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Moisture-modulated thermo-physical analysis of sweetsop seed (*Annona squamosa* L.): A potential biofuel feedstock plant

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Abstract

Sweetsop seed holds significant economic value as an oil seed, with ca. 25% oil content that finds applications as a feedstock for energy generation. The moisture-modulated thermophysical properties of the seed were determined at varying moisture contents (8.0%–32.5%). Physical properties (length [L], width [W], thickness [T], arithmetic [A_{md}], and geometric mean diameters [G_{md}], sphericity [S_{ty}], surface area [S_A], and bulk density [ρ_d]) were determined using standard methods while the thermal properties (specific heat capacity [SH_C], thermal conductivity [T_{cd}], and thermal diffusivity [T_{df}]) were analyzed using a TEMPOS thermal analyzer. The results showed that the seed L, W, T, A_{md}, and G_{md}, S_{ty}, S_A, and ρ_d ranged from 13.22–14.95 mm, 7.32–7.95 mm, 5.25–5.35 mm, 8.60–8.75 mm, and 7.96–8.11 mm, 0.61–0.60, 196.72–205.28 mm^2, and 210.00–270.00 kg m^{-3}, respectively. The SH_C, T_{cd}, and T_{df} ranged from 0.14–0.52 J kg^{-1} K^{-1}, 0.17–0.35 W m$-^{1}$ K^{-1}, and 0.10–0.20 m^2 s^{-1}, respectively. The ANOVA results indicated that the thermo-physical properties studied were significantly ($p \leq 0.05$) affected by moisture content. By utilizing the determined properties, engineers can develop efficient machines to harness the economic potential of sweetsop seed oil in various industries, including biofuel generation.

Practical applications

The thermal and physical properties of sweetsop seed are needed by agricultural and mechanical engineers and food scientists to explore the potential application of the seed and the seed product, like oil for industrial and commercial purposes. Data obtained on the specific heat capacity of the seed would be valuable in designing of heating compartment of an oil expeller, thermal conductivity and diffusivity would be needed to design drying systems that balance efficiency and quality preservation, facilitate efficient removal of moisture from the seed while minimizing the risk of over-drying or under-drying. Thus, affects the design of the seed storage systems. Data on the seed axial dimensions, sphericity, mean diameters, surface area, and bulk density would be useful in the design and fabrication of agricultural equipment like sheller, grinder, packaging machines, discharge chute, aperture, and planter, to ensure proper seed placement, flow and to determine machine throughput capacity.

KEYWORDS
agricultural processing machines, biofuel feedstock, moisture content, physical properties, sweetsop seed, thermal properties

1 | INTRODUCTION

Sweetsop (*Annona squamosal* L.), also known as sugar apple or custard apple, is a popular fruit that belongs to the Annona family. It is native to the tropical climates of the Americas and West Indies where about 387.26 tons are produced annually and is widely cultivated in tropical regions (NHB, 2021; Oloyede et al., 2015). The fruit has a spherical–conical shape with a thick rind composed of twisted segments. It is usually pale-green, and pink-bluish in some varieties. Sweetsop is a segmented fruit that separates when ripe, revealing white flesh and oil-bearing seeds (Eshra et al., 2019). The oil-bearing seeds of sweetsop, are hard, glossy, and black. In Nigeria, the fruit is known as "*Ebo*" or "*Apekan*" among the Yoruba-speaking tribe, "*Tuwon Biri*" in the Hausa language, and "*Sawansop*" in the Igbo language. Most Annona families like Sweetsop are mostly grown in home gardens in Nigeria because of their tolerance to poor soil (Oloyede et al., 2017).

The fruit is highly valued for its sweet and custard-like flavor, and its seeds are often discarded as waste. However, recent studies have shown that sweetsop seeds possess various bioactive compounds with potential applications in the cosmetics, and pharmaceutical industries, for biodiesel production (Nagaraja et al., 2016; Sundaramahalingam et al., 2021). According to Nagaraja et al. (2016), the seed of sweetsop is poisonous and causes ocular toxicity, keratoconjunctivitis, and severe conjunctival congestion due to the presence of steroids, terpenoids, glycoside, alkaloid, flavonoid saponin, phenolic compounds, and acetogenins which when comes in contact with the eyes causes severe inflammation, thus making its oil inedible. On average, the seeds contain 24.23% oil per 100 g, with oleic acid (39.72%), linoleic acid (29.13%), palmitic acid (17.79%), stearic acid (4.29%), and lauric acid (0.08%) being the major fatty acids in the oil (Yadav et al., 2019). The oil falls into the oleic-linoleic group with high monounsaturated fatty acids in the oil (Ashokkumar et al., 2020). It also possesses specific physicochemical properties such as a saponification value of 192 mg of KOH g^{-1} of oil, specific gravity at 32°C of 0.897, iodine value of 115–118 mg of iodine g^{-1} of oil, acid value of 1.93–3.08 mg of KOH g^{-1} of oil, free fatty acid of 1.54%, kinematic viscosity value of 42.63 mm^2, and peroxide value of 1.96 mEq kg^{-1} (Hotti & Hebbal, 2015; Sundaramahalingam et al., 2021). Due to its low free fatty acid composition and high monounsaturated fatty acid content, It's therefore a potential feedstock for biodiesel production.

Designing specific processing machines and equipment is necessary to explore the potential use of the seeds. The design of such machines by the engineers needs a comprehensive analysis of the thermal and physical behavior of sweetsop seeds. Analyzing these properties would help researchers in analyzing the seed products' behavior, gaining a better understanding of these products' potential applications in biofuel production, pharmaceutical formulation, storage stability, and optimization of process conditions (Sundaramahalingam et al., 2021). The seeds' physical and thermal properties are significantly influenced by their moisture content (mc) (Hashemifesharaki, 2021). Its impact on physical characteristics, including the density, size, and shape, can affect how handling, storing, dehulling, and quality preservation are managed during processing. The mechanism of heat transfers during roasting, drying, or other thermal attributes can also be influenced by mc. Therefore, compared to dry seed, an oilseed with a higher mc requires more energy to heat or cool (Hashemifesharaki, 2021). Researchers have extensively studied the thermal and physical properties of various seeds and kernels, such as soursop seed and kernel (Oloyede et al., 2015, 2017), Australian chia seed (Timilsena et al., 2017), white mustard seed (Ropelewska et al., 2018), camelina seed (Ropelewska & Jankowski, 2019), African star apple (Onwe et al., 2020), paddy and wheat seed (Jadhav et al., 2020), arugula seed (Mirzable et al., 2021), maize seed (Hernández et al., 2023), and wild banana seed powder (Meghwal et al., 2024). However, information specifically on the thermal and physical behavior of sweetsop seeds has not been reported in the literature. Therefore, the novelty of this study lies in its focus on analyzing the moisture-modulated thermo-physical properties of sweetsop seeds to fully exploit the economic potential of sweetsop seed oil for industrial production and energy generation via mechanical handling.

2 | MATERIALS AND METHODS

2.1 | Sample collection, preparation, and the determination of mc

Sweetsop fruits (green cultivar) were collected from Ogbomoso South (8.0794°N, 4.2231°E) and North (8.1335°, 4.2538°E) Local Government Area, Nigeria, due to their availability in that region. The seeds were manually removed from the white flesh and washed to remove foreign materials, then stored at room temperature ranging between 20 and 23°C, overnight. The seeds were then dried under solar irradiation for 3 days to reduce their mc to a safe storage moisture level. The seed's initial mc on a dry basis (db), before and after sun-drying was determined according to ASABE S352.2 (2001) in Oloyede et al. (2017) using an oven drying method at a temperature of 103 ± 2°C using a laboratory oven (DGH-9101.USA) and was found to be 11.5% and 5.3% (db), respectively. This was done by measuring 5.0 g of each of the sweetsop seeds sample into three different cans of predetermined weights. The sample and empty can weight were recorded using an electronic digital weighing balance (MP 1001, 0.1 g sensitivity). The sample was then placed inside the empty can and both were kept inside an oven. The weights were noted at 3-h intervals until a constant weight was reached and the average readings were taken. Equation (1) (Onwe et al., 2020) was used to calculate the seed mc.

$$mc_{db}(\%) = \frac{M_w - M_D}{M_D} \times 100 \tag{1}$$

where mc = moisture content (%, db), M_w = initial mass of the seed (g), M_D = mass of dry matter (g).

The samples were conditioned to five different moisture levels (8.0, 11.9, 15.4, 22.5, and 32.5% db). These desired moisture levels were chosen according to Oloyede et al. (2015, 2017). Conditioning of the seed sample was done using a rewetting method. This involves adding a calculated amount of clean water to a sample of known mc and weight. The sample was then sealed in a ziploc bag and placed in a refrigerator (Thermocool T1001) at a temperature 5 ± 2°C of for at least 7 days for even moisture circulation within the samples. Before commencing the test, the required amount of sample was taken out from the refrigerator and allowed to reach room ambient temperature. The amount of water to be added was determined using Equation (2) (Jaiyeoba et al., 2022).

$$Q = \frac{W(W_f - W_i)}{100 - W_f} \times 100 \tag{2}$$

where Q = amount of water added (g), W = sample's initial weight (g), W_f = sample desired moisture level (%, db), and W_i = sample's initial mc (%, db).

2.2 | Analysis of thermal properties of sweetsop seeds

The volumetric heat capacity (C_V), thermal conductivity (T_{Cd}), and thermal diffusivity (T_{df}) of the seed sample were determined using a SH-1 dual-needle sensor coupled to a TEMPOS thermal analyzer (Meter Group, USA) with an accuracy of ±0.1, following the procedure described by Oloyede et al. (2017), Singh et al. (2016), and Yu et al. (2015). Proper insertion of the sensor into the sample in a measuring cylinder was ensured and the meter was put on. After about 180–200 s, the data on C_V, T_{Cd}, and T_{df} was recorded from the digital screen of the analyzer (Figure 2). The specific heat capacity (SH_C) of the seed was determined from Equation (3). The thermal analysis was determined in triplicate.

$$SH_C = \frac{C_v}{\rho_d} \tag{3}$$

where SH_C is the specific heat capacity in kJ kg^{-1} K^{-1}, C_v, is the volumetric heat capacity in kJ m^{-3} K^{-1} and ρ_d is the bulk density in kJ kg^{-1} K^{-1}.

2.3 | Analysis of physical properties of sweetsop seed

The principal axial dimensions (length [L], width [W], and thickness [T]) of sweetsop seed were measured from randomly selected 100 seeds through a digital Vernier caliper (GMC-20; accuracy = 0.01 accuracy). The seed mean diameters (arithmetic, A_{md}, and geometric, G_{md}), sphericity (S_{ty}), and surface area (S_A) were determined using Equations (4–7), respectively (Meghwal et al., 2024; Oniya et al., 2016).

$$A_{md} = \frac{L + W + T}{3} \tag{4}$$

$$G_{md} = (LWT)^{1/3} \tag{5}$$

$$S_{ty} = \frac{G_{md}}{L} \tag{6}$$

$$S_A = \pi (G_{md})^2. \tag{7}$$

The sample bulk density was determined by filling an empty 100 mL volumetric cylinder with the sample, which was poured from a constant height. The cylinder was then weighed. Equation (7) was used to calculate the sample ρ_b (Gierz et al., 2022; Idowu & Oloyede, 2022). The bulk density was replicated in triplicate.

$$\rho_d = \frac{M}{V} \tag{8}$$

where ρ_d is the bulk density kg m^{-3}, M is the bulk mass of the sample (kg), and V is the volume of the cylinder (m^3). The pictorial view of the experimental procedure is shown in Figure 1.

2.4 | Statistical analyses

The IBM SPSS software (version 21) was used to perform statistical analyses on the obtained data at a significance level of 0.05 using one-factor Analysis of Variance (ANOVA). This was done to show how the seed's varying mc significantly affect its thermal and physical properties. To test for significant variations between the mean data values at different moisture levels, Duncan's Multiple Range Test (DMRT) was done at a $p \leq 0.05$ probability level.

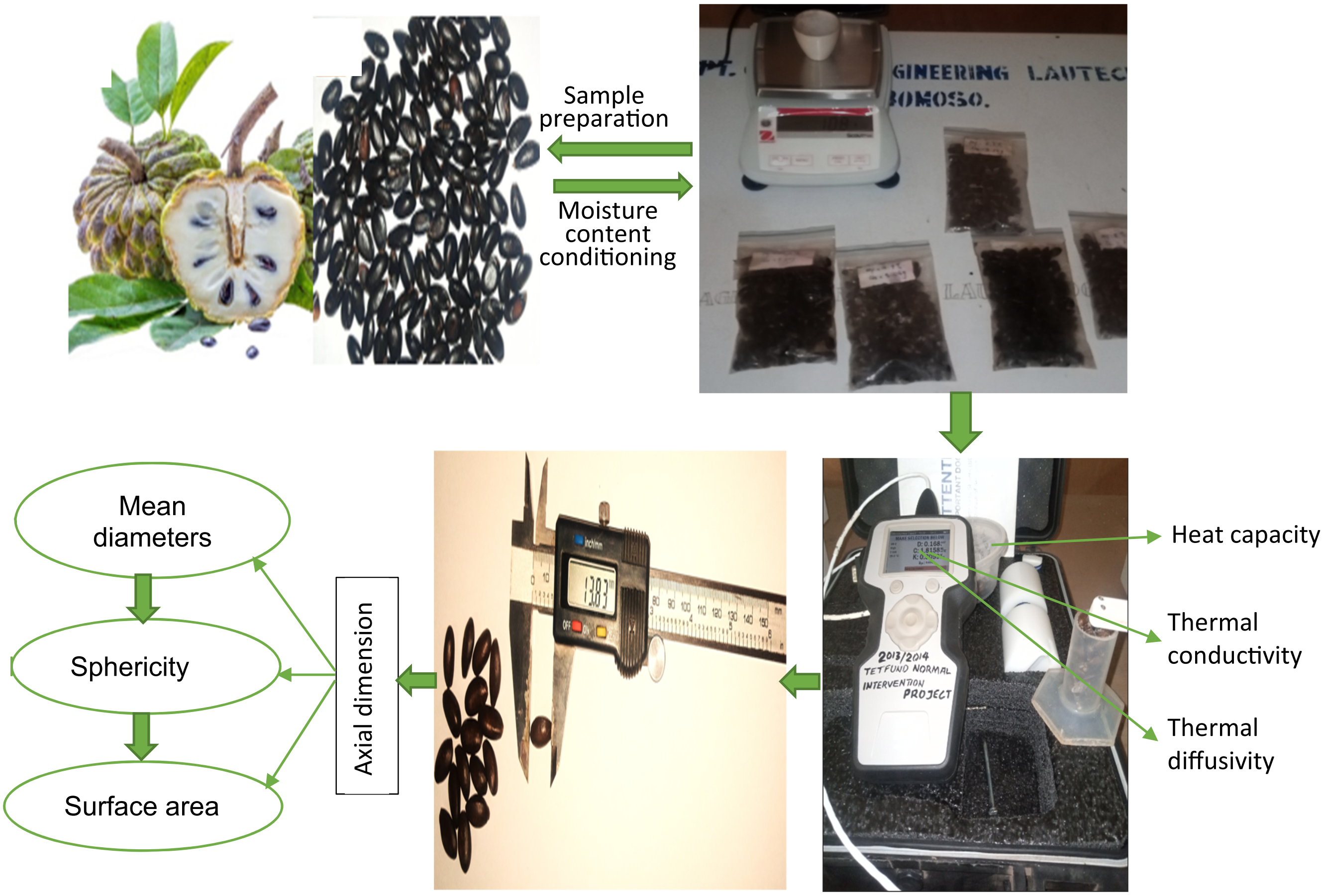

FIGURE 1 Sweetsop seed physical and thermal measurement procedure.

3 | RESULTS AND DISCUSSION

3.1 | Thermal properties

3.1.1 | SH_C of sweetsop seeds

The average values of sweetsop seed SH_C increased linearly from 0.014 to 0.052 J kg^{-1} K^{-1} as mc increased linearly from 8.0% to 32.5% (db) (Figure 2). This shows that the amount of heat energy required to raise the temperature of the unit mass of the seed is a function of mc. This behavior has been attributed to the increase in water content present in the sample at different moisture levels (Ghodki & Goswami, 2016). Tables 1 and 2 revealed significant differences at $p \le 0.05$ in the mean value of the seed SH_C, and that mc has a significant effect on SH_C with an *F*-value of 10.750 and *p*-value less than 0.05. A similar trend was observed by Suleiman et al. (2019) and Oloyede et al. (2017) for triticale and soursop seed with an increase in SH_C from 1.60 to 2.25 J kg^{-1} K^{-1} and 0.01 to 0.05 J kg^{-1} K^{-1}, respectively. There was a strong positive correlation between SH_C and mc (Table 3). Data obtained on SH_C of the seed would be useful for the engineers in the design of the oil expeller heating compartment.

3.1.2 | T_{cd} of sweetsop seeds

Figure 2 also, shows the relationship between the seed's T_{CD} and mc. With the increase in moisture level from 8.0% to 32.5% (db), the seeds' T_{cd} increased logarithmically from 0.168 to 0.345 W m^{-1} K^{-1}. This behavior might be due to the higher T_{cd} of moisture in the seed compared with the samples' dry material associated with air-filled pores (Hernández et al., 2023; Singh & Meghwal, 2019). The differences between the mean values of the seed T_{cd} were statistically significant ($p \le 0.05$) at all moisture levels as analyzed using DMRT except at 22.6% and 32.5% is shown in Table 2. The significant effect is confirmed via ANOVA result (Table 1). A strong positive correlation was observed between T_{Cd}, and mc (Table 3). The *p*-value less than 0.05 confirmed the significant model term. A positive linear correlation was also observed for the T_{cd} of psyllium seed (Hashemifesharaki, 2021) whose T_{cd} increased from 0.235–0.322 W m^{-1} K^{-1}, with respect to mc. Data on the T_{CD} of sweetsop seed is valuable for engineers in the design of heating or cooling compartments for uniform temperature distribution during seed processing. It could also be useful to design drying systems that balance efficiency and quality preservation and, therefore, can affect the design of storage systems

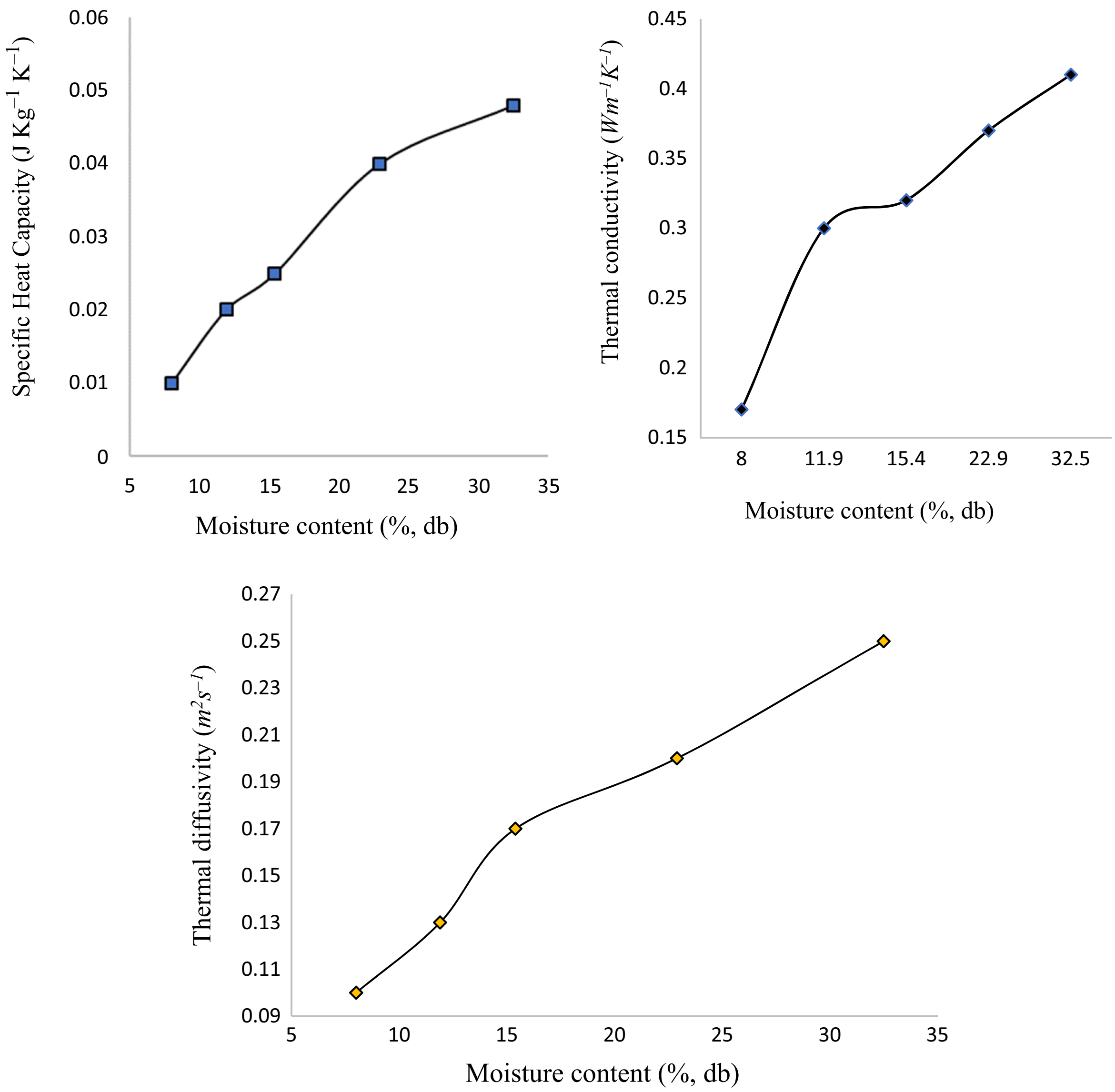

FIGURE 2 Effect of moisture content on, specific heat capacity, thermal conductivity, and thermal diffusivity of sweetsop seed. db, dry basis.

TABLE 1 ANOVA results showing a significant effect of moisture content on thermal properties of sweetsop seed at $p \leq 0.05$.

Parameter	Sum of squares	df	Mean square	*F*	Sig.
Thermal diffusivity					
Between groups	0.023	4	0.006	43.476	0.0001
Within groups	0.001	10	0.000		
Total	0.025	14			
Thermal conductivity					
Between groups	0.055	4	0.014	11.985	0.0001
Within groups	0.011	10	0.001		
Total	0.066	14			
Specific heat capacity					
Between groups	0.003	4	0.001	10.750	0.0001
Within groups	0.001	10	0.000		
Total	0.004	14			

TABLE 2 The mean values and standard deviation of physical and thermal properties of sweetsop seed by Duncan's Multiple Range Test ($p \le 0.05$).

	Moisture content (%, db)				
Parameters	**8**	**11.9**	**15.4**	**22.6**	**32.5**
Thermal properties					
Specific heat capacity (J kg^{-1} K^{-1})	0.014 ± 0.006^{a}	0.02 ± 0.006^{ab}	0.025 ± 0.02^{b}	0.04 ± 0.005^{c}	0.052 ± 0.009^{cd}
Thermal conductivity (W m^{-1} K^{-1})	0.168 ± 0.12^{a}	0.269 ± 0.06^{b}	0.292 ± 0.04^{b}	0.365 ± 0.02^{b}	0.405 ± 0.02^{b}
Thermal diffusivity (m^{2} s^{-1})	0.99 ± 0.006^{a}	0.131 ± 0.01^{b}	0.169 ± 0.02^{c}	0.199 ± 0.006^{d}	0.254 ± 0.04^{d}
Physical properties					
Length (mm)	13.22 ± 0.12^{a}	13.39 ± 0.27^{a}	14.01 ± 0.5^{b}	14.54 ± 0.03^{c}	14.95 ± 0.02^{d}
Width (mm)	7.32 ± 0.02^{a}	7.44 ± 0.05^{b}	7.81. ± 0.07^{c}	7.93 ± 0.02^{d}	7.95 ± 0.08^{d}
Thickness (mm)	5.25 ± 0.03^{a}	5.28 ± 0.03^{ab}	5.30 ± 0.03^{abc}	5.34 ± 0.03^{bc}	5.35 ± 0.04^{d}
Arithmetic mean diameter (mm)	8.6 ± 0.03^{a}	8.61 ± 0.03^{a}	8.67 ± 0.03^{b}	8.72 ± 0.03^{c}	8.75 ± 0.03^{c}
Geometric mean diameter (mm)	7.96 ± 0.03^{a}	8.00 ± 0.03^{ab}	8.04 ± 0.03^{bc}	8.09 ± 0.03^{cd}	8.11 ± 0.03^{d}
Sphericity	0.62 ± 0.03^{a}	0.604 ± 0.03^{a}	0.603 ± 0.03^{a}	0.601 ± 0.03^{a}	0.6 ± 0.03^{a}
Surface area (mm^{2})	196.72 ± 2.31^{a}	199.40 ± 1.16^{b}	201.16 ± 1.16^{bc}	203.93 ± 0.60^{cd}	205.28 ± 0.60^{d}
Bulk density (Kg m^{-3})	210.0 ± 2.88^{a}	215.0 ± 2.89^{b}	227.5 ± 1.15^{c}	247.5 ± 2.88^{d}	270.0± 2.89^{e}

Note: a, b, c, d, and e—suggest that superscripts with different mean letters in the same row differ considerably, but superscripts with the same mean letters in the same row imply that the moisture levels between "ab, bc, cd" are not significantly different.

TABLE 3 Regression model shows the relationship between moisture content (mc), and thermo-physical properties of sweetsop seed.

Regression models	R^2
Thermal properties	
$SH_C = 0.0015\ mc + 0.0005$	0.920
$T_{CD} = 0.159\ln(mc) - 0.131$	0.918
$T_{df} = 0.006\ mc - 0.062$	0.971
Physical properties	
$L = 0.099\ mc + 12.506$	0.938
$W = 0.0281\ mc + 7.181$	0.789
$T = 0.0057\ mc + 5.190$	0.988
$A_{md} = 0.0075\ mc + 8.511$	0.896
$G_{md} = 0.0061\ mc + 7.910$	0.912
$S_{ty} = 1e - 0.0\ mc^2 - 0.00\ mc$	0.971
$S_A = 1.965\ mc + 196.81$	0.988
$\rho_b = 2.5413\ mc + 187.9$	0.994

Abbreviations: A_{md}, arithmetic mean diameters; G_{md}, geometric mean diameters; L, length;S_A, surface area; SH_C, specific heat capacity; S_{ty}, sphericity; T, thickness; T_{cd}, thermal conductivity; T_{df}, thermal diffusivity; W, width; ρ_d, bulk density.

(Ghodki & Goswami, 2016). Thus, seeds with higher T_{CD} may require additional insulation to maintain their quality during storage and prevent heat buildup (Ikegwu, 2021). However, in this study, the sweetsop seed has low T_{cd}, therefore, additional insulation would not be required when designing a storage system for the seed.

3.1.3 | T_{df} of sweetsop seeds

The T_{df} of sweetsop seeds increased linearly with an increase in mc from 8.0% to 32.5% (db). It is also shown in Figure 2. This denotes that mc of sweetsop seed is directly proportional to its T_{df}. This value ranged from 0.102 to 0.203 m^2 s^{-1}. This shows that the seed T_{df} is directly proportional to mc. Understanding this would help engineers in the design of drying systems that facilitate efficient removal of moisture from the seed while minimizing the risk of over-drying or under-drying. The impact of mc on the seed T_{df} was statistically significant ($p \le 0.05$). The mean values of T_{df} at all examined mc varied significantly except at 22.6% and 32.5% (Table 2). A strong positive correlation between T_{df}, and mc was also observed (Table 3). A Similar, trend was detailed by Ikegwu (2021), Oloyede et al. (2017), and Pohndorf et al. (2017) for pigeon pea seed, soybean, and soursop seed, respectively. However, a decrease in the T_{df} of psyllium seed with mc was reported by (Hashemifesharaki, 2021).

3.2 | Physical properties

3.2.1 | Principal axial dimension of sweetsop seed

The seed mean lengths (L), widths (W), and thicknesses (T) ranged from 13.13–13.47, 7.29–7.4, and 5.23–5.32 mm, respectively, within the mc range of 8.0%–32.5% (db). Table 2 shows that the mean values for the L and W, were significantly different ($p \le 0.05$) at all moisture levels except for the L at 8.0%–11.9% (db), and W at 15.4%–22.9% (db) which could be as a result of the low water absorption capacity of

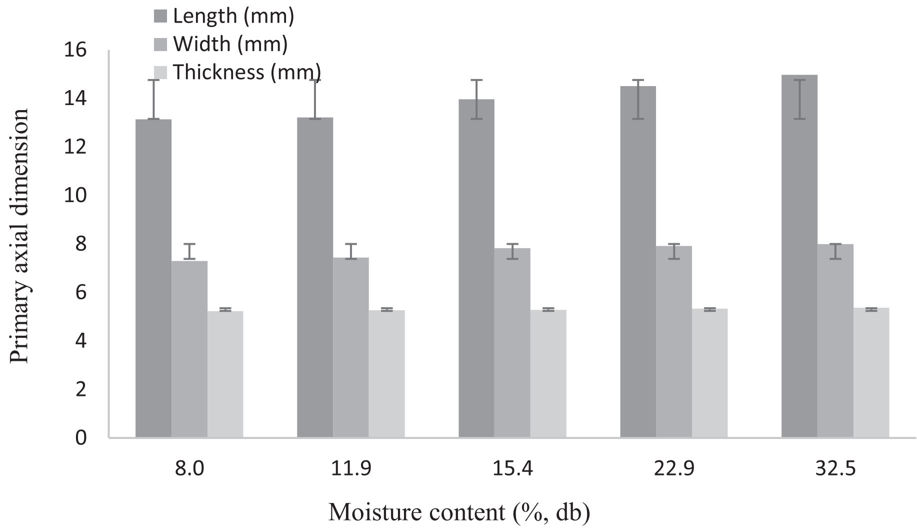

FIGURE 3 Effect of moisture content on principal axial dimensions of sweetsop seed. db, dry basis.

TABLE 4 ANOVA shows a significant effect of moisture content on the physical properties of the sweetsop seed at $p \leq 0.05$.

Physical properties	Sum of squares	df	Mean square	*F*	Sig.
Length					
Between groups	6.527	4	1.632	90.925	0.0001
Within groups	0.179	10	0.018		
Total	6.707	14			
Width					
Between groups	1.015	4	.254	77.508	.0001
Within groups	0.033	10	0.003		
Total	1.048	14			
Thickness					
Between groups	0.019	4	0.005	5.597	0.013
Within groups	0.008	10	0.001		
Total	0.027	14			
Arithmetic mean diameter					
Between groups	0.071	4	0.018	21.168	0.0001
Within groups	0.008	10	0.001		
Total	0.079	14			
Geometric mean diameter					
Between groups	0.046	4	0.012	13.860	0.0001
Within groups	0.008	10	0.001		
Total	0.055	14			
Sphericity					
Between groups	0.000	4	0.000	0.017	0.999
Within groups	0.008	10	0.001		
Total	0.008	14			
Surface area					
Between groups	141.961	4	35.490	18.357	0.0001
Within groups	19.333	10	1.933		
Total	161.295	14			
Bulk density					
Between groups	7257.900	4	1814.475	261.703	0.0001
Within groups	69.333	10	6.933		
Total	7327.233	14			

the seed at that level (Pohndorf et al., 2017). However, the seed thickness showed no statistically significant difference except at 8.0% and 32.5% (db). Data on axial dimensions would be useful for engineers in designing agricultural equipment like planters, to ensure proper seed placement, and flow, and prevent seed damage (Onwe et al., 2020). The relationship between mc and sweetsop seeds *L*, *W*, and *T* is shown in Figure 3. It demonstrates that the seeds *L*, *W*, and *T* increased linearly with an increase in mc. This indicates the seed size is mc dependent. The ANOVA result indicated that mc has a significant effect ($p \le 0.05$) on the seed *L*, *W*, and *T*, with model *F*-values of 90.925, 77.508, and 5.597, respectively. Strong positive correlations between *L*, *W*, and *T* and mc were confirmed by high, R^2 (Table 4). Bajpai et al. (2019) reported similar results for the principal axial dimensions of Jamun seed at varying mc.

3.2.2 | Arithmetic and geometric mean diameters

As the seed mc increased from 8.0% to 32.5%, the seed arithmetic (A_{md}) and geometric (G_{md}) mean diameters increased linearly from 8.55–8.73 and 7.94–8.09 mm, respectively (Figure 4). Differences between the mean diameters at all moisture levels were significantly different ($p \le 0.05$). Data on mean diameters would be useful for engineers designing farm machines like oil expellers or shellers to determine machine throughput capacity (Adeyanju et al., 2021). The ANOVA result presented significant model *F*-values of 21.168, and 13.860 for the arithmetic and geometric mean diameters, respectively. The *p*-value less than 0.05 indicates the model terms are significant. Hence, shows that the seed mean diameters are significantly ($p \le 0.05$) affected by mc. A similar linear increasing trend was observed by Singh and Meghwal (2019) for Ajwain seed.

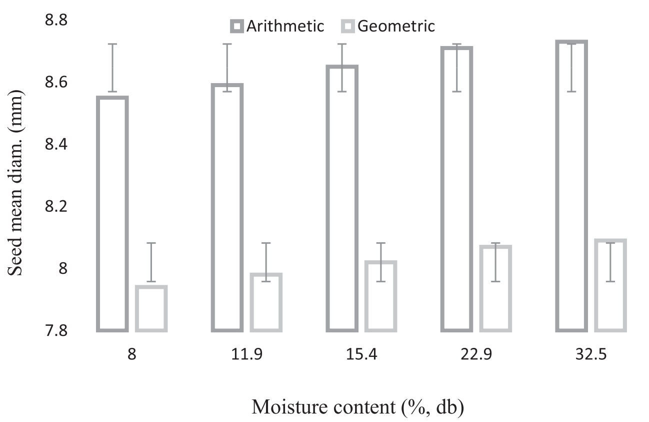

FIGURE 4 Effect of moisture content on the arithmetic (A_{md}), and geometric (G_{md}) mean diameter of sweetsop seeds. db, dry basis.

3.2.3 | Sphericity and S_A of sweetsop seeds

The sweetsop seed mean sphericity value ranged from 0.605 to 0.601 as mc increased from 8.0% to 32.5% (db). This showed that the seed's sphericity decreased parabolically with an increase in mc with the second-order polynomial model (Table 1) as shown in Figure 5. The highest value of 0.605% at 32.5% (db) mc presents that the seed is oval. Habibiasr et al. (2020) likewise reported a similar trend for tenera palm kernel. No significant differences between sphericity mean values were observed at $p \le 0.05$ for all moisture levels and confirmed by ANOVA results with *p*-value > 0.05 (Tables 2 and 4). Similar ranges and non-significant effects of moisture on sphericity were reported for soursop kernels by Jaiyeoba et al. (2022). Likewise, the seed S_A increased linearly with mc from 198.06 to 205.61 mm^2 (Figure 5). This might likely be due to changes in seed surface texture with mc. Differences between the mean values of S_A with mc were significant except at 15.4%–22.9% mc and were also established by ANOVA results with significant *F*-values of 18.357 and a *p*-value less than 0.05. The R^2 value of 0.913 confirmed a strong correlation between S_A and mc. A similar trend was also reported by Adeyanju et al. (2021) for Ofada rice. Data on S_A of the seed could help engineers design effective heat exchangers for oil extraction processes.

3.2.4 | Bulk density of sweetsop seeds

As the mc increased from 8.0% to 32.5% (db), the bulk density (ρ_b) of sweetsop seeds increased linearly from 210 to 270 kg m^{-3} (Figure 6). Demonstrating that the mc of the seed affects its ρ_b. DMRT analysis

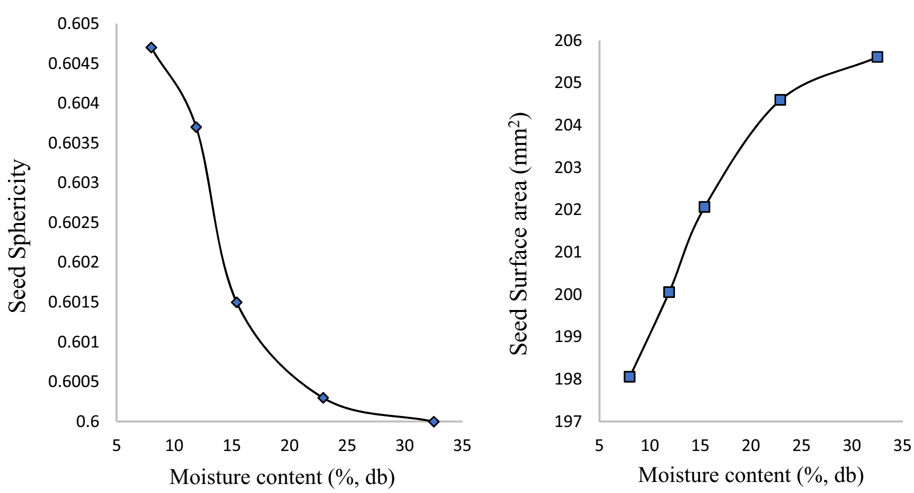

FIGURE 5 Effect of moisture content on the seed sphericity and surface area. db, dry basis.

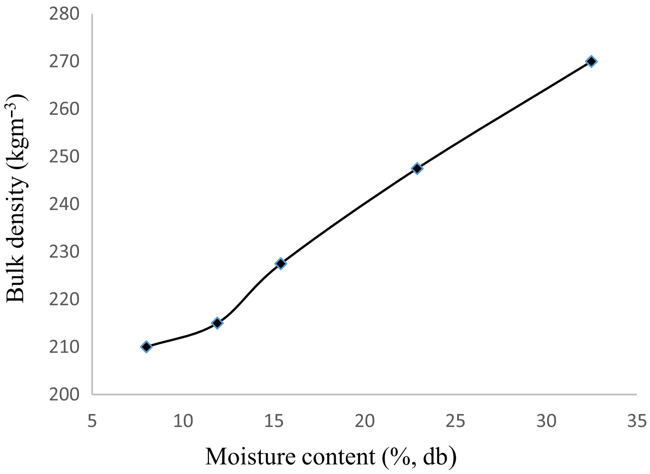

FIGURE 6 Effect of moisture content on the bulk density of sweetsop seed. db, dry basis.

revealed significant differences ($p \leq 0.05$) in the mean value of ρ_b for every experimental mc (Table 2). The ANOVA results confirmed that with a significant model *F*-value of 261.70 and a *p*-value less than 0.05, mc had a significant effect ($p \leq 0.05$) on ρ_b (Table 3). Data on bulk density would be useful for engineers in designing the throughput capacity of conventional sweetsop seed processing equipment and when packaging the seed. There was a strong positive correlation between ρ_b, and mc (Table 4). This finding agreed with the study of Nkambule et al. (2023) for Bambala groundnut seed which observed an increasing trend in the seed bulk density with increased mc.

4 | CONCLUSION

This study explored the thermo-physical behavior of sweetsop seed at various mc ranges of 8.0%–32.5% (db) and the impact of mc on the physical and thermal parameters was investigated. The following conclusions were drawn from the study:

1. The effect of mc on the SH_C, and T_{df} of sweetsop seed was significant at $p \leq 0.05$ significant level except for the T_{cd}. It was observed that an increase in the mc of the seed results in to increase in the mean value of these thermal properties.
2. The behavior of the seed's physical properties revealed that mc has a significant effect on the seed's length, width, arithmetic and geometric mean diameter, and surface area except for the seed's sphericity and thickness. The increase in mc increases the physical properties parameters investigated except for the seed sphericity.
3. The strong positive coefficient of regression, R^2 was observed for the thermal and physical properties variables and mc.

Hence, data obtained in this study would play a significant role in the extractability of optimum oil yields, the efficiency of extraction machinery, heat transfer kinetics, storage stability, and overall process design which would directly affect the technical and economic viability of sweetsop seed as a potential feedstock for biofuel production.

AUTHOR CONTRIBUTIONS

Christopher Tunji Oloyede: Conceptualization (equal); investigation (equal); methodology (equal); resources (equal); writing – original draft (equal); review and editing (equal); supervision (equal). **Simeon Olatayo Jekayinfa**: Conceptualization (equal); supervision (equal); visualization (equal). **Samuel Adeyemi Adebonojo**: Writing, review, editing and methodology (equal). **Alexander Adebola Uduaghan**: Writing, review, editing and methodology (equal). **Johnson Mobolaji Adebayo**: Resources and methodology (equal). **Fattah Islam Md Rizwanul**: review and editing (equal); supervision (equal).

CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest in the article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Adeyanju, J. A., Abioye, A. O., Adekunle, A. A., Olokoshe, A. A., Ibrahim, T. H., & Faboade, A. L. (2021). Investigation on the effect of moisture content on physical and thermal properties of ofada rice (*Oryza sativa* L.) relevant to post-harvest handling. *LAUTECH Journal of Engineering and Technology*, *15*(1), 108–116.

Ashokkumar, S., Elanthiraiyan, A., Shagu, S., & Srinivasan, M. (2020). Science and engineering comparison and analysis of custard apple seed oil with engine lubricant (bio lubricant) comparison and analysis of custard apple seed oil with engine lubricant (bio lubricant). *IOP Conf. Series: Materials Science and Engineering*, *990*, 012008. https://doi.org/10.1088/1757-899X/993/1/012008

Bajpai, A., Kumar, Y., Singh, H., & Prabhakar, P. K. (2019). Effect of moisture content on the engineering properties of jamun (*Syzgium cuminii*) seed. *International Journal of Food Science and Biotechnology*, *43*, e13325. https://doi.org/10.1111/jfpe.13325

Eshra, D. H., Shehata, A. R., Ahmed, A. A., & Saber, J. I. (2019). Physicochemical properties of the seed kernels and the oil of custard apple (*Annona squamosa* L.). *International Journal of Food Science and Biotechnology*, *4*(4), 87–93. https://doi.org/10.11648/j.ijfsb.20190404.12

Ghodki, B. M., & Goswami, T. K. (2016). Thermal and mechanical properties of black pepper at different temperatures. *Journal of Food Process Engineering*, *40*, e12342. https://doi.org/10.1111/jfpe.12342

Gierz, Ł., Kolankowska, E., & Markowski, P. (2022). Applied sciences measurements and analysis of the physical properties of cereal seeds depending on their moisture content to improve the accuracy of DEM simulation. *Applied Sciences*, *12*, 549. https://doi.org/10.3390/app12020549

Habibiasr, M., Mokhtar, M. N., Ibrahim, M. N., Yunos, K. F. M., & Ibrahim, N. A. (2020). Study on the effects of physical properties of tenera palm kernel during drying and its moisture sorption isotherms. *Processes*, *8*(12), 1658. https://doi.org/10.3390/pr8121658

Hashemifesharaki, R. (2021). Moisture-dependent engineering characterization of psyllium seeds: Physical, frictional, aerodynamic, mechanical, and thermal properties. *Biosystems Engineering*, *45*(2020), 374–384.

Hernández, G. L., Aguilar, C. H., Domínguez Pacheco, A., Sibaja, A. M., Orea, A. A. C., & de Jesus Agustin Flores Cuautle, J. (2023). Thermal properties of maize seed components. *Cogent Food & Agriculture*, *9*(1), 2231681. https://doi.org/10.1080/23311932.2023.2231681

Hotti, S. R., & Hebbal, O. D. (2015). Biodiesel production process optimization from sugar apple seed oil (*Annona squamosa*) and its characterization. *Journal of Renewable Energy*, *2015*, 1–6. https://doi.org/10.1155/2015/148587

Idowu, D. O., & Oloyede, C. T. (2022). Comparative study of engineering properties of four selected cowpea (Vigna Unguiculata) varieties. *International Journal of Research and Review*, *9*(3), 75–82. https://doi.org/10.52403/ijrr.20220309

Ikegwu, O. J. (2021). Effect of moisture and temperature on thermal conductivity of pigeon pea seeds. *Agricultural Engineering International: CIGR Journal*, *23*(1), 217–224.

Jadhav, M. L., Maharani, D., Nandede, B., & Kumar, M. (2020). Engineering properties of paddy and wheat seeds in context to design of pneumatic metering devices. *Journal of the Institution of Engineers (India): Series A*, *101*, 281–292. https://doi.org/10.1007/s40030-019-00430-7

Jaiyeoba, K., Idowu, D., Oloyede, C., Akande, F., Oniya, O., Popoola, A., & Jekaayinfa, S. (2022). Exploring soursop kernel as a sustainable biofuel: Analyzing physical and solid flow properties for feasibility assessment. *LAUTECH Journal of Engineering and Technology*, *16*(2), 190–199.

Meghwal, M., Lekhwar, C., Kumar, Y., Kumar, V., Suhag, R., & Prabhakar, P. K. (2024). Modulation of physical and thermal properties in wild banana (*Musa balbisiana* Colla) seed powder by moisture variations. *International Journal of Science*, *2024*, 1–11.

Mirzable, A. H., Hajiahmad, A., & Asadollahzadeh, H. A. (2021). Moisture-dependent engineering properties of arugula seed relevant in mechanical processing and bulk handling. *Journal of Food Process Engineering*, *44*, e13704. https://doi.org/10.1111/jfpe.13704

Nagaraja, H., Kugar, T., Shivanna, Y., Agrawal, A., & Shetty, R. (2016). Ocular toxicity by seeds of *Annona squamosa* (custard apple). *Indian Journal of Ophthalmology*, *64*, 611–613. https://doi.org/10.4103/0301-4738.191514

National Hoticulture Board. (2021). *Indian production of cutard apple* (p. 10). National Hoticulture Board.

Nkambule, S., Workneh, T., Sibanda, S., Alaika, K., & Lagerwall, G. (2023). The effect of moisture contents on the physical properties of both Bambara Groudnut seeds and Ppds in South Africa. *African Journal of Food, Agriculture, Nutrition and Development*, *23*(6), 23817–23834.

Oloyede, C. T., Akande, F. B., & Oniya, O. O. (2015). Moisture dependent physical properties of sour-sop (*Annona muricata* L.) seeds. *Agricultural Engineering International: CIGR Journal*, *17*(2), 185–190.

Oloyede, C. T., Bukola, A. F., Oriola, K. O., & Oniya, O. O. (2017). Thermal properties of soursop seeds and kernels. *Research in Agricultural Engineering*, *63*(2), 79–85. https://doi.org/10.17221/22/2016-RAE

Oniya, O. O., Oloyede, C. T., Akande, F. B., Adebayo, A. O., & Onifade, T. B. (2016). Some mechanical properties of soursop seeds and kernels at different moisture contents under compressive loading. *Research Journal of Applied Sciences, Engineering and Technology*, *12*(3), 312–319. https://doi.org/10.19026/rjaset.12.2338

Onwe, D. N., Umani, C. K., Olosunde, W. A., & Ossom, I. S. (2020). Comparative analysis of moisture-dependent physical and mechanical properties of two varieties of African star apple (*Chrysophyllum albidum*) seeds relevant in engineering design. *Scientific African*, *8*, e00303. https://doi.org/10.1016/j.sciaf.2020.e00303

Pohndorf, R. S., Cunha, J., Lindemann, I., Brod, W., Maurício, P., Moacir, D. O., & Elias, C. (2017). Physical properties and effective thermal diffusivity of soybean grains as a function of moisture content and Broken Kernels. *Journal of Food Process Engineering*, *41*, e12626. https://doi.org/10.1111/jfpe.12626

Ropelewska, E., & Jankowski, K. J. (2019). Thermophysical properties of camelina (*Camelina sativa* (L.) *crantz*) seeds fertilized with nitrogen. *Journal of Food Process Engineering*, *42*, e13161. https://doi.org/10.1111/jfpe.13161

Ropelewska, E., Jankowski, K. J., Zapotoczny, P., & Bogucka, B. (2018). Thermophysical and chemical properties of seeds of traditional and double low cultivars of white mustard. *Zemdirbyste-Agriculture*, *105*(3), 257–264. https://doi.org/10.13080/z-a.2018.105.033

Singh, A. K., Singh, P. K., & Kumar, R. (2016). Moisture dependent thermal properties of ground flaxseed (*Linum usitatissimum*). *CIGR*, *18*(1), 256–262.

Singh, H., & Meghwal, M. (2019). Physical and thermal properties of various ajwain (*Trachyspermum ammi* L.) seed varieties as a function of moisture content. *Journal of Food Process Engineering*, *43*, e13310. https://doi.org/10.1111/jfpe.13310

Suleiman, R., Xie, K., & Rosentrater, K. A. (2019). Physical and Therma properties of chia, Kaniwa, triticale, and Farro seeds as a function of moisture content. *ASABE*, *35*(3), 417–429.

Sundaramahalingam, M. A., Karthikumar, S., Kumar, R. S., & Samuel, K. J. (2021). An intensified approach for transesterification of biodiesel from *Annona squamosa* seed oil using ultrasound-assisted homogeneous catalysis reaction and its process optimization. *Fuel*, *291*, 120195. https://doi.org/10.1016/j.fuel.2021.120195

Timilsena, Y. P., Vongsvivut, J., Adhikari, R., & Adhikari, B. (2017). Physicochemical and thermal characteristics of Australian chia seed oil. *Food Chemistry*, *228*, 394–402. https://doi.org/10.1016/j.foodchem.2017.02.021

Yadav, A. K., Emran Khan, M., & Pal, A. (2019). Custard apple seed oil as promising biodiesel feedstock using advanced techniques and experimental investigation on diesel engine. *International Journal of Oil, Gas and Coal Technology*, *20*(4), 473–492. https://doi.org/10.1504/IJOGCT.2019.099174

Yu, D. U., Shrestha, B. L., & Baik, O. D. (2015). Thermal conductivity, specific heat, thermal diffusivity, and emissivity of stored canola seeds with their temperature and moisture content. *Journal of Food Engineering*, *165*, 156–165. https://doi.org/10.1016/j.jfoodeng.2015.05.012

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