15.585	16.180	A
Density (g cm⁻³)				
6.08%	0.918	0.906	0.930	B
9.85%	0.930	0.918	0.942	AB
12.39%	0.941	0.929	0.953	A
14.20%	0.945	0.933	0.957	A
16.23%	0.948	0.936	0.960	A
Porosity (%)				
6.08%	39.189	38.427	39.950	B
9.85%	40.053	39.292	40.815	AB
12.39%	40.738	39.977	41.500	A
14.20%	41.006	40.244	41.767	A
16.23%	41.121	40.359	41.882	A
CoF – Plywood				
6.08%	0.237	0.229	0.245	E
9.85%	0.326	0.318	0.334	D
12.39%	0.349	0.341	0.357	C
14.20%	0.369	0.361	0.377	B
16.23%	0.408	0.400	0.416	A

CI = confidence interval; MC = moisture content (wet basis).

The average values of the thickness, density, porosity, and all the surfaces for the coefficient of friction for the dried date were compared pairwise (Table 2), and the results show that the difference in their averages is statistically significant at = 0.05 and the opposite is true for all other parameters. The physical characteristics of biological material, such as its size, shape, specific gravity, surface roughness, colour, etc., are crucial for the

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development of various kinds of cleaning, grading, and separating equipment. Shape and size of the biological material, as well as angle of inclination, vibration amplitude, and frequency of screens, are all taken into consideration while developing an air screen grain cleaner. In order to communicate the properties of solid materials via air or water, the form of the seed is a crucial factor. Calculating different cooling and heating loads for food products takes form into account as well. In order to choose a separation and storage media, it is vital to take into account the surface properties, colour, and appearance of the dried date.

Table 6: Regression equations relating statistically significant engineering properties to moisture content treatment level. δ(MC%) denotes an indicator variable equal to 1 for the stated MC level and 0 otherwise; the reference level is 16.23% (w.b.).

Parameter	Regression Equation (MC treatment coded as dummy δ)	Fit
Thickness (T, mm)	T = 15.883 − 0.648·δ(6.08%) − 0.323·δ(9.85%) − 0.132·δ(12.39%) − 0.042·δ(14.2%)	$R^2 = 0.024$
Density (D, g cm⁻³)	D = 0.948 − 0.030·δ(6.08%) − 0.018·δ(9.85%) − 0.007·δ(12.39%) − 0.003·δ(14.2%)	$R^2 = 0.032$
Porosity (ε, %)	ε = 41.121 − 1.932·δ(6.08%) − 1.067·δ(9.85%) − 0.382·δ(12.39%) − 0.115·δ(14.2%)	$R^2 = 0.034$
CoF – Glass	μg = 0.362 − 0.019·δ(6.08%) − 0.007·δ(9.85%) − 0.003·δ(12.39%)	$R^2 = 0.023$
CoF – Plywood	μp = 0.408 − 0.171·δ(6.08%) − 0.082·δ(9.85%) − 0.059·δ(12.39%) − 0.039·δ(14.2%)	$R^2 = 0.662$
CoF – Galv. Steel	μs = 0.274 − 0.020·δ(6.08%) − 0.002·δ(9.85%) − 0.002·δ(12.39%) − 0.003·δ(14.2%)	$R^2 = 0.047$

Note: The exceptionally high R^2 for CoF on plywood (0.662) relative to other surfaces confirms that plywood surface friction is uniquely sensitive to moisture variation, a finding of direct engineering design relevance.

Effect of Moisture Content on Gravimetric Properties

Table 1 also displays the typical values for the gravimetric parameters (bulk and true densities, and porosity) of the dried dates between the moisture levels of 6.08 and 16.23% (w.b). As the seed moisture content increased, the values of the characteristics rose, as illustrated in Figs. 2 and 3. As the moisture level rose from 6.08% to 16.23% (w.b), it was commonly noted that the average geometric characteristics of the dried dates gradually increased. when a consequence, it was clear that the bulk and actual densities of the dried dates ranged from 701 to 1165 kg/m3 (summary statistics Table 1). This was especially true when the moisture content rose from 6.08 to 16.23% (w.b). The findings showed that, when the moisture level rose from 6.08 to 16.23% (w.b), the bulk and actual densities of the dried dates ranged from 701 to 1165 kg/m3 (summarized statistics Table 1).

The systematic increase in all geometric parameters with rising moisture content reflects the progressive absorption of water into the interstitial and intracellular spaces of the mesocarp and pericarp tissues of the dried fruit. Water uptake induces osmotic swelling of cell walls and turgor-driven expansion of parenchymatous cells, mechanisms that are well documented in hygroscopic agricultural produce (Mohsenin, 1980; Bajpai et al., 2020). Because the fruit is initially in a substantially dehydrated, low-turgor state at 6.08% (w.b.), early-stage rehydration produces relatively rapid dimensional gains; incremental expansion becomes more gradual at higher

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moisture levels as cells approach their maximum volumetric capacity, consistent with the trend observed across the five MCL in the present study.

The corresponding increases in density and porosity — properties that might at first appear contradictory — are reconcilable through their distinct physical bases. Density rises because the mass increment from absorbed water outpaces the volumetric expansion of the fruit, since the specific density of liquid water (≈ 1.0 g cm^{-3}) exceeds the mean fruit density at the lowest MCL (0.918 g cm^3). Porosity, defined here as the ratio of inter-fruit void space to total bulk volume, increases because moisture-swollen fruits pack less efficiently, enlarging the air spaces between individual fruits in a bulk assembly. A similar co-increase in both density and porosity with moisture has been reported for date fruit varieties (Ghonimy et al., 2025), jatropha seed (Bamgboye and Adebayo, 2012), and Jamun seed (Bajpai et al., 2020). The practical implication is that aeration and drying systems must account for increasing bulk resistance to airflow at higher moisture contents, favouring forced convection over natural convection for the moisture range studied.

(Bamgboye & Adebayo, 2012) for Jatropha seeds, (Kingsly et al., 2006) for dried pomegranate seeds, and (B. A., 2012) for Moringa oleifera Seed also reported a positive pattern. However, (Sachin et al., 2012), found that when the moisture content of the seed rose, the real density of soybean dropped.

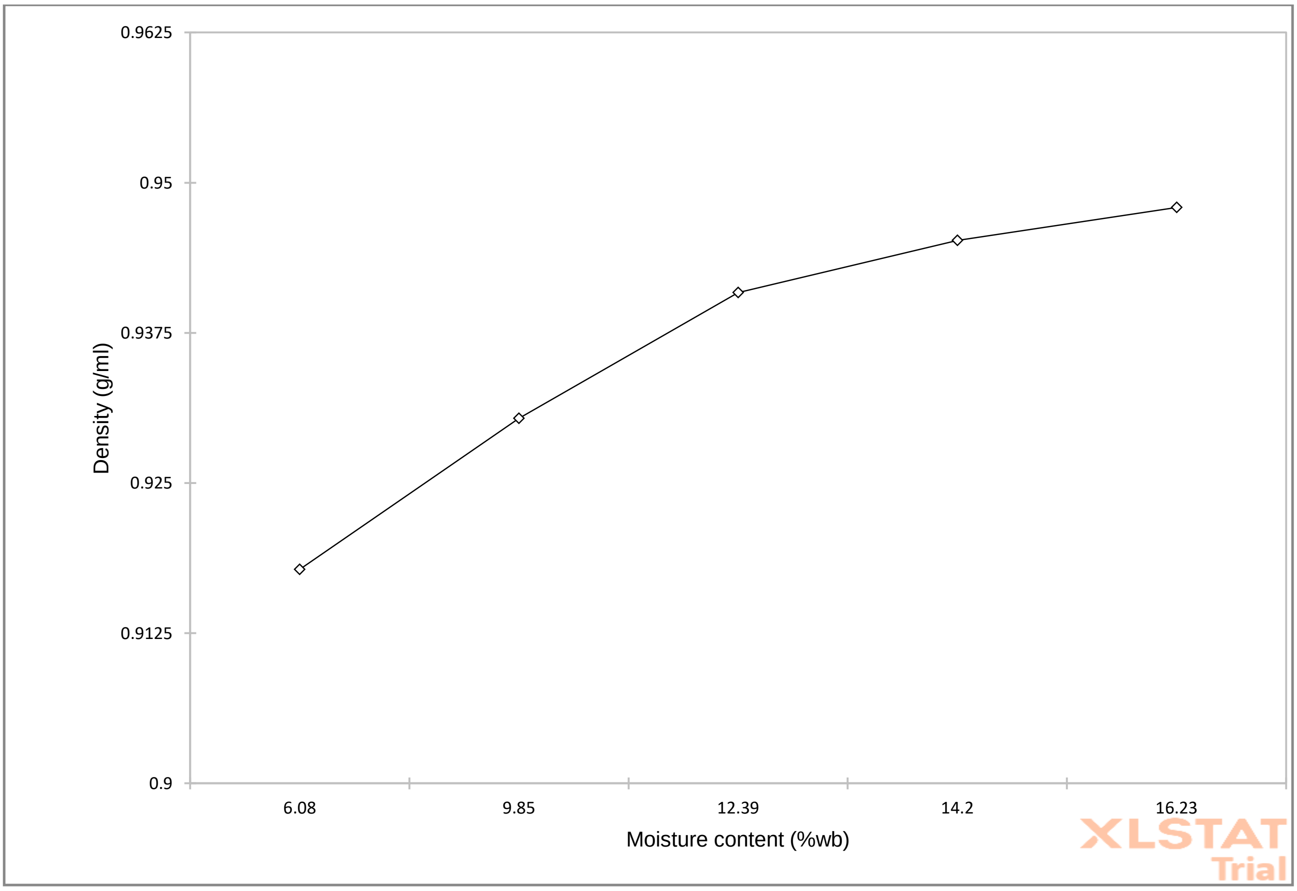

Figure 2: Variation in Density with increase in moisture content of Date fruits

Figure 2: Variation in Density with increase in moisture content of Date fruits

Porosity is an important property to impacts the resistance to air flow. It can influence the drying rate while storage. For this study, when fruit moisture rose from 6.08% to 16.23% (w.b), the average values of porosity for the biological material followed a linear curve (Figure 3) showing and increase from 39.19 – 41.12 % (Values in Table 1). An important factor that impacts the resistance to airflow within bulk seeds is the porosity of the seed. The following studies corroborate the outcome of this study: jatropha and corn, (Bamgboye & Adebayo, 2012) and (Seifi & Alimardani, 2010) observed an increase in porosity at higher moisture levels. For watermelon,

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Moringa oleifera, and sesame seeds, respectively, (Koocheki et al., 2007), (B. A., 2012), and (Darvishi, 2012) observed an increase in porosity with increasing moisture level.

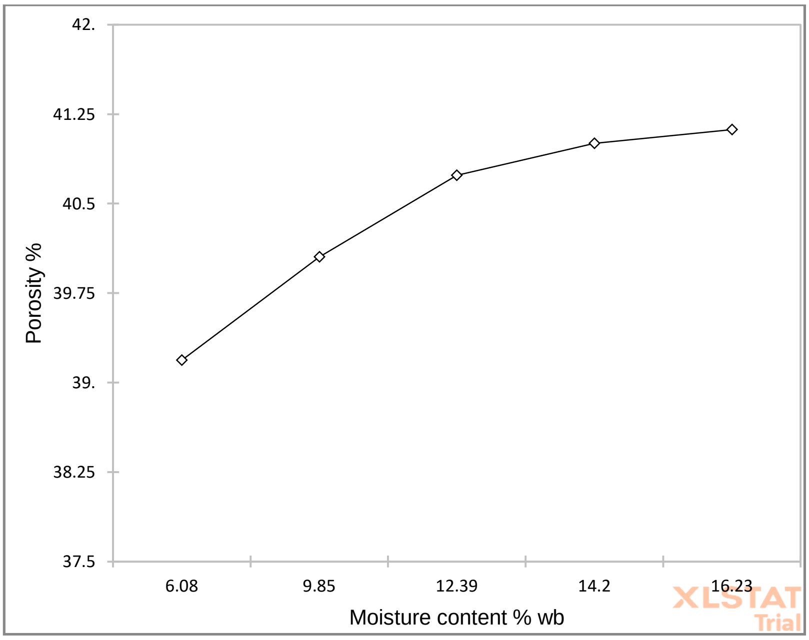

Figure 3: Variation of Porosity with increase in moisture content

The average values of the mean gravimetric characteristics of dried dates as determined by the Analysis of Variance (ANOVA) findings indicate that the effects are statistically significant at the 5% level of significance. According to a pairwise comparison of the average values of biological material's gravimetric characteristics, the difference in their means is statistically significant at = 0.05.

Table 8: Mc/Duncan/Analysis of the differences between the categories with a confidence interval of 95%

Contrast	Difference	Standardized difference	Critical value	Pr > diff	Alpha (modified)	Significant		
16.23 VS 6.08	0.030	3.477	3.096	0.005	0.185	Yes		
16.23 VS 9.85	0.018	2.026	3.023	0.180	0.143	No		
16.23 VS 12.39	0.007	0.818	2.925	0.692	0.098	No		
16.23 VS 14.2	0.003	0.315	2.779	0.753	0.050	No		
14.2 VS 6.08	0.027	3.162	3.023	0.009	0.143	Yes		
14.2 VS 9.85	0.015	1.712	2.925	0.202	0.098	No		
14.2 VS 12.39	0.004	0.504	2.779	0.615	0.050	No		
12.39 VS 6.08	0.023	2.658	2.925	0.022	0.098	Yes		

12.39 VS 9.85	0.010	1.208	2.779	0.228	0.050	No		
9.85 VS 6.08	0.013	1.450	2.779	0.148	0.050	No		

All ten pairwise contrasts were statistically significant ($p < 0.05$), confirming that CoF on plywood increased monotonically and distinctly with each incremental addition of moisture. This surface warrants particular attention in conveyor and handling system design.

When constructing specific machinery or forecasting the behaviour of dried date fruit during handling, gravimetric parameters like bulk and true densities and porosity are crucial. While the surface area, related diameters, and density are crucial for determining the terminal velocity of the dried date fruit, the density determined will determine the size of the screening surface. For the purpose of separating lighter materials in air screen grain cleaners, the winnowing velocity of the air blast must be determined. In order to calculate the heat diffusivity during heart transfer procedures, determine Reynold's number, and handle fruit pneumatically and hydraulically during processing, it is necessary to know the density and specific gravity of the material.

Effect of moisture content on the frictional properties

In the Summary statistics Table (Table 1), the average values of the frictional characteristics of dried date fruit at different moisture levels are displayed. The angle of repose, for dried dates fruits had and inverse relationship with the moisture level content (Fig. 4) from the 6. O8 % wb to 4.198 where it showed a different trend by showing an increase at 16.23 % wb. Figures 4 and 5 demonstrate, respectively, how the angle of repose and static coefficient of friction of dried date fruit vary with moisture content. Angles of repose for the dried dates varied from 32.29 to 38.78°, while the coefficients of static friction for surfaces made of glass, plywood, and galvanized sheet ranged from 0.249 to 0.499, 0.176 to 0.544, and 0.158 to 0.344, respectively (Summary statistics Table). With an increase in moisture content, the angle of repose decreases (Fig. 4), with the exception of the ultimate moisture level (16.23%), which deviates from the trend and tends to rise. This outcome is comparable to that which Oyelade et al., 2005, and Onwe et al., 2020, reported for African Star Apple (Chrysophyllum albidum) seed, which was in the range of 13.01-14.69, and for two types of African Star Apple studied. Bamgboye & Adebayo, 2012, found for jatropha seed a similar tendency of a decline in the angle of repose with seed moisture content. As the biological material's moisture content increased, the static coefficient of friction on the three surfaces—glass, plywood, and galvanized sheet—increased as well. Zareiforoush et al., 2009, for paddy grains and Sachin et al. for soybean showed a similar pattern of an increasing coefficient of friction with moisture content. Additionally, it was shown that the dried date's coefficient of friction decreased with the smoothness of the structural surface. When calculating the different forces necessary to translate and compress the dried date and its seeds during the seed oil expression process, knowledge of the coefficient of friction would be helpful. Ajav & Fakayode, 2013, observed a similar observation for moringa seeds. The physical traits of the dried date's specie may be the cause of the variance in its frictional behaviour. The angle of repose is essential in the design of machines for mass flow and transportation of the product.

The progressive increase in CoF with moisture content across all three structural surfaces is attributable to the formation of thin water films at the fruit surface–substrate interface. These films increase the effective contact area by filling microscopic asperities on both surfaces, thereby amplifying adhesive forces through hydrogen bonding and surface tension effects (Koocheki et al., 2007; Tavakoli et al., 2009). At lower moisture levels, the relatively dry, waxy pericarp of the dried date generates lower adhesion to structural surfaces, permitting easier sliding. As moisture content increases, the pericarp becomes progressively more pliable and tacky, yielding higher static friction coefficients. This mechanism is analogous to observations on paddy grains (Zareiforoush et al., 2009), Moringa seeds (Ajav and Fakayode, 2013), and soybean (Sachin et al., 2012), wherein wetter seed surfaces consistently produced higher CoF values.

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The markedly different sensitivity of the three surface types to moisture requires specific explanation. The plywood surface exhibited by far the strongest dependence on moisture content ($R^2 = 0.662$), with CoF increasing from 0.237 at 6.08% to 0.408 at 16.23% (w.b.) — a 72% relative increase. The wood grain of plywood provides a macroscopically rough interface characterised by interlocking fibres; water absorption softens both the fruit surface and the wood fibres, dramatically enhancing mechanical interlocking and adhesion. By contrast, the smooth glass surface produced moderate moisture sensitivity ($R^2 = 0.023$; CoF range 0.343–0.362), since the uniformly flat glass surface offers few mechanical interlocking sites, and adhesion is governed primarily by thin-film surface tension rather than fibre interlocking. The galvanised steel surface produced intermediate sensitivity ($R^2 = 0.047$; CoF range 0.254–0.274), consistent with its moderate surface roughness and the relatively low affinity of the galvanised zinc oxide layer for water-swollen organic surfaces. These distinctions carry direct implications for conveyor belt, hopper, and storage-bin design: plywood or wood-lined surfaces should be avoided in humid handling environments, and stainless steel or smooth aluminium should be preferred to minimise adhesion-induced blockages.

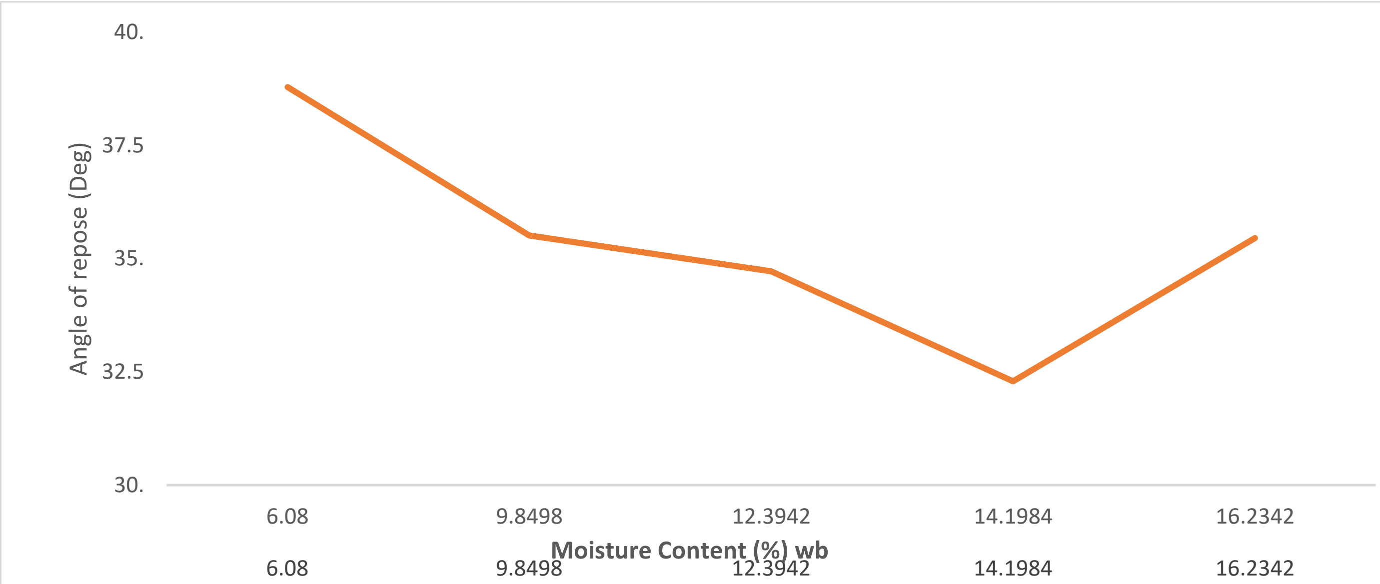

Fig. 4: The effects of moisture content on the Angle of repose of Date fruits

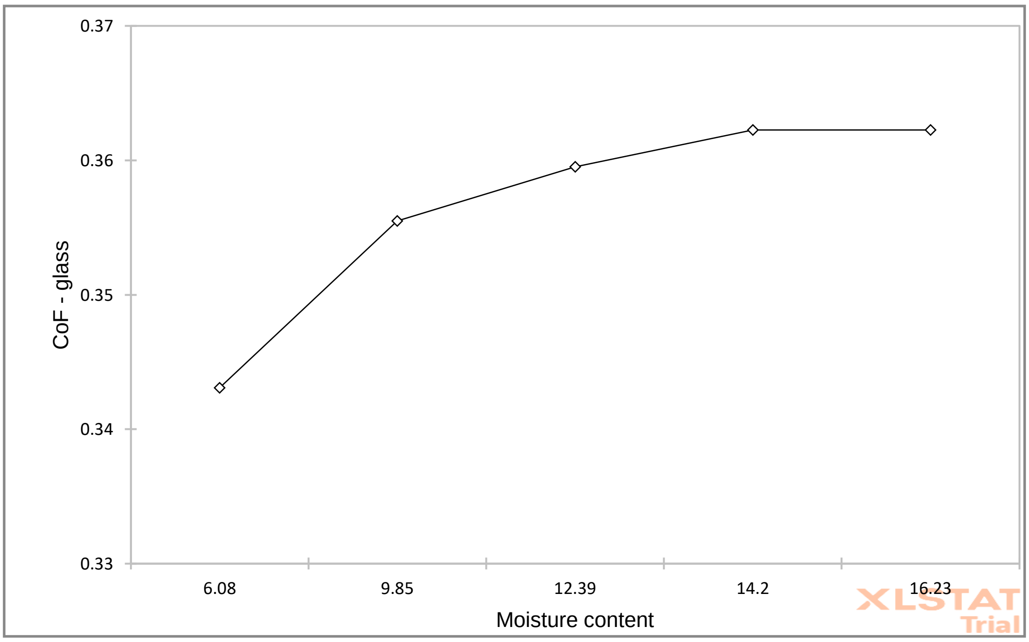

Figure 5. Effects of increased moisture content on the COF of dried dates fruits on glass

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Figures 4 and 5 demonstrate, respectively, how the static coefficient of friction and dynamic angle of repose of dried date fruit vary with moisture content. Angles of repose for the dried dates varied from 32.29 to 38.78°, while the coefficients of static friction for surfaces made of glass, plywood, and galvanized sheet ranged from 0.249 to 0.499, 0.176 to 0.544, and 0.158 to 0.344, respectively (Summary statistics Table).

With an increase in moisture content, the angle of repose decreases (Fig. 4), with the exception of the ultimate moisture level (16.23%), which deviates from the trend and tends to rise.

The observed inverse relationship between angle of repose and moisture content from 6.08% to 14.20% (w.b.) is mechanistically distinct from the positive moisture–CoF relationship. The angle of repose reflects the tendency of individual fruits to slide relative to one another in a bulk pile; it is determined by the balance between inter-fruit friction and gravitational forces. At low moisture levels, partially rehydrated fruit surfaces exhibit a relatively firm, wrinkled texture that promotes mechanical interlocking between adjacent fruits and therefore sustains steeper pile angles. As moisture increases, the mesocarp swells and the surface becomes smoother and more rounded, reducing the degree of mechanical interlocking and permitting fruits to roll past one another more readily, thereby lowering the angle of repose. This is consistent with results reported for African star apple seeds (Oyelade et al., 2005; Onwe et al., 2020) and jatropha (Bamgboye and Adebayo, 2012). The anomalous increase at 16.23% (w.b.) is tentatively attributed to the onset of surface tackiness at high moisture, which may locally increase inter-fruit adhesion and partially counter the smoothing effect. Further investigation across a wider moisture range would be required to confirm whether this represents a genuine reversal or a transient phenomenon near the upper hygroscopic limit of the dried fruit under ambient conditions.

According to the Analysis of Variance (ANOVA) results, the effects of moisture content on the typical values of the frictional characteristics of dried dates are statistically significant at the 5% level of significance. Tables 6 reveals that when frictional characteristics of dried dates are compared pairwise, their differences are statistically significant at = 0.05, particularly for the plywood surface.

The Pearson Correlation matrix summary

Table 2 presents the Pearson correlation matrix for all observed properties. The correlations between pairs of axial dimensions (length–width: 0.573; length–thickness: 0.501; width–thickness: 0.495) were moderate and positive at $p = 0.05$, indicating that changes in moisture content bring about relatively modest corresponding changes across axial dimensions of the biological material. Similar observations were reported by Onwe et al., 2020, for two varieties of African star apple (Chrysophyllum albidum), and by Bajpai et al. (2020) for Jamun seed, where all principal dimensions responded significantly but with moderate intercorrelation

The correlation matrix also indicated a strong and positive relationship at 5% level of significance for the correlation between each of the length, width and thickness attribute of the biological material and the mass, surface area, volume and mean diameters. This indicates that an increase or decrease in either the length, width and thickness attribute as a result of changes in the moisture content of biological material will result in a corresponding increase or decrease in the mass, surface area, volume and mean diameters of Phoenix dactylifera. However, the Pearson correlation matrix for the length, width and thickness attributes in correlation with density and porosity of the biological material was recorded as 0.181 and 0.176, respectively, indicating a weak and positive significant correlation. This shows that there is no link between these attributes. By this, a change in the physical properties of the biological material due to increase in the level of moisture content will not affect or cause a corresponding change in the density and porosity of the material at 5% level of significance.

The matrix also records an average negative significant correlation between the length attribute and the sphericity and aspect ratio of the biomaterial product. This indicates that an increase in the length of the biomaterial product due to changes in the level of moisture content of the Dried date will only bring about a relatively slight decrease in the sphericity and aspect ratio of the material, and vice versa. Unlike the correlation between the sphericity and the mass, geometric mean diameter, arithmetic mean diameter, equivalent mean diameter, square mean diameter, and volume of the biological material which shows a strong negative correlation, indicating that an increase in these attributes due to changes in the level of moisture content will cause a corresponding decrease

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in the sphericity of the biological material. On the contrary, the relationship between the sphericity of the material with the width is an indicative of a weak positive correlation, which suggest that a change in the width property of the material will not affect or cause any corresponding change in the sphericity of the material. Whereas, the relationship between the thickness attribute of the biomaterial product with the sphericity and aspect ratio is a weak positive significant relationship and a strong negative non-significant relationship respectively. While the relationship with the sphericity indicates no relationship between the two properties, the relationship between the thickness property and the aspect ratio of the biomaterial product shows an increase in the thickness attribute due to changes in the moisture content will affect a corresponding decrease in the aspect ratio of the biomaterial product at 5% level of significance.

The Pearson correlation matrix for the density and porosity of the biological material with other attributes like mass, geometric mean diameter, arithmetic mean diameter, equivalent mean diameter, square mean diameter, surface area, volume, sphericity, aspect ratio, as well as the coefficient of friction for glass surface, wood surface and steel surface. With increasing level of moisture content, the table confirms that there was an increase in all the observed properties of the biological material with increase in the level of moisture content, except for the angle of repose.

Finally, the Pearson correlation matrix revealed that an there is no relationship between the length, thickness and width attribute of the biomaterial product with the coefficient of friction property on any of the adopted surfaces due to changes in its moisture content, as a change in one attribute will not cause any corresponding effect on the other.

Table 2: The Pearson Correlation matrix

Var	L	W	T	M	GMD	AMD	SMD	EMD	S. Area	Vol.	Density	Sphericity	A ratio	Porosity	Glass	Wood	Gal. Steel
L	1	0.573	0.501	0.780	0.834	0.922	0.873	0.880	0.764	0.773	0.181	-0.578	-0.490	0.176	0.061	0.136	0.021
W	0.573	1	0.495	0.768	0.825	0.785	0.818	0.812	0.836	0.754	0.236	0.172	0.425	0.262	0.051	0.160	0.007
T	0.501	0.495	1	0.721	0.818	0.730	0.780	0.777	0.845	0.711	0.198	0.303	-0.016	0.223	0.082	0.229	0.127
M	0.780	0.768	0.721	1	0.917	0.905	0.916	0.915	0.922	0.972	0.312	-0.063	-0.042	0.330	0.049	0.208	0.069
GMD	0.834	0.825	0.818	0.917	1	0.982	0.997	0.996	0.988	0.904	0.248	-0.036	-0.040	0.268	0.081	0.215	0.066

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AMD	0.922	0.785	0.730	0.905	0.982	1	0.994	0.995	0.950	0.894	0.236	-0.220	-0.179	0.248	0.076	0.194	0.050
SMD	0.873	0.818	0.780	0.916	0.997	0.994	1	1.000	0.976	0.904	0.245	-0.111	-0.091	0.262	0.078	0.206	0.059
EMD	0.880	0.812	0.777	0.915	0.996	0.995	1.000	1	0.974	0.903	0.244	-0.125	-0.106	0.260	0.079	0.206	0.058
S. Area	0.764	0.836	0.845	0.922	0.988	0.950	0.976	0.974	1	0.907	0.253	0.074	0.050	0.273	0.070	0.213	0.068
Volume	0.773	0.754	0.711	0.972	0.904	0.894	0.904	0.903	0.907	1	0.088	-0.071	-0.053	0.111	0.057	0.191	0.050
Density	0.181	0.236	0.198	0.312	0.248	0.236	0.245	0.244	0.253	0.088	1	0.042	0.062	0.992	0.033	0.147	0.103
Sphericity	-0.578	0.172	0.303	-0.063	-0.036	-0.220	-0.111	-0.125	0.074	-0.071	0.042	1	0.831	0.075	0.011	0.068	0.059
A. Ratio	-0.490	0.425	-0.016	-0.042	-0.040	-0.179	-0.091	-0.106	0.050	-0.053	0.062	0.831	1	0.091	-0.007	0.019	-0.014
Porosity	0.176	0.262	0.223	0.330	0.268	0.248	0.262	0.260	0.273	0.111	0.992	0.075	0.091	1	0.046	0.157	0.107
Coefficient Of Static Friction																	
Glass	0.061	0.051	0.082	0.049	0.081	0.076	0.078	0.079	0.070	0.057	0.033	0.011	-0.007	0.046	1	0.112	-0.020
Wood	0.136	0.160	0.229	0.208	0.215	0.194	0.206	0.206	0.213	0.191	0.147	0.068	0.019	0.157	0.112	1	0.169
Gal. Sheet	0.021	0.007	0.127	0.069	0.066	0.050	0.059	0.058	0.068	0.050	0.103	0.059	-0.014	0.107	-0.020	0.169	1

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CONCLUSION

Several post-harvest physical and engineering properties of whole dried fruits of Phoenix dactylifera were investigated across a systematically controlled moisture content range of 6.08–16.23% (wet basis), using five conditioning treatment levels and 100 replicate measurements per level (n = 500 total). The following conclusions are drawn from the experimental data and statistical analyses:

(a) Moisture content exerted a statistically significant effect (one-way ANOVA, $p \leq 0.05$) on thickness, density, porosity, and CoF on all three structural surfaces tested (glass, plywood, and galvanised steel). Statistically significant differences in these properties were confirmed by Duncan's pairwise comparison at $\alpha = 0.05$.

(b) All engineering properties increased monotonically with moisture content, with the exception of the angle of repose, which declined from 6.08% to 14.20% (w.b.) before rising at the uppermost moisture level (16.23%). This behaviour reflects a transition from mechanical interlocking-dominated bulk behaviour at low moisture to surface-adhesion-dominated behaviour at high moisture.

(c) CoF on the plywood surface demonstrated the strongest and most consistent dependence on moisture content ($R^2 = 0.662$; $F_{4,495} = 242.65$; $p < 0.0001$), with every pairwise comparison between moisture levels being statistically significant. This indicates that plywood and wood-lined handling surfaces pose a substantially higher adhesion risk in humid post-harvest environments and should be avoided in equipment design for dried dates.

(d) The mechanistic basis for the observed trends is the progressive hydration of the pericarp and mesocarp tissues: water uptake drives osmotic swelling, increases contact area at fruit–surface interfaces, and modifies the balance between mechanical interlocking and surface adhesion in bulk assemblies.

(e) The regression equations developed (Table [Z]) provide predictive tools for estimating engineering property values at intermediate moisture levels within the studied range, supporting equipment design calculations for conveyors, hoppers, storage bins, and aeration systems.

(f) Individual whole dried date fruits are denser than water (mean density 0.936 g cm^{-3}), enabling hydraulic density separation of whole fruits from lower-density contaminants and pits. Based on the porosity values obtained (39.19–41.12%), natural convection is insufficient for bulk aeration and drying; forced convection with adequately powered fans is recommended.

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