EXPLORING SOURSOP KERNEL AS A SUSTAINABLE BIOFUEL: ANALYZING PHYSICAL AND SOLID FLOW PROPERTIES FOR FEASIBILITY ASSESSMENT

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ABSTRACT

Soursop kernel is an oil-bearing seed containing about 25% non-edible oil per 100 g sample making it a potential feedstock for biofuel production. However, exploring the full potential of the oil requires data to design and fabricate appropriate machines for its processing. So, this necessitates a thorough examination of its physical and solid flow behaviour in relation to moisture contents. The experiments conducted on rewetted samples revealed that as moisture content (mc) increased from 8% to 32.5% dry basis (db), the length, width, thickness, arithmetic and geometric mean diameter, volume, surface area, sphericity, and thousand kernels weight increased from 11.40-12.06 mm, 7.04-7.92 mm, 4.58-5.34 mm, 7.69-8.44 mm, 7.12-7.49 mm, 6.5–8.13 cm^3, 160.19-199.05 mm^2, 0.62- 0.66 and 186.4–291 g, respectively. The true density decreased from 720 to 670 kg/m³, whereas the bulk density increased from 470 to 570 kg/m³. The angle of repose linearly increased from 25.8° to 39.2° as moisture content increased. The highest mean values for coefficients of friction were observed on mild steel surfaces (0.44 for static and 0.53 for dynamic) at 8.0% mc (db) while the lowest values were recorded on stainless steel surfaces (0.20 for static and 0.37 for dynamic) at both 32.5% and 8.0%, (mc, db). The data obtained will prove beneficial to engineers in the design and development of appropriate machines, as well as other handling and processing equipment such as oil expellers, so as to explore the full industrial application of the oil for biodiesel production and other chemical production.

Keywords: *Soursop kernel, Biofuel, Physical properties, Solid flow properties, Machine design*

INTRODUCTION

Soursop (*Annona muricata* L.) is a fruit native to tropical North and South America belonging to the genus *Annona* of the family *Annonaceae* which has about 100 species of trees (Oloyede et al., 2015). Today this crop is widely cultivated in the tropical region and has many potentially useful applications in chemical industries (Syahida *et al.,* 2012). In Nigeria, soursop trees yield up to 10 t/ha and the fruits weigh between 0.5 to 2.0 kg, contain shiny dark brown seeds and abound most in the Western part of the country; commonly cultivated in the home garden and are generally known as '*cha chap'* (Oniya et al., 2016; Oloyede et al., 2017). The most frequently investigated studies on the kernel were the physicochemical and the fatty acid composition of the oil which showed the potential application of the oil in chemical industries and for biofuel production (Onu et al. 2022). Likewise, soursop seed oil has been found to have a high percentage of unsaturated fatty acids, making it an attractive feedstock for biodiesel production. The utilization of soursop seed oil for biodiesel production would contribute to the utilization of agricultural waste products, thus improving the sustainability of biodiesel production (Yadav et al., 2019; Oloyede et al., 2022 and Oloyede et al., 2022). There have been numerous attempts by researchers to utilize energetically available agricultural products and residues to produce renewable energy (Adebayo et al., 2014, Jekayinfa and Scholz, 2007; Orisaleye et al., 2019 and Oloyede et al., 2023).

Physical and solid flow properties of soursop kernel are to be known for design and development of mechanical oil-expeller, storage bin and other relevant equipment by the engineers for the bulk handling and processing of the soursop kernel (Oloyede et al., 2015; Idowu and Oloyede, 2022). Today, different researchers have worked on the physical properties of biomaterials like watermelon seed (Koocheki et al., 2007), apple seed (Manzoor et al., 2021), pearl millet seed (Ojediran et al., 2010) maize seed (Findura et al., 2018), *Citrillus lanatus* seed (Idris et al., 2017), *jatropha curcas,* (Karaj and Muller, 2012), psyllium seed (Barnwal et al., 2012), maize grain (Aviara et al., 2014), and eurycoma seed (Moitaba et al., 2015). Moreover, Oloyede et al. (2015) studied the moisture-dependent physical properties of soursop seed which is useful for the design of seed dehuller among other processing equipment. The Compression loading behaviour of soursop kernel and seed have also been studied by Oniya et al. (2016). However, there is limited information on physical and solid flow properties of soursop kernel relevant to design of mechanical oil-expeller to explore the kernel oil as feedstock for chemical and biofuel synthesis.

The physical and solid flow properties were determined as a function of moisture varying contents. Knowing the moisture dependent is useful for the design of soursop kernel oil-expeller and for further investigation in its handling and processing. Expeller designed without taken into cognizance data on their engineering properties yield low efficiency (Davies, 2010). This study therefore aimed at studying the feasibility of soursop oil for biofuel production via the physical and solid flow behaviour of soursop kernel at varying moisture contents and to investigate their dependence on moisture content.

MATERIALS AND METHODS

The soursop seeds used for all experiments were obtained from Ogbomoso, Oyo State, Nigeria. The seeds were manually cleaned and stored at room temperature (28-32^{o}C) for 48 hours after which they were manually cracked to obtain the kernel. The initial moisture content of the sample was determined by oven drying at 103 ± 2^{o}C until a constant weight was obtained (Davies et al., 2010). Samples of desired moisture content were prepared by adding calculated amount of water, thoroughly mixing and then sealed in separate polythene bags. The samples were kept in a refrigerator (Thermocool, HR-170T) for at least seven days at temperature of 5 ± 2^{o}C to enable the uniform distribution of moisture throughout the samples. The required quantities of the seed were allowed to warm to room temperature prior to each test (Oloyede et al., 2017).

To determine the physical properties such as principal axial dimensions (length, with and thickness) of the kernel, a sample of 100 kernel was randomly selected and measured using a digital caliper (GMC-20) to an accuracy of 0.01 mm. Arithmetic mean diameter (A_{md}), geometric mean diameter (G), sphericity (S) and porosity (P) were calculated according to Aghkhani et al. (2012). To evaluate thousand kernel weight (TSW), 100 kernel were randomly selected from each moisture level then weighed using digital weighing balance (MP 1001, Gallenkamp) to an accuracy of 0.1 g and then multiplied by ten as used by (Oloyede et al., 2015). Surface area (S_A), true density (ρ_t), bulk density (ρ_b) and volume (V) were determined according to ASAE (2001) in Oniya et al. (2016).

Solid flow properties such as static coefficient of friction (μ_s) on three surfaces [stainless steel (St), galvanized steel (Gv) and mild steel (Ms)] were determined using standard methods according to Oloyede et al. (2015) and Davies (2010). The angle of repose (A_r) was determined according to Refik et al. (2006) by using open-ended cylinder.

DATA ANALYSIS

The data analysis of this study was statistically carried out using Analysis of Variance (ANOVA) in SPSS (20) to show the effect of moisture content on the selected properties under investigation. The graphical representations were plotted using MS-excel (2019) while differences between the mean data were tested for significance using Duncan multiple range at probability level of 0.05.

RESULTS AND DISCUSSIONS

Physical properties

Within moisture content ranged of 8.0 to 32.5% (db), the mean values for the principal axial dimensions (length, width and thickness) of sour-sop kernel increased from 11.4 -12.06 mm, 7.04 - 7.42 mm and 4.58 - 5.34 mm, respectively. This indicates that on moisture absorption, the kernel expands in its principal axial dimensions. These values have practical application in determining the clearance between the expeller and the expeller chamber. Mean values for the kernel arithmetic mean diameter, geometric mean diameter, surface area, sphericity and volume increased from 7.69 – 8.44 mm, 7.12 – 7.95 mm, 160.19 – 199.05 mm^2, 0.62 - 0.66 and 6.5 – 8.13 cm^3, respectively.

The increase in the mean values of kernel diameters, surface area and sphericity were attribute to increase in its principal axial dimensions owing to moisture absorption. The data for the kernel diameter will be of important consideration in the theoretical determination of kernel volume, which will be useful in the design of expeller throughput capacity. Also, data on kernel surface area will be useful to evaluate the rate of heat transfer for heating and drying and thus, to design heat exchanger in expeller and to determine rate of heat transfer in dryer. Similarly, data obtained for sphericity will be useful in the design of hopper for the expeller. So, the hopper should be designed to allow the free flow of kernel. Similar range was observed for cucurbit (*Cucurbitacea specie*) seed by Milani et al. (2007) and maize kernel by Barnwal *et al.* (2012).

The true density, bulk density and thousand kernel weight ranged from 720 – 670 kg/m^3, 470 – 570 kg/m^3 and 186 – 291 g, respectively. These values will be useful to design the size of expeller chamber, expeller throughput capacity and to estimate the overall bulk weight of kernel during bulk handling. Aghkhani *et al.* (2012) and Saeeid *et al.* (2009) reported similar range for lima bean and groundnut kernel respectively. The differences between the mean data for the physical properties under investigation were found to be significant ($P \leq 0.05$) except for the mean data of true density which shown no differences at all experimental moisture contents (Table 1).

The effect of moisture content on soursop kernel are shown in Figure 1 – 7. The figures shown that the length (L), width (W), thickness (T), arithmetic mean diameter (A_{md}), geometric mean diameters (G_{md}), sphericity (S_{ty}), surface area (S_A), thousand kernel weight (TKW) and bulk density (ρ_b) increased linearly, volume (V) increased quadratically, while true density (ρ_t) decreased linearly with increasing moisture content. This show that moisture content has significant ($P \leq 0.05$) effect on the physical properties' parameters. Similar trend was reported for lima bean seed by Aghkhani et al. (2012) and rape seed by Izli et al.

(2009). Reverse trend was observed for maize kernel in which its bulk density and thousand seed weight decreased with increase in moisture content (Barnwal et al., 2012).

Table 1: The mean values and standard deviation of the physical properties of soursop kernel analysed using Duncan's multiple range test *(P ≤ 0.05)*

Moisture Content (%, db)					
Parameters	**8**	**11.9**	**15.4**	**22.6**	**32.5**
Length (mm)	11.40±0.82^{a}	11.50±0.8^{a}	11.609±0.82^{ab}	11.81±0.84^{ab}	12.06±0.85^{c}
Width (mm)	7.04±0.81^{a}	7.15±0.81^{a}	7.47±0.73^{b}	7.60±0.73^{b}	7.92±0.81^{c}
Thickness (mm)	4.58±0.73^{a}	4.75±0.58^{ab}	4.86±0.55^{b}	5.09±0.57^{c}	5.34±0.5^{d}
Art. M. diam. (mm)	7.69±0.50^{a}	7.80±0.43^{a}	7.98±0.42^{b}	8.17±0.45^{c}	8.44±0.45^{d}
Geo. M. diam. (mm)	7.12±0.54^{a}	7.26±0.4^{a}	7.46±0.39^{b}	7.67±0.42^{c}	7.95±0.39^{d}
Surface area (mm^2)	160.19±22.9^{a}	166.32±18.4^{a}	175.3±17.1^{b}	185.2±29.0^{c}	7.95±0.39^{d}
Sphericity	0.62±0.5^{a}	0.63±0.4^{a}	0.65±0.34^{b}	0.65±0.34^{cd}	0.66±0.32^{d}
Volume (cm^3)	6.5±0.1^{a}	6.65±0.01^{a}	6.75±0.01^{a}	6.80±0.4^{a}	8.13±0.7^{b}
True den. (kg/m^3)	720±0.02^{ns}	710±0.02^{ns}	700±0.2^{ns}	690±0.04^{ns}	670±0.03^{ns}
Bulk den. (kg/m^3)	470±0.03^{a}	490±0.01^{a}	500±0.01^{a}	530±0.03^{ab}	570±0.04^{b}
W_{1000} (g)	186.4±0.4^{a}	203±0.3^{b}	218.1±0.1^{c}	249±0.4^{d}	291±0.3^{e}

a, b, c, d, e – implies superscript with different letters of means in the same row differ significantly, 'ns' means not significant while 'ab', 'bc' and 'cd' means not significantly different between those moisture levels.

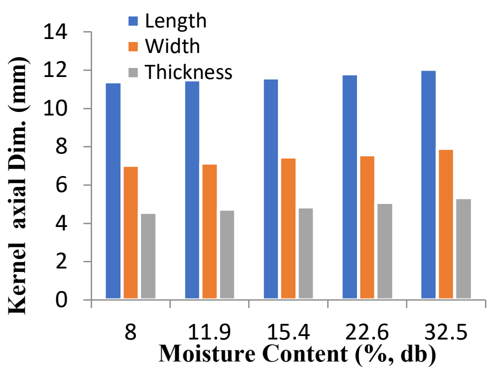

Fig. 1: Effect of moisture content on kernel axial dimensions

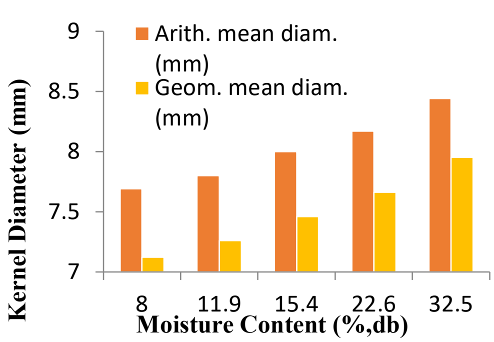

Fig. 2: Effect of moisture content kernel axial diameter

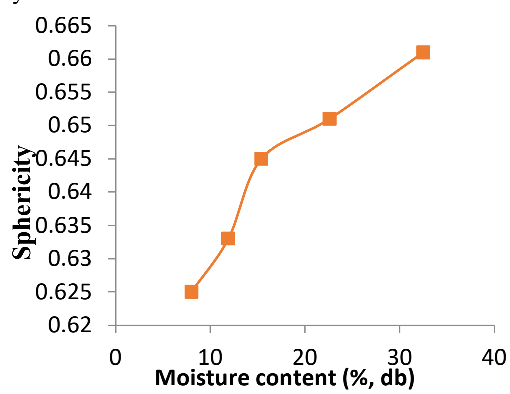

Fig.3: Effect of moisture content on sphericity of soursop kernel

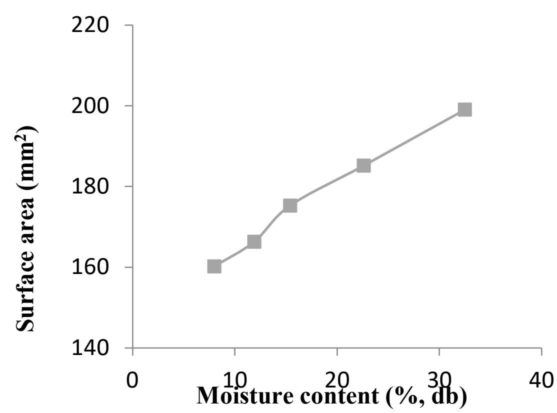

Fig.4: Effect of moisture content on surface area of soursop kernel.

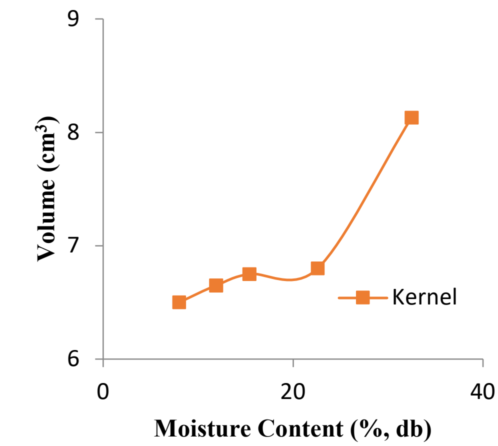

Fig.5: Effect of moisture content on volume of soursop kernel

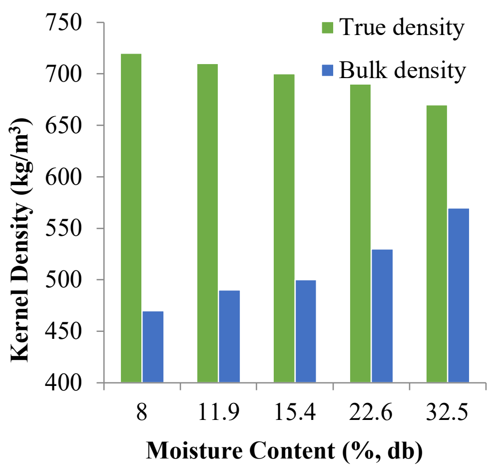

Fig.6: Effect of moisture content on density of soursop kernel

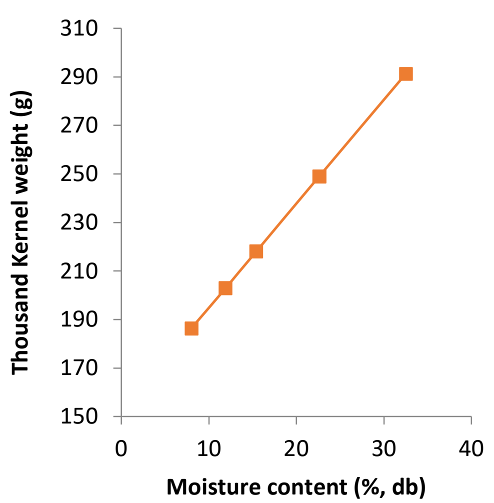

Fig.7: Effect of moisture content on thousand kernel weight of soursop kernel

Regression equations showing the relationships between moisture content and physical properties of soursop kernel with high correlation coefficients (R^2) are shown in Table 2.

Solid flow properties of Soursop kernel

The mean values for the angle of repose of soursop kernel ranged from 25.8 – 39.2°, the static coefficients of friction ranged from 0.34 – 0.20 on stainless steel surface (μ_{st}), 0.39 – 0.32 on galvanized steel surface (μ_{gv}), 0.44 – 0.24 on mild steel surface and from 0.41 – 0.36 on hardwood surface; and dynamic coefficients of friction ranged from 0.38 – 0.40 on stainless steel surface (μ_{st}), 0.46 – 0.42 on galvanized steel surface (μ_{gv}), 0.53 – 0.40 on mild steel surface and from 0.50 – 0.42 on hardwood surface as moisture content ranged from 8.0 – 32.5% (db). Highest value for both coefficients of friction were observed on mild steel at the lowest moisture content of 8.0% (db). This may be owing to more unpolished surface of mild steel. Similarly, the lowest values for both coefficients of friction were observed on stainless steel which may be due to its smoother and more polished surface. These results were similar to those reported by Mojtaba et al. (2015) for eurycoma seed and Hojat et al. (2009) for fennel seed.

Differences between the mean data for both static and dynamic coefficients of friction were significant (*$P \leq 0.05$*) as shown in Tables 3. These properties are the key elements for the calculation of flow behaviour of soursop kernel when designing hoppers for its oil expeller. This means that the angle of kernel hopper has to be greater than the angle of repose for good free flowing. It can also be used for the calculation of compressibility and flow behaviour of materials used in designing kernel bins and other storage structures (Karaj et al., 2010)

Table 3: The mean values and standard deviation of the solid flow properties of soursop kernel analysed using Duncan's multiple range test *(P ≤ 0.05)*

Moisture Content (%, db)					
Parameter	**8.0**	**11.9**	**15.4**	**22.6**	**32.5**
Angle of rep. (°)	25.80±0.20ᵃ	27.90±0.10ᵇ	31.60±0.30ᶜ	34.80±0.40ᵈ	39.20±0.2ᵉ
Static coefficients of friction					
Stainless steel	0.34±0.05ᵉ	0.27±0.06ᵈ	0.24±0.006ᶜ	0.22±0.005ᵇ	0.2±0.006ᵃ
Galvanized steel	0.39±0.01ᵈ	0.36±0.06ᶜ	0.35±0.06ᶜ	0.34±0.05ᵇ	0.33±0.06ᵃ
Mild steel	0.44±0.05ᵉ	0.34±0.01ᵈ	0.30±0.01ᶜ	0.27±0.005ᵇ	0.24±0.01ᵃ
Hardwood	0.41±0.01ᵃ	0.39±0.01ᵇ	0.38±0.005ᵇ	0.37±0.01ᵃ	0.36±0.01ᵃ
Dynamic coefficients of friction					
Stainless steel	0.38±0.01ᵃ	0.39±0.00ᵇ	0.39±0.01ᵇ	0.39±0.01ᵇ	0.40±0.81ᵇ
Galvanized steel	0.46±0.01ᶜ	0.44±0.005ᵇ	0.43±0.005ᵇ	0.42±0.01ᵃᵇ	0.42±0.01ᵃᵇ
Mild steel	0.53±0.06ᶜ	0.45±0.01ᶜ	0.43±0.01ᵃᵇ	0.42±0.01ᵃᵇ	039±0.005ᵃ
Hardwood	0.50±0.01ᵈ	0.46±0.01ᶜ	0.44±0.01ᵇ	0.43±0.01ᵃᵇ	0.42±0.01ᵃᵇ

a, b, c, d, e – implies superscript with different letters of means in the same row differ significantly, 'ns' means not significant while 'ab', 'bc' and 'cd' means not significantly different between those moisture levels.

The effect of moisture content on solid flow properties of soursop kernel are shown in Figure 8 – 10. It can be depicted from these figures that the kernel angle of repose and dynamic coefficients of friction on stainless steel surface increased linearly with increase in moisture content. Increase in angle of repose may be due to an increase in the internal friction with the kernel moisture content while, increase in dynamic coefficients of friction may be owing to increased cohesive force of wet kernel with the stainless surface. However, for all surfaces (except dynamic coefficients of friction on stainless steel surface), both static and dynamic coefficients of friction decreased logarithmically with increasing moisture content. This shows that moisture content has significant ($P \leq 0.05$) effect on static and dynamic coefficients of friction of soursop kernel. Turkan et al. (2006) and Ayman (2009) reported similar linear trends of coefficients of friction with moisture content for safflower seeds and flax seed. Relationships between moisture content (*mc*), angle of repose (Θ_r) and coefficients of friction for soursop kernels with their correlation coefficients (R^2) are presented in Table 4.

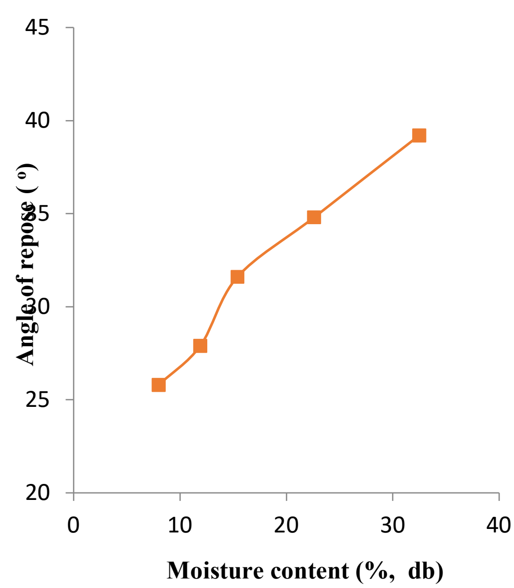

Fig.8: Effect of moisture content on angle of repose of soursop kernel

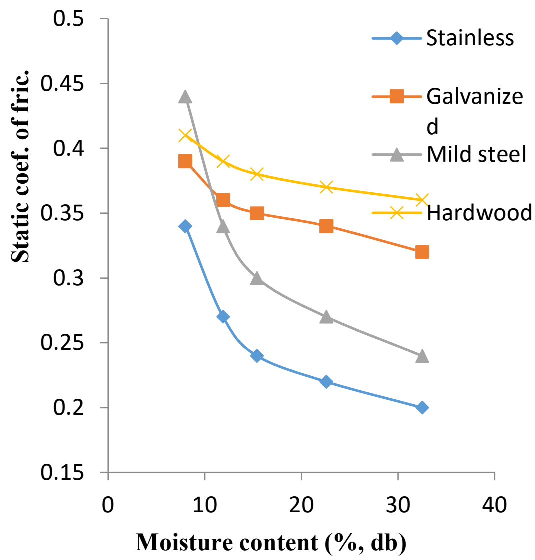

Fig.9: Effect of moisture content on coefficients of static friction

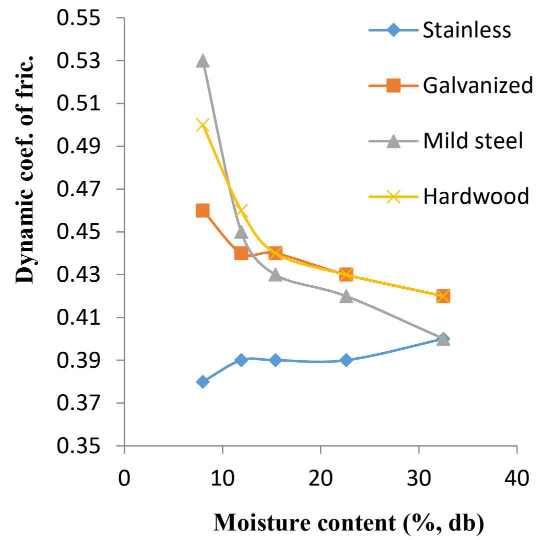

Fig.10: Effect of moisture content on coefficients of static friction

Table 4: Equations representing relationship between moisture content and solid flow parameters

	Equation	R^2
Angle of repose:	$\Theta_r = 0.3076mc + 23.378$	0.995
Static coefficient		
Stainless:	$\mu_{St} = -0.096ln\ (mc) + 0.52$	0.913
Galvanized:	$\mu_{Gv} = -0.0476ln\ (mc) + 0.481$	0.964
Mild steel:	$\mu_{Ms} = -0.0136ln\ (mc) + 0.697$	0.918
Mild steel:	$\mu_{Ms} = -0.035ln\ (mc) + 0.479$	0.974
Dynamic coefficient		
Stainless:	$\mu_{St} = 0.012ln\ (mc) + 0.357$	0.825
Galvanized:	$\mu_{Gv} = -0.026ln\ (mc) + 0.511$	0.943
Mild steel:	$\mu_{Ms} = -0.084ln\ (mc) + 0.680$	0.836
Mild steel:	$\mu_{Ms} = -0.055ln\ (mc) + 0603$	0.898

CONCLUSIONS

The investigation on the physical and solid flow behaviour of soursop kernel at different moisture contents revealed that within moisture content range of 8.0 to 32.5% (db):

i. sour-sop kernel showed increasing in length, width, thickness, arithmetic and geometric mean diameter, volume, surface area, sphericity and thousand kernel weight from 11.40-12.06, 7.04-7.92, 4.58-5.34, 7.69-8.44, 7.12-7.49 mm, 6.5–8.13 cm^3, 160.19-199.05 mm^2, 0.62- 0.66 and 186.4–291 g, respectively. A decreasing trend for true density was observed from 720 – 670 kg/m^{-3} while the bulk density increased from 470 – 570 kg/m^{-3}.

ii. The mean values for the angle of repose of soursop kernel increased linearly from 25.8 – 39.2° and static and dynamic coefficients of friction decreased linearly on all surfaces except for dynamic coefficient of friction on stainless steel surface which increased linearly with increasing moisture content. Highest mean value for static and dynamic coefficients of friction were observed on mild steel (0.44 and 0.53) at the moisture content of 8.0% (db) while lowest mean value was observed on stainless steel surface (0.20 and 0.37) at 32.5% and 8.0% (db) respectively.

iii. The moisture content has significant ($p \leq 0.05$) effect on physical and solid flow properties of soursop kernel and differences between their mean values were significant ($p \leq 0.05$) except for the kernel true density as tested using Duncan multiple range test,

iv. The data obtained is useful for engineer in the design of soursop kernel oil-expeller among other machines and processes involve its processing. Hence, applying the data obtained in the design and development of mechanical oil expeller for the soursop kernel will enhance the bulk application of its oil in biofuel synthesis and other chemical production.

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