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Modeling and optimization of dynamic isothermal compressibility features on flowability of *Canarium schweinfurthii* Engl nutshell powder

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Abstract: The compressibility features (bulk density, tapped bulk density, porosity, coefficient of compressibility and Hauser ratio) of *Canarium schweinfurthii* engl. nutshell powder as it affects flowability during densification process were investigated. Three different moisture contents (10.13, 15.07 and 20.11% wet basis; w.b.) and particle sizes of 0.659 7, 1.26 and 2.05 mm were considered at pressure range of 2 to 10 MPa. The compressibility relationship with the factors were modelled and the optimum flow conditions were also determined. The obtained results showed that particle size and moisture content had incremental influence on the compression features studied except moisture content on bulk density. The compressibility of the nut shell powder increased from 17.44 to 28.18% and decreased from 29.41%to 18.79% as moisture content and particle size increased respectively. Medium particle size had the least Hausner ratio (1.16) and the best flow behaviour than other sizes for all the studied moisture contents. The linear model developed and its features had significant relationship with compressibility. The optimum values of pressure, moisture content and particle size required to achieve 17.45% compressibility for good flow are 4.88 MPa, 10.91% and 0.863 8 mm respectively.

Keywords: coefficient of compressibility; Hausner ratio; model particle size; optimum

Canarium schweinfurthii Engl. nutshell houses a triplet melon-shaped edible kernel rich in oil. It is obtained as the by-product of the kernel extraction after cracking the nut. The nut is from dark-skinned fruit of the *C. schweinfurthii* tree, a forest tree crop that belongs to the family of *Burseraceae* (Orwa 2009). It is mostly grown in the equatorial forest region of East, West and Central Africa (Orwa 2009) and popularly called ubemgba in the Eastern part of Nigeria.

C. schweinfurthii nutshell possess great potential for generating energy, good for storing energy in dry cells and as a filter in sewage plants when converted to biochar. Its ash content, moisture content, vol-

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atile matter and fixed carbon are 0.45, 8.92% wet basis (w.b.), 79.0% and 11.55% respectively. The lignin (32.24%), cellulose (32.58%), hemicellulose (41.67%), fat (3.55%), nitrogen (1.30%) and sulphur (0.096%) with high carbon content (42.77%) makes it enviable for biofuel generation. The nutshell is difficult to burn as a whole, but burns effectively when the surface area is reduced to smaller particles through grinding.

Compressibility of granular materials measures the ability of particles of bulk solid to compact together by their own weight during storage and transportation (due to vibration) which cause flow problems. The compression features of ground agricultural materials vary under various applied loads, particle sizes, chemical composition, particle density and moisture contents (Adapa et al. 2009; Aulton and Taylor 2017).

The values of compressibility have been used to classify the flowability of bulk materials from excellent to poor flow as: excellent flow (5 to 15%), good flow (12 to 16%), flowable powder granules (18 to 21%), poor flow (23 to > 40%) (Fayed and Skocir 1997). Poor flow of bulk solids encourages arching and segregation associated with mass and funnels flow in storage bins, feeding and discharge units during handling of bulk materials. Arching occurs due to interlocking of large particles that result from a high cohesive force between the particles when they interact within the bulk during flow operation. Also, when the size or density of solid particles under flowing, vibrating or shaking conditions is not the same, segregation takes place (Gharat 2019). Inter-particulate interactions are the major challenge in the flow of solid particles (Ghosal et al. 2010; Aulton 2013; Shi et al. 2018). Coefficient of compressibility, Hausners ratio, density and porosity are indices that aid in understanding the potentials of solid particles inter-particle interaction during flow operations (Jan et al. 2018; Shah et al. 2008) and determining the amount of work needed to produce high quality solid fuel for a particular biomass.

Several efforts have been made to study the inter-particle relationship of various biomass solids considering their different physical features. Five ground biomasses (corn stover, switchgrass barley straw and wheat straw) were compressed at 12 and 15% moisture content w.b., three particle sizes (0.8, 1.6 and 3.2 mm) and 2–4.4 kN pressure by Mani et al. (2006) in order to determine how pellet density depend on the parameters. They observed that the pellet density of wheat straw does not depend significantly on particle size, while that of other biomass samples studied depends on process factors considered. Zhou et al. (2008) opined that the compressibility indices (compressibility index, Hausner ratio and porosity) of ground corn stover (6.4 to 1.6 mm particle size) studied at moisture contents of less than 20% and more than 20% w.b. indicate poor flow characteristics. Adapa et al. (2010) also carried out a comprehensive study on the compression characteristics of ground (6.40, 3.20 and 1.60 mm screen sizes) non-treated and steam-exploded barley, canola, oat, and wheat straw at 10% moisture content w.b. and pressures of 31.60, 63.20, 94.70, and 138.90 MPa. They concluded that stream treated straw had more void spaces and was more compressed than the untreated straw. Matúš et al. (2014) also evaluated the effect of size fraction on the compressibility of pin saw dust and reported that particle size increase has a reducing effect on the coefficient of compressibility and energy efficiency of densification of pin saw dust. Besides, moisture content had negligible effect on the compressibility of pi saw dust. Other studied biomasses are, peat moss, wheat straw, oat hull, and flax shive grinds evaluated at 9 to 10% and 15.8 to 138.9 MPa moisture content and pressure respectively (Shaw and Tabil 2007); corn cobs at particle size and moisture ranges of 0.73–0.90 mm 10.04–20.13% respectively (Probst et al. 2013); stool wood, mahogany, oil bean saw dust and rice husk at 0.2–1.4 mm particle size, 8–12% moisture content w.b. and 1.8–2.2 MPa pressure (Ogbuagu et al. 2019) and cocoa pod husk at particle size and moisture ranges of 4.76–0.297 mm and 30–100% w.b. respectively (Forero-Nuñez et al. 2015)

The nutshell compressibility features in relation to physical properties of solid fuel production, is yet to be recorded like the other biomass materials. Hence, the aim of the study is to evaluate, model and optimise the compressibility features of *C. schweinfurthii* nutshell for easy flow during the densification process.

MATERIAL AND METHOD

C. schweifurthii nutshell (Figure 1C) used for this study was obtained from the local market of Ebonyi (6°15' N 8°05' E) State of Nigeria and the experiment was conducted in the Bioresources Engineering Department of McGill University, Macdonald

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Figure 1. *Canarium schweinfurthii* Engl.: (A) fruit, (B) nut and (C) nutshell

campus, Canada. The nutshell samples were extracted from the nuts of the fruits (Figure 1A and B) after de-pulping. The flow chat in Figure 2 is the step-by-step activities that produce the nutshell.

They were conditioned to three different particle sizes (0.659 7, 1.26 and 2.05 mm) using a hammer mill and three moisture contents (10.13, 15.07 and 20.11%) w.b.using laboratory oven set at 105 °C. Compression test was carried out at 2 to 10 MPa for all the conditioned nutshell powder. The bulk

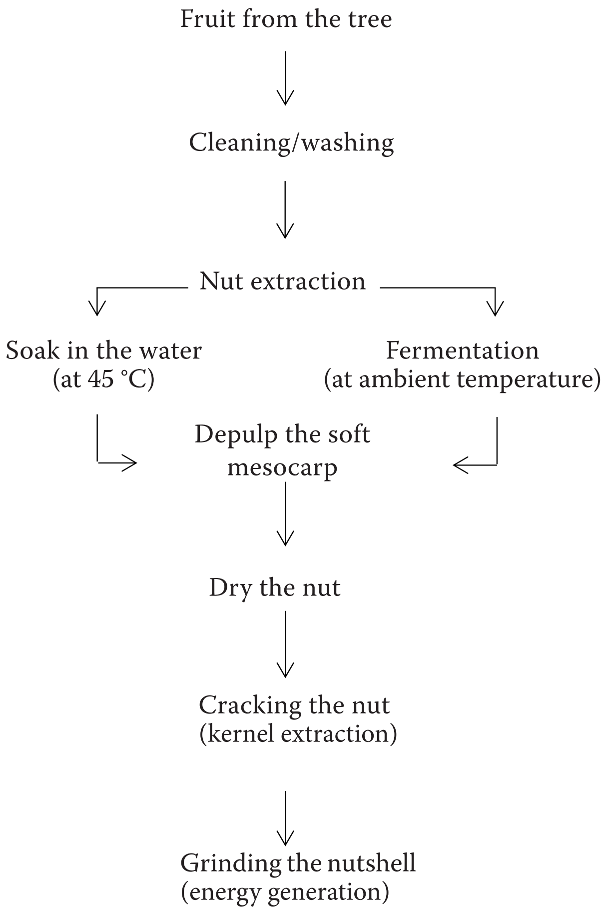

Figure 2. The flows chat of processing *Canarium schweinfurthii* Engl. fruit to nutshell

density of the conditioned nutshell was determined by the mass of the bulk nutshell that filled a container of 0.021 m diameter and 0.350 m high divided by the volume of the container.

Tap bulk density was determined by filling a 250 cm^3 measuring cylinder with samples of each size and moisture content and tapped fifty times on a platform until no reduction in volume was observed. The difference in the height of the sample in the cylinder was taken as the tapped bulk volume. Tapped bulk density was calculated as the ratio of bulk sample mass to the difference in volume. Particle density of the conditioned nutshell was determined using helium pycnometer (Multivolume pycnometer 1305; Multivolume, USA). The mean particle volume calculated was used to divide the mass of the bulk for each particle size of moisture content studied. The process was replicated three times for all the physical properties considered. Porosity was calculated using the values of solid and bulk density obtained as given in Equation (1) (Al-Muhtaseb et al. 2004):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} \times 100 \qquad (1)$$

where: ε – porosity; ρ_b – bulk density; ρ_s – particle density.

Compressibility of the conditioned nutshell was determined using texture analyser with a cylinder of diameter and height of 0.022 08 m and 0.059 m respectively and a piston diameter of 0.02206 m. The cylinder was filled with the sample and levelled with a flat surface object. The analyzer was run at a steady speed of 1 mm s until it stopped automatically when the sample was compressed. The depth travelled by the piston was recorded by the analyser and the difference in height was used to calculate the volume. Percentage compressibility (C_m) was computed as given in Equation (2) (Adapa et al. 2009):

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$$Cm = 100\left(\frac{v_f}{v_i}\right) \quad (2)$$

where: V_i – initial volume (cm^3); V_f – compressed volume (cm^3).

The coefficient of compressibility is the densification indices that explain the character of particles during compression process. It was determined as a function of density ratio due to applied pressure ratio using the simplified formular given by Balshin (year), as in Equation (3) (Matúš et al. 2014):

$$\frac{P}{P_0} = A\left(\frac{\rho}{\rho_0}\right)^K \quad (3)$$

where: P – pressure at a given point; P_0 – initial pressure; A = constant, ρ = density at a given point, ρ_o = initial density; K – coefficient of compressibility.

The slope of the linear plot of log p/p_0 against log of ρ/ρ_0 for interaction of moisture content and particle size was taken as the determined coefficient of compressibility.

The Hausner ratio (HR) which relates to the inter-particle fraction in a moving powder bed is calculated as Equation (4) (Hao 2015):

$$HR = \frac{\rho_b}{\rho_t} \quad (4)$$

where ρ_b = bulk density, ρ_t = tapped bulk density.

Each experiment was replicated three times while the data generated were analysed using regression statistical tool and Response Surface Methodology (RSM) in Excel (version 14.0) and Design Expert Statistical software (version 6.0.8) for determining the optimum conditions for the compressibility of the nutshell.

RESULTS AND DISCUSSION

Tap bulk density, bulk density and porosity dependence on moisture content and particle size of the nutshell powder. Tap bulk density increased from 0.672 6–0.901 2 g·cm^{-3} (mean values) as particle size increased from 0.659 7–2.05 mm (Table 1). This agrees with the report of Oluwatosin (2016) for loblolly pine but contrary to the report of Littlefield (2010) for pecan shell, as particle size increased from 0.212 mm–0.2194 mm. Tap bulk densities had a nonlinear relationship with moisture content. Coarse size had the highest tap bulk density while fine size had the least. This is because fine particles occupy the void space easily than the coarse size (Lam et al. 2008).

The coarse size of the nutshell had the largest bulk density and porosity values while fine size had the least (Table 1). This means that the coarse size is bulkier and more porous than other sizes and can be attributed to an increase in weight of the shell with relatively no increase in bulk volume. Besides, fine particles tend to occupy the void spaces more than the coarse size. Similar trends were reported of coir pith and wheat by Manickam and Suresh (2011) and Kheiralipour et al. (2009) respectively. Lam et al. (2008) observed an increase in bulk density of switchgrass from 149–194 kg·m^{-3} as particle size increased from 0.25–0.71 mm. Lui (2008) also reported that the bulk density of larger aggregate is higher than the smaller ones. Contrary-wise, Adapa et al. (2011) opined that the bulk density of wheat and barley decreased (154–107 kg·m^{-3} and 155–199 kg·m^{-3} respectively) with an increase in particle size. Decrease in bulk density with increase in moisture content has also been reported by Kheiralipour et al. (2009) and Mahapatra et al. (2010) for wheat and sericeal lespedeza pellets at 8–18% and 7.26–15.55% wet basis respectively. Moisture content and particle size

Table 1. Mean bulk density and porosity of different particle sizes of *Canarium schweinfurthii* nutshell

MC	Bulk density		
	fine	medium	coarse
M_1	0.6188 ± 0.21	0.6783 ± 0.11	0.7164 ± 0.06
M_2	0.5583 ± 0.04	0.6293 ± 0.02	0.6639 ± 0.01
M_3	0.4794 ± 0.03	0.5273 ± 0.06	0.5634 ± 0.03
	Porosity		
M_1	0.4927 ± 0.42	0.531 ± 0.06	0.578 ± 0.05
M_2	0.5261 ± 0.07	0.5883 ± 0.21	0.6186 ± 0.09
M_3	0.6061 ± 0.13	0.6693 ± 0.03	0.6902 ± 0.11
	Tapped bulk density		
M_1	0.6588 ± 0.03	0.7299 ± 0.02	0.7456 ± 0.13
M_2	0.6624 ± 0.04	0.7144 ± 0.01	0.7395 ± 0.08
M_3	0.6966 ± 0.06	0.7199 ± 0.05	1.22 ± 0.03

MC – moisture content; M_1 = 10.13%; M_2 – 15.07%; M_3 – 20.11% wet basis

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had significant ($P < 0.05$) effects on tapped bulk density, bulk density, porosity and interaction of tapped bulk density, while interactions of bulk density and porosity were not. Experimental models of tap bulk density, bulk density and porosity in relation to particle size and moisture content as shown in Equations (5–7) indicated good fit.

These results indicate that during transportation of the fine particles, compaction will occur which will cause discharge problems, hence an agitator should be incorporated in the system during discharge operation.

Effect of moisture content on mechanical compressibility of the nutshell. Moisture content dependent of the mechanical compressibility of *C. schweinfurthii* engl. nutshell increased significantly ($P < 0.05$) with increase in moisture content and pressure as shown in Figure 3a. A similar trend has been reported for poultry litres, and wormy compost dust by Bemhart and Fasina (2009) and Kianmehr et al. (2024). In comparison, the nutshell compressibility ranged from 0.174 4–0.281 9 and increased by 38.14% as moisture increased from 10.13–20.11% while wormy compost increased by 78.51% at moisture range of 25–30%. This could be because wormy compost has more void spaces and elastic structure than canarium nutshell.

In Table 2, at 2 MPa of all moisture levels, compressibility values are within the recommended range for excellent flow operation, while 10 MPa had values that ranged from poor flow to extremely poor flow behaviour. Hence, for easy flow operation of *C. schweinfurthii* engl nutshell, the moisture level of the product and flow pressure should be kept low.

Table 2. Compressibility range for moisture content at low and high applied pressures

Moisture content (w.b.; %)	Applied pressure (kPa)	
	2	10
10.13	0.057 8*	0.290 8*
15.07	0.077 6*	0.232 1*
20.11	0.126 0*	0.461 3*

*Significant ($P < 0.05$)

Effect of particle size on mechanical compressibility of the nutshell. Mechanical compressibility of ground *C. schweinfurthii* engl nutshell decreased significantly ($P < 0.05$) as particle size increased and correlated linearly with applied pressure (Figure 3B). Ogbuagu et al. (2019) has observed the same trend with stool wood at particle size and pressure ranges of 0.1–1.3 mm and 1.8–2.2 MPa respectively while Kianmehr et al. (2024) reported the opposite trend for wormy compost at particle size and pressure ranges of 0.3–1.18 mm and 2–4 kN respectively. The nutshell particle size resisted compression (36.12%) more than the wormy compost (6.37%) as size increased. At low applied pressure, compressibility results in excellent flow (described as free flow granules by Fayed and Skocir 1997) while at higher pressure, compressibility produced extremely poor flow.

This is because the cohesive properties of fine particles are stronger and similar to those of fine powder. Besides, the fine particles have a higher tendency to re-orient and occupy the void spaces in the bulk than other particle sizes. Low values for medium and coarse particle sizes observed can be attributed to their high resistance to deformation under pressure (Babosa-Canovas 2005). The relationship between compressibility of ground *C. schweinfurthii* engl nutshell and varied parameters is given in a linear regression model presented in Equation (8). The variation between the compressibility of coarse and medium particle sizes is not significant ($P < 0.05$) due to slight similarity in their consistent behaviour.

$$C = 25.10 + 14.41P + 4.12M - 6.77P_Z + 4.98MP_Z \qquad (8)$$

where: C = compressibility; P_s = particle size; M = moisture content, P = pressure (MPa).

Evaluation of fitted model. The summary of the analysis conducted on the linear regression model developed is presented in Table 3. The result revealed that the linear model developed and its factors had significant ($P < 0.05$) relationship with compressibility. The interaction of pressure

$$TBD = 0.2921 + 0.0167M + 0.1637P_s + 0.0308MP_s \quad R^2\,(0.69) \quad \text{RMSE}\ (0.123) \qquad (5)$$

$$BD = 0.3806 + 0.0232M - 0.0969Ps + 0.0011MP_s \quad R^2\,(0.89) \quad \text{RMSE}\ (0.311) \qquad (6)$$

$$\varepsilon = 0.3826 + 0.0217M - 0.0919Pz + 0.0002MP_s \quad R^2\,(0.98) \quad \text{RMSE}\ (0.611) \qquad (7)$$

where: TBD – tapped bulk density; BD – bulk density; M –moisture content; P_S – particle size; P_S – particle size; RMSE – root mean square error.

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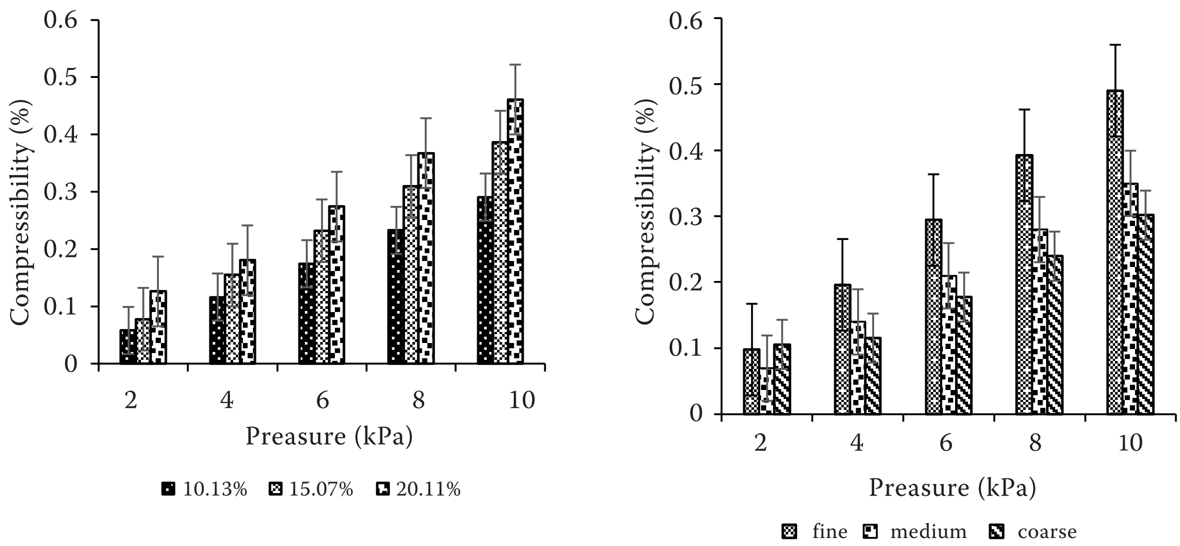

Figure 3. The plot of compressibility of *Canarium schweinfurthii* engl nutshell against applied pressures for (A) moisture content and (B) particle size

and moisture content also had substantial influence on the compressibility of the nutshell. Pressure had the highest effect as pointed out by *F*-value of 105.22 while particle size had the least value (8.48). Unlike other factors and interaction, the change in percentage compressibility per unit change in particle size as other factors are kept constant yielded negative coefficient result as seen in the model. This confirms the decreased trend in Figure 3B. The high value of R^2 (0.886 9) and, the difference between adjusted R^2 (0.863 1) and the predicted R^2 (0.819 6) being less than 2 implied that the model was well fitted.

The non-significant ($P < 0.05$) effect of lack of fit showed that the compressibility of the nutshell was well predicted with the developed model (Figure 4). Besides, *F*-value of 1.73 for lack of fit revealed that there are 20.11% probabilities that large *F*-value could occur as a result of noise. The signal to noise ratio value obtained (16.61) is desirable being higher than 4 hence, the ratio is sufficient to produce enough signal, meaning that the developed model had the best fitness.

Optimisation of the considered factors. Numerical optimization of the considered factors was analysed focusing on the percentage compressibility

Table 3. The ANOVA for selected factorial model

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value
Model	7 157.23	4	1 789.31	37.25	< 0.000 1*
A	5 054.12	1	5 054.12	105.22	< 0.000 1*
B	407.22	1	407.22	8.48	0.008 9*
C	1 101.07	1	1 101.07	22.92	0.000 1*
A×B	594.81	1	594.81	12.38	0.0023*
Residual	912.61	19	48.03		
Lack of Fit	223.53	3	74.51	1.73	0.201 1**
Pure Error	689.08	16	43.07		
Total Correction	8 069.84	23			
R^2	0.8869				
Adjusted R^2	0.863 1				
Predicted R^2	0.8196				
Adeq Precision	16.604 9				

*,**The asterisks indicate significant and non-significant values, respectively ($P < 0.05$); A – pressure; B – moisture content; C – particle size

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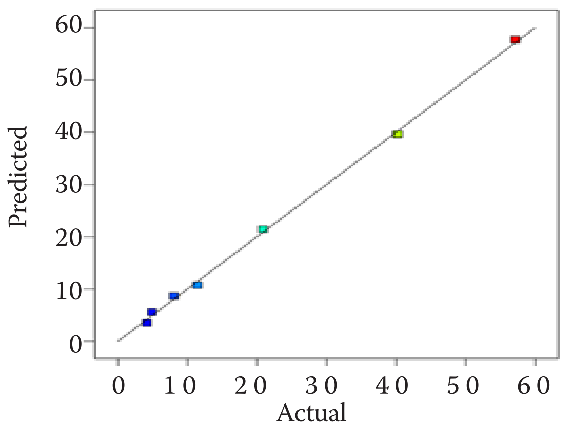

Figure 4. The plot of predicted values against actual values

required for free flow powdered granules. The optimum values of pressure, moisture content and particle size required to achieve a compressibility of 17.45% [value within the range for good flow (Fayed and Skocir (1997)] are 4.88 MPa, 10.91% and 0.863 8 mm respectively. The outcome of the analysis showed that the factors and their interaction are desirable (1 – highly desirable), meaning that they are suitable for obtaining acceptable flow behaviour for easy handling of the nutshell.

Coefficient of compressibility of the nutshel. The coefficient of compressibility (K) as observed decreased with increase in particle size and increased as moisture content increased from 10.13 to 20.11 % wet basis (Figure 5). Particle size had a non-significant ($P < 0.05$) effect on the K of the nutshell unlike the moisture content that influenced the values significantly ($P < 0.05$). Matúš et al. (2014) reported different behaviour for pin saw dust at particle size and moisture ranges of 0.5–4 mm and 9.8–15.5% respectively. In comparison, the values of K for pin saw dust (8.03–3.35: Matúš et al. (2014)), corn stover, dry corn stalks and soyabean straw [3.21, 3.45 and 4.17 respectively: Franz (2009)] and, wet corn stalks and dry alfalfa hay [4.17 and 4.35 respectively: Pelt (2003)] are higher than that of the nutshell (1.032–1.020) and could be attributed to cultivar, structural and compositional differences.

This result means that the nutshell would compress more easily with less energy than the cited biomass materials hence, the densification process and the cost of production would be more effective.

Hausner ratio. The effect of moisture content and particle size on the Hausner ratio as presented in Figure 3 revealed that medium particle size at all moisture content levels considered had the least ratio (mean value of 1.16) while coarse at 20.11%, wet basis, had the highest value (1.71). This means that medium size had the best flow characteristic with values that are less than the 1.20 ratio (Princy et al. 2018, Chinwan and Castell-Perez 2019) required for good flow behaviour. The Hausner ratio had a non-significant ($P < 0.05$) irregular relationship between moisture content and particle size. The mean ranged from 1.23 to 1.38 for moisture content and, 1.32, 1.16 and 1.39 for fine, medium and coarse sizes respectively. These values are lower than the findings of Nwajiobi et al. (2019) for

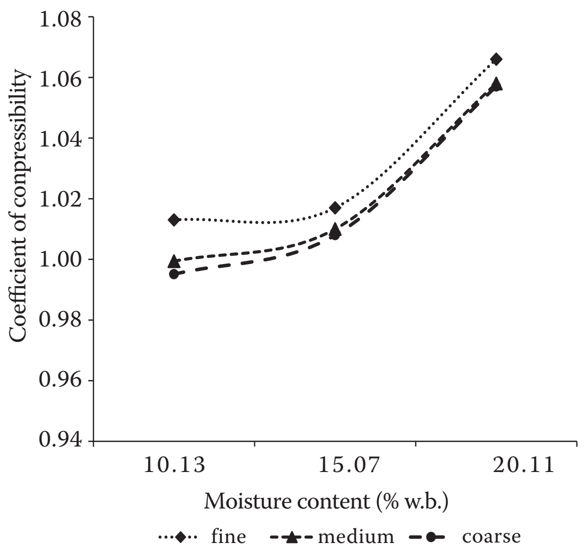

Figure 5: Coefficient of compressibility of the nutshell against moisture content for different particle sizes

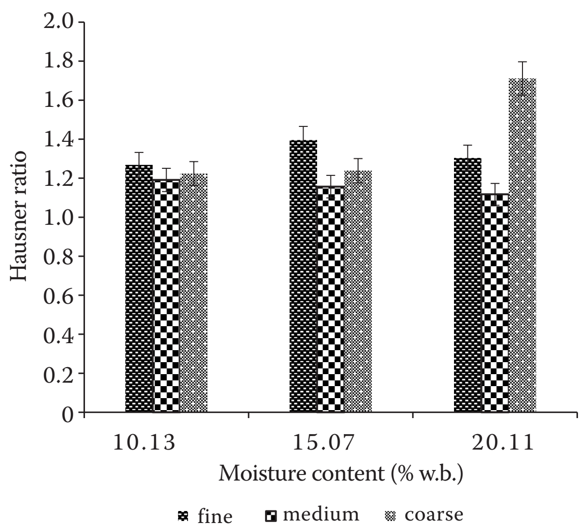

Figure 6. Hausner ratio versus moisture content as a factor of particle size

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breadfruit seed hull (1.52), Oluwasina et al. (2014) for plant waste (*Musa Sapientum, M. paradisiaca* and *Titihonia diversifolia*) (1.48, 1.42 and 1.46 respectively) and Achor et al. (2014) for water gourd (1.31). These findings signify that the nutshell inter-particle interactions are low, hence flow would be easily achieved especially with medium-size particle of the nutshell.

This study has established the compressibility features of *C. schweifurthii* engl nutshell that would enhance densification process into pellets and briquettes and reduce cost of production. A mathematical also developed has the capability of predicting the compressibility of the nutshell at any given physical conditions.

CONCLUSION

The larger the particle size and more moisture *Canarium schweinfurthii* engl nutshell powder contains, the more difficult to compress the particles. The compressibility of the nut shell powder increased from 17.44 to 28.18% and decreased from 29.41 to 18.79% as moisture content and particle size increased respectively. Besides, tapped density, bulk density and porosity also ranged from o.672 6–0.901 2 g·cm^{-3}, 0.522 2–0.647 9 g·cm^{-3} and 0.541 6 – 0.628 9 respectively. Medium particle size had the least Hausner ratio (1.16) and the best flow behaviour than other sizes for all the studied moisture contents. Nutshell inter-particle interactions are low, hence flow would be easily achieved and less energy would be required to achieve a desired dense mass, especially with medium sized particle. Good flow of the nutshell would be achieved with the optimum values the 4.88 MPa (pressure), 10.91% (moisture content) and 0.863 8 mm (particle size). The linear mod el developed and its factors had significant (P < 0.05) relationship with compressibility. Future study will be directed towards the flow of the nutshell through different orifice shapes to ascertain the best shape of opening for continuous flow at a given condition.

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