academicJournals

Vol. 8(5), pp. 47-57, November 2016
DOI: 10.5897/JETR2016.0593
Article Number: E76F83E61699
ISSN 2006-9790

http://www.academicjournals.org/JETR

Journal of Engineering and Technology Research

Full Length Research Paper

Measurement of energy requirements for size reduction of palm kernel and groundnut shells for downstream bioenergy generation

Macmanus Ndukwu, Nnaemeka Nwakuba* and Orunta Henry

Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, P. M. B. 7267 Umuahia, Abia State, Nigeria.

Received 8 May, 2016; Accepted 28 July, 2016

The study estimated the amount of energy required for grinding palm kernel shell and groundnut shell using laboratory hammer mill and also characterize their ground physical properties. The material type and hammer mill screen aperture significantly influenced the energy requirement for grinding the two materials. For a given screen aperture size, groundnut shell consumed more energy than palm kernel shell. The energy relationship with hammer mill screen exhibited a second order polynomial form. Within the same hammer mill screen aperture range, the energy requirements for palm kernel and groundnut shell were considerably lower than most grass based biomass or straw. The bulk and particle density of groundnut shell decreased with increased geometric mean diameter while that of palm kernel shell increased with geometric mean. The two materials ground exhibited a lognormal particle size distribution at hammer mill screen of 5 and 3 mm, while 0.8 mm screen aperture exhibited a normal size distribution. The total particle and surface area estimate in a charge was sensitive to the screen sizes. Energy equations: Ratzinger's, Kicks and Bond's were used to investigate the results of the biomass comminution with Ratzinger's equations showing a higher R^2 value for palm kernel shell while Kick's equation showed a higher R^2 value for groundnut shell.

Key words: Milling, energy consumption, groundnut shell, palm kernel shell, grinding.

INTRODUCTION

The thermo-chemical treatment step in the biomass conversion process of plant materials or crop residues requires preliminarily size reduction to increase gas yield and reaction rates (Repellin et al., 2001). Better digestibility and increased efficiency of biomass in bio-refineries has been reported when they are subjected to size reduction than when used in bales bales (Wu et al., 2007; Hess et al., 2008). In the compaction process during densification, particle size reduction will increase the inter-particle bonding by increasing the particle surface area, pore sizes and contact points (Mani et al., 2004). Particle size affects significantly the physico-

*Corresponding author. E-mail: nrnwakuba@gmail.com.

chemical properties of biomaterials in biochemical reactions (Kumar et al., 2009; Song et al., 2014). The process of feedstock production in bio-refinery such as hydrolysis, fermentation, gasification, pyrolysis and chemical synthesis has been reviewed by Miao et al. (2011). They concluded that the potential pathway to undertake all this process requires feedstock materials in particulate forms which can only be achieved through size reduction. Also, production of uniform aggregate in the reinforcement utilization of agricultural residues requires size reduction. Milling is one of the most commonly adopted size reduction method for bioconversion (Datta, 1981). The use of hammer mill in milling provides a cheap, efficient and flexible milling process that can provide wide range of particulates and has been used in the study of grinding process of various biomaterials (Hill and Pulkinen, 1988; Samson et al., 2000; Paulrud and Mattsson, 2002). However, a lot of energy is dissipated in the residue grinding before material failure. Consequently, grinding of biomass and biomaterials is energy consuming and influences the cost of downstream production process (Searcy et al., 2007; Cundiff and Grisso, 2008; Hess et al., 2009).

Energy consumption for size reduction has been linked to specific material denoted by its material compositions (c), material bulk density (ρ_b) and particle density (ρ_p, initial moisture content (mc) and geometric particle size (x), type of milling mechanism employed, machine parameters, throughput capacity and the desired particle shape for the final product (Mani et al., 2004; Song et al., 2014; Esteban and Carrasco, 2006; Zhu et al., 2009; Bridgeman et al., 2010). Also, moisture content, bulk density, solid density, geometric mean size and shapes of biomaterial after grinding is very important in downstream processing including determination of combustion characteristics, performance of proximate analysis, aggregate formation and fermentation (Mani et al., 2004; Kuma et al., 2009; Song et al., 2014). Studies on most of the above parameters have been focused mostly on crops like alfalfa, switch grass, corn stover, willow, energy cane and miscanthus (Repellin et al., 2001; Mani et al., 2004; Miaoa et al., 2011). Despite the utilization of ground groundnut shell and palm kernel shell in bio-energy generation mostly marketed in pellets, studies on the aspect of grinding process and kinetics are very scarce. Determination of these parameters is also a necessary step in designing the grinding process and pulverizers. Knowledge of size reduction of biomass would enhance the choice of equipment types for the material, reduce operating costs, reduce biomass losses, tailor its physical characteristics towards the combustion need and help in the provision of uniform quality biomass for downstream bio-energy production. The objective of this research work is to estimate the energy required for grinding palm kernel shell and groundnut shell, using hammer mill of various sieve sizes and to characterize the grind particle sizes of various hammer sieves for downstream bio-energy production. Also, analysis of particle sizes of the ground after size reduction will affect the choice and desired results for a particular purpose.

MATERIALS AND METHODS

Palm kernel and groundnut shell

Cracked palm kernel shell obtained from a local palm kernel cracking factory located in Abia state, Nigeria made up of mostly durra species which is characterized with thick shells. The shells were manually sorted for uncracked and partially cracked palm nuts, stones and palm fruit fibers. The wholly cracked shells devoid of debris were sieved with a 4750 µm (4.75 mm) sieve, to ensure uniformity in dimensions. Palm kernel shells that passed through the sieve were further sieved with 0.6 mm sieve to remove dust particles. Also, raw groundnut pods were obtained from the local market and were manually selected and split to separate the shell from the seed. The groundnut shells were sun dried for one week to reduce its moisture level, so as to ensure a smooth grinding operation.

Grinding of biomass and measurement of energy consumption

A laboratory hammer mill shown in Figure 1 (Animal ration shredder hammer mill foliage, Model: TRF 400; 1.5kW; 10 swinging hammers) was used for grinding of the palm kernel and groundnut shell. The mill was charged at a constant mass (m_t) of 200 g for groundnut shell and 300 g for palm kernel shell. The mass of charge (m_t) was determined by using a mill filling degree between 28 - 35% of the available hammer mill volume (Fortsch, 2006). The feeding chute was locked during milling to avoid escape of tumbling material during milling operation.

The energy drawn by the hammer mill was measured using a voltmeter-ammeter setup with electric motor of 0.65 power factor as multiplier and previously calibrated with a Watt meter. The ammeter and voltmeter were connected in parallel as shown in Figure 2 and hooked to the single phase hammer mill electric motor. The initial power consumption when the machine was running idle was recorded several times and subtracted from subsequent calculated power under load during grinding. However, several idle run of idle power consumptions (P_0) were measured for each machine run in order to determine the magnitude of fluctuations in current over time caused by varying mechanical friction. Miao et al. [8] stated that at 95% confidence level, if the power consumed by milling machine while grinding residues is equal or larger than ($P_0 \pm t_{n-1, 1-\alpha/2} \times (\alpha/\sqrt{n})$), the net power consumption $\Delta P_t = (P_t - P_0)$ was assumed owing to biomass grinding; otherwise, ΔP_t was attributed to random current fluctuations over time and P_t was set to zero. α is the standard deviation of power measurements during idle running of the milling machines, n is the number of repetition (n = 7), $t_{n-1, 1-\alpha/2}$ is the upper critical value of 95% confidence intervals for the standard normal distribution.

Three hammer mill screens with round aperture of sizes 5.0, 3.0 and 0.8 mm, were used in milling the two residues. Each experiment was repeated five times with single run for each test (open circuit). During milling, transparent nylon sack was strapped on the hammer mill discharge chute to collect the grounds, prevent weight loss, dust pollution and to monitor when to stop the machine. The time required to grind the residue was recorded along with the power drawn by the hammer mill motor, which was recorded from the Ammeter-Voltmeter deflection every 20 s. Steady voltage was maintained with a voltage stabilizer (CVR-TUB, 5000VA: Century), therefore power surge was assumed due to material grinding. The specific energy consumption was calculated from Equation 1 of

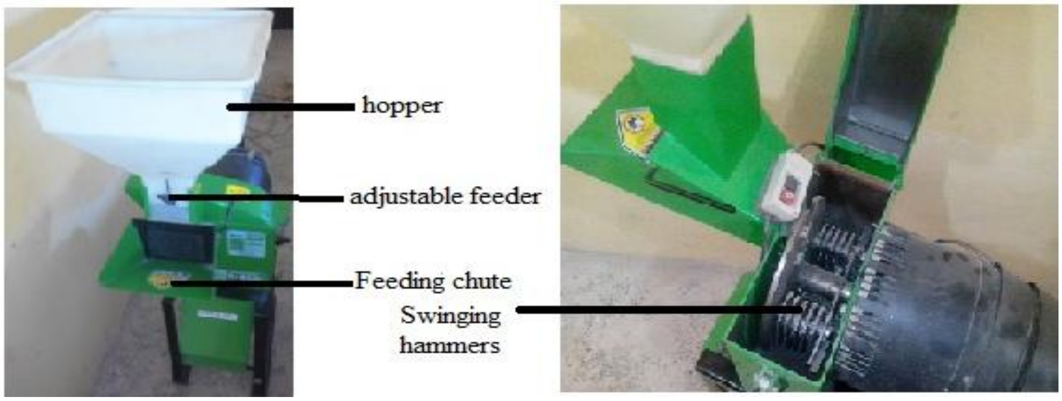

Figure 1. Hammer mill.

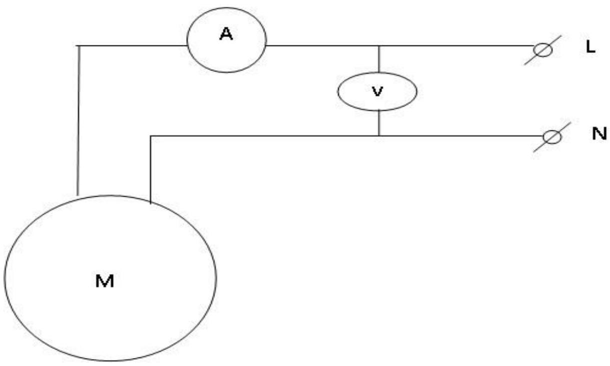

Figure 2. Experimental setup. M: Machine (hammer mill); A: ammeter; V: voltmeter.

Miao et al. (2011) as follows:

$$E = \frac{\int_0^T (P_t - P_0)dt}{m} = \frac{\int_0^T (\Delta P_t)dt}{m} \quad (1)$$

Where: E is the total specific net energy for milling a unit of dry matter (kWh/t), P_t is power (Watt) consumed by milling machines while milling feedstock at time t, P_0 is the average power consumption in Watt under idle conditions (without feeding materials) of the milling machines, ∆Pt is net power consumption in kilo Watt of the milling machines to grind biomass at time t, and m is dry matter mass in kg of material feedstock to be ground.

Fitting of energy curves

Theoretical considerations show that the energy dE, required to produce a small change dx, in the size of a product is governed by: $\mathrm{dE}/_{\mathrm{dx}} = {-\mathrm{k}}/_{\mathrm{x}^n}$ where; k and n are constants. The data obtained experimentally was plotted in the form of the energy per unit mass against average initial size of the material x_1 and the average final size of the product x_2 (in each case x_1 and x_2 were simplified to fit into the governing equation). The curve obtained was fitted into the three classical laws (McCabe et al., 2005), Equations 2 to 4 for grinding of dry materials. Higher coefficient determination (R^2) was the criterion for selecting the best equation to define the energy curves of the biomass.

Ritinger's Law:

$$E = k_1\left[\frac{1}{x_2} - \frac{1}{x_1}\right] \quad (2)$$

Kick's Law:

$$E = k_2 In\left[\frac{x_1}{x_2}\right] \quad (3)$$

Bond's Law:

$$E = k_3\left[\frac{1}{\sqrt{x_2}} - \frac{1}{\sqrt{x_1}}\right] \quad (4)$$

Particle size distribution and density measurements of biomass grounds

The particle size analysis was carried out according to American Society of Agricultural Engineers' Standard ASAE (2001). A ground sample of 100 g was placed in a stack of standard sieves (Okhard machine tools Ltd., Nigeria) arranged from the largest to the smallest opening. The following sieve sizes (Orkhard, Nigerian sieves) were used for the sieve analysis; 2.0, 1.18, 0.60 and 0.425 mm. The set of sieves were placed on the mechanical Ro-Tap sieve shaker (Okhard machine tools Ltd., Nigeria) for 10 min (Mani et al., 2004; Miaoa et al., 2011). After sieving, the mass retained on each sieve was weighed and the percentage of mass retained was calculated. The geometric mean diameter (dgw) of the sample ground by mass and the geometric standard deviation of the particle diameter (Sgw) by mass were calculated according to Equations 5 and 6 of ASAE (2001).

$$dgw = log^{-1}\left[\frac{\sum_{i=1}^{n}(Wi \log \bar{d}i)}{\sum_{i=1}^{n} Wi}\right] \quad (5)$$

$$Sgw = \left[\frac{\sum_{i=1}^{n} Wi(\log \bar{d}i - \log dgw)^2}{\sum_{i=1}^{n} Wi}\right]^{1/2} \quad (6)$$

where $\bar{d}i = (d_i \times d_{i+1})$; d_i is nominal sieve aperture size of the i^{th} sieve, (mm), d_{i+1} is nominal sieve aperture size of the i^{th}+1 sieve (mm), n is number of sieves plus one pan, Wi is mass on i^{th} sieve.

The bulk density of the ground samples was determined by the use of a standard measuring beaker. The bulk density of the solid sample was calculated from the net weight per standard volume and reported at the particular moisture content. The particle density of the biomass ground was determined with density bottle and also reported at the particular moisture content.

Estimation of biomass grounds specific surface area and number of particles

The total particle surface area per unit of mass and the number of particles in a charge was calculated with Equations 7 and 8 following ASAE (2001).

$$A_{st} = \frac{\beta_s m_t}{\beta_v \rho} exp\left(4.5\sigma_{In}^2 - In\mu_{gw}\right) \quad (7)$$

$$N_t = \frac{m_t}{\beta_v \rho} exp\left(4.5\sigma_{In}^2 - 3In\mu_{gw}\right) \quad (8)$$

Where A_{st} is the estimated total specific surface area per unit of mass (cm^2/g dry matter), βs is shape factor used for calculating the surface area of particles: for cubes β_s = 6 and for spheres β_s = π, β*v* is a shape factor. To calculate the volume of particles, the factors are given as follows: for cubes β*v* = 1 and for spheres β*v* = π/6. ρ is the material particle density (g/cm^3), σ_{ln} is the log-normal geometric standard deviation of a parent population by mass in natural logarithm (using S_{ln} as an estimate), μ_{gw} is the geometric mean particle diameter of a parent population by mass (using dgw as an estimate), and m_t is the mass of the charge (g).

RESULTS AND DISCUSSION

Energy requirement for grinding

The specific energy requirement ($kWht^{-1}$) for grinding palm kernel and groundnut shells using hammer mill with round aperture milling screen sizes of 0.8 to 5 mm is shown in Figure 3. The specific energy consumption for grinding palm kernel shell with the hammer mill screen sizes is inversely related to the screen aperture. The inverse relationship of hammer milling screens with energy consumption for size reduction of dry biomaterial like alfalfa, switch grass, corn stover, etc. has also been reported by Cadoche and Lopez (1989), Miaoa et al. (2011) and Mani et al. (2004). Therefore, the larger the hammers mill screens size, the lower the specific energy consumption and grinding time. A regression equation of quadratic form $E = ax^2 + bx + c$ fitted well with the specific energy requirement ($kWht^{-1}$), while a linear equation of the type: T = ax + c fitted well with time for grinding of palm kernel shell and groundnut shell using hammer mill screen sizes ranging between 5.0 and 0.8 mm. Where: E = specific energy consumption ($kWht^{-1}$), x = the aperture sizes (mm), t = time for grinding (min) for one test run (open circuit), a and b are regression coefficients shown in Table 1; c is constant. Logarithmic relationship [E = aIn (x) + c] was also exhibited between geometric mean diameter by mass and specific energy consumption (palm kernel shell: a = - 1.187, c = 2.356, R^2= 0.983; groundnut shell: a = - 1.82, c = 2.737, R^2= 0.998) for the two materials. Higher specific energy consumption was recorded for groundnut shell at the same screen aperture. However, in grinding of biomaterials, factors such as difference in moisture content, and fibrous nature of groundnut shell might have contributed to this (Himmel et al., 1985; Schnatz et al., 2000; Mani et al., 2004; Djantou et al., 2007; Bitra et al., 2009; Hess et al., 2009; and Miaoa et al., 2011).

The energy requirements for grinding the two biomass is lower than most grass based biomass or straw as shown in Table 2, within the same range of hammer mill screen size. However , the various researchers have reported varying results for the same kind of biomass feedstock which show that energy requirement for biomass grinding is a function of both machine and biomass parameters. Also, the amount of charging of the mill is also a major factor, which implies that the specific energy requirement for a laboratory hammer mill and industrial hammer mill will vary. According to Chung (1998) and Fortsch (2006), loading a mill less than 14% of its total volume will increase its specific power consumption as compared to when it is loaded greater than 25% of its total volume. According to the authors, there is a very large gap in a charge in lower percentage loading than higher percentage loading at critical speed which generates more counteracting action rather than cascading action which is required for higher grinding efficiency because of more contact with the material which will reduce grinding time. The results of this work showed that the energy consumption of groundnut shell is 15 to 70% higher than that of palm kernel shell. The higher variation was experienced at a higher screen aperture and decreased greatly as the screen aperture decreased. Because the mill was loaded at more than 25% of its volume, the difference in energy consumption is attributed more to the biomass feedstock parameters rather than machine parameters in this case. Comparatively, low specific energy usage especially of palm kernel shell as compared to most biomass feedstock despite its high net and gross calorific value is good for bioenergy industries in the cost of production of biofuel. The result showed that while palm kernel shell consumes 0.2 to 2.3 kWh of energy per ton during size reduction (screen aperture 5 - 0.8 mm, 10.6% wb), according to some research, it produces a net calorific heat value of 4900 kWh/MT, that is, 17.45 GJ/MT (www.palm shells.com, 2014). The result obtained using the laboratory mill can be scaled up to match the commercial mill energy consumption. Miaoa et al. (2011) reported a model equation of the form $A_j = W_i\,[1- (\delta_1/\delta_2)^{-½} / \delta^{½}_2]\,(\pi_{G0} / \pi_{G1})^{½}$, which can be used to rationalize a bench scale mill with an industrial (commercial mill) scale. Where W_i (= K_b / 0.3162) is Bond's index corresponding to the strength of the material, K_b is bonds constant, δ_1 and δ_2 are the degrees of dispersion of the initial material characterized by the mesh size of the sieve with a 20% residue; π_{G0} and π_{G1} are the production levels (ton h^{-1}) of the initial scale and up-scaled mills. It is also worthy of note that most authors in Table 2 ground

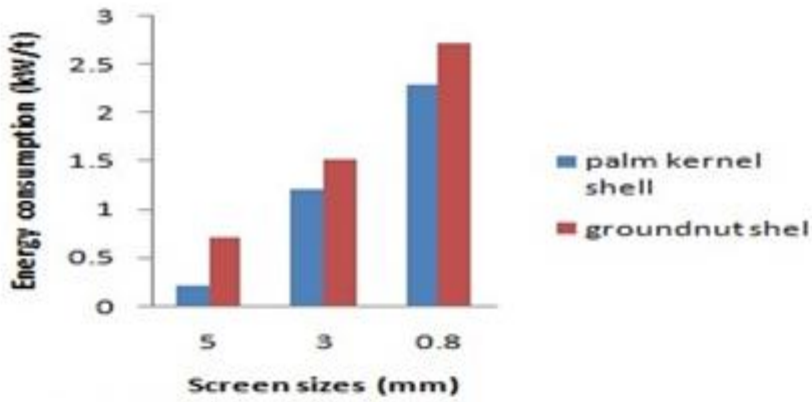

Figure 3. Average energy consumption.

Table 1. Coefficients of regression model for energy consumption ($kWht^{-1}$) and grinding time (min).

Residues	Dependent variable	a	b	c	R^2
Palmkernel shell (10.6% wb)	E	0.0400	0.8900	-0.73	1.00
	T	-1.330	-	4.273	0.938
Groundnut shell (12.8% wb)	E	0.1900	0.2500	0.2600	1.00
	T	-1.07	-	4.19	0.993

Table 2. Comparison of specific energy consumption with some other biomass.

Biomass	Moisture content	Screen Size (mm)	Energy consumption	Source
Miscanthus	7–10% wb	4 (hammer mill)	184 kJ/ kg	Miao et al., 2011
Switch grass	7–10% wb	4 (hammer mill)	172 kJ/ kg.	Miao et al., 2011
Corn Stover	6.5% wb	0.8 (hammer mill)	79.2 kJ/kg	Mani et al.,2004
Corn Stover	6.5% wb	1.6 (hammer mill)	53.28 kJ/kg	Mani et al.,2004
Corn Stover	6.5% wb	3.2 (hammer mill)	25.2 kJ/kg	Mani et al., 2004
Corn Stover	12% wb	3.2 (hammer mill)	34.30 kWh/t	Mani et al., 2004
Corn Stover	12% wb	1.6 (hammer mill)	19.84 kWh/t	Mani et al., 2004
Corn Stover	12% wb	0.8 (hammer mill)	11.04 kWh/t	Mani et al., 2004
Hard wood	-	1.6 (Knife mill)	130 kWh/t	Cadoche and Lopez, 1989
Corn stover	-	3.2 (hammer mill)	10 kWh/t	Cadoche and Lopez, 1989
Corn Stover	-	1.6 (hammer mill)	14 kWh/t	Cadoche and Lopez, 1989
Corn stover	-	9.5(Knife mill)	3 kWh/t	Cadoche and Lopez, 1989
Corn Stover	-	3.2(Knife mill)	20 kWh/t	Cadoche and Lopez, 1989
Corn stover	-	3.2mm (hammer mill)	14 kWh/t	Himmel et al 1985
switchgrass	-	5.6 (hammer mill)	44.9 kWh/t	Samson et al. (2000)
Switch grass	8.5 % wb	7 mm (Hammer mills)	60 kWh/t	Mani et al. (2002)
Palm kernel shell	10.6 % wb	5.0 (hammer mill)	0.20 kWh/t	Present work
		3.0 (hammer mill)	1.21 kWh/t	Present work
		0.8 (hammer mill)	2.30 kWh/t	Present work
Groundnut shell	12.8% wb	5.0 (hammer mill)	0.70 kWh/t	Present work
		3.0 (hammer mill)	1.52 kWh/t	Present work
		0.8 (hammer mill)	2.72 kWh/t	Present work

Table 3. Grinding coefficients determined through method of slopes for all hammer mill screen and residues.

Hammer mill screen aperture	0.8 mm			3 mm			5 mm		
Constants	K_1	K_2	K_3	K_1	K_2	K_3	K_1	K_2	K_3
Palm kernel shell	13.919	26.111	38.509	2.648	3.904	6.464	0.42448	0.4536	0.8837
Groundnut shell	2.362	4.325	5.148	0.2993	0. 910	0.5866	0.0134	0.0476	0.0645

K_1– Rattingers constant; K_2- Kicks constant; K_3– Bonds constant.

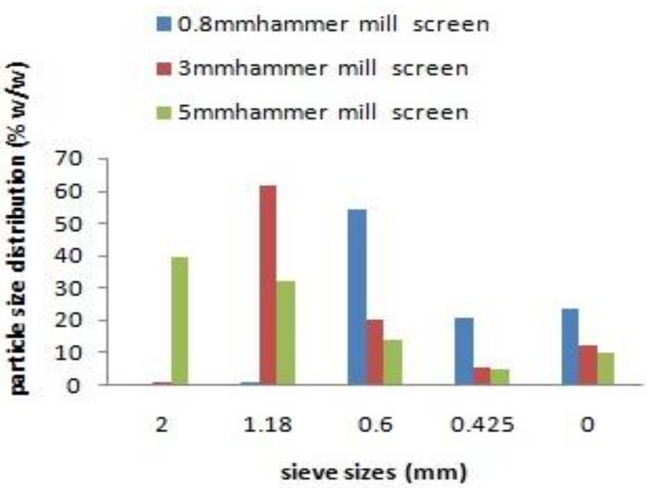

Figure 4. Particle size distribution of groundnut shell.

Table 4. Result of fitting statistical data.

Grinding law	Palm kernel shell	Groundnut shell
	R^2	R^2
Rattingers	0.993	0.997
Kicks	0.987	0.999
Bonds	0.932	0.978

the biomass until they obtained a desired particle size due to the nature of the biomass.

Grinding energy kinetics

The various geometric mean data generated from different hammer mill screens after grinding was fitted into various grinding equations (Equations 2 - 4) with the initial residues geometric mean. The equations were fitted with the method of slopes. The fitting constants are shown in Table 3 for each biomass at different hammer mill screens, while the values are plotted in Figures 9 and 10. Regression analysis with R^2-value being the main determinant for the success of the curves to define the grinding characteristic for the residues. Higher R^2 value shows the best fitting equation. The calculated R^2 value for each equation is presented in Table 4. The values show high goodness of fit for all the equations but when the R^2 values are closely considered, Ritinger's equation gave a higher correlation for palm kernel shell while Kicks equation gave a higher correlation for groundnut shell. This is somewhat justified because palm kernel shell gave finer particles as shown in the particle size distribution in Figure 5 while groundnut shell gave more coarse particles as illustrated in Figure 4.

Physical properties of the grounds

Table 5 shows the geometric mean particle diameter and geometric mean standard deviation of palm kernel and groundnut shell grinds. Also, Figures 4 and 5 show the particle size distribution of the grind from each aperture for the two residues. As expected, the bigger screen of 5 mm has the larger geometric mean particles and a wider size distribution and the result is similar to the grinding of alfalfa and corn stover as reported by Mani et al. (2004) and Badger and Fransham (2006). According to Mani et al. (2004), this is good for densification process because during pelleting, better compaction can be achieved when smaller particles rearranges and fill the space created by the larger particles. However, 3 mm hammer mill aperture showed a more uniform ground for groundnut shell which skewed towards the 1.18 mm size as shown in Figure 4, while 0.8 mm hammer mill sieve aperture showed a better uniform size for the palm kernel shell ground and skewed towards 0.6 mm size as also shown in Figure 5. The lower aggregate size of the palm kernel shell ground can be attributed to the lower moisture content than groundnut shell and also the fibrous nature of the groundnut shell. This is because while palm kernel shell shatters and separates on impact groundnut shell does not separate much and requires some shear force to separate. The choice of hammer mill mesh for grinding biomass is important because grinding is energy-consuming, therefore, there is need to identify energy saving methods. Although, ANSI/ASAE standard S319.4 was used for particle size distribution, not all screen sizes were logarithmic normally distributed as can be seen in Figures 4 and 5. While grounds from aperture sizes 5 and 3 mm skewed towards the left (logarithmic normal distribution) for the two materials, the 0.8 mm screen assumed normal distribution. This agrees with the

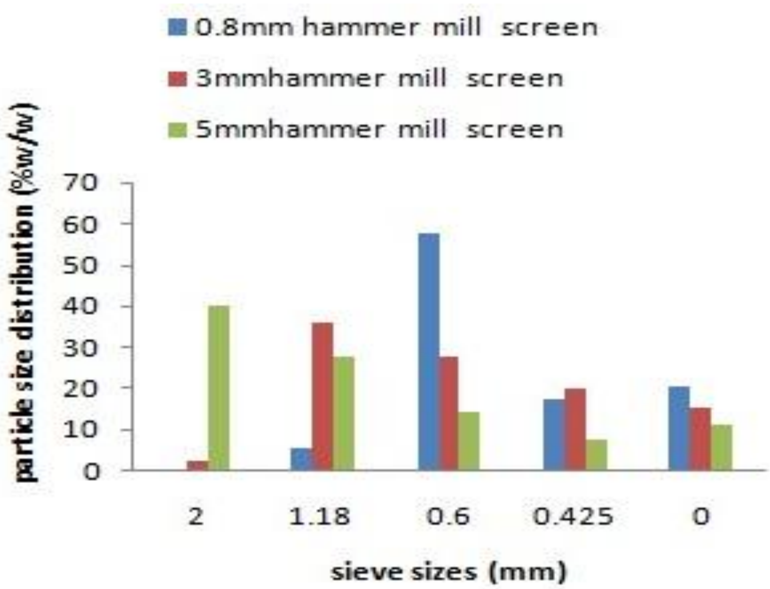

Figure 5. Particle size distribution of palm kernel shell.

Table 5. Geometric mean particle diameter and standard deviation.

Biomass grounds	Moisture content (% wb)	Hammer mill screen size (mm)	Average geometric mean particle diameter (mm)	Average geometric standard deviation (mm)
Palm kernel shell	10.6	5.0	0.99	0.18
		3.0	0.68	0.05
		0.8	0.55	0.01
Groundnut shell	12.8	5.0	0.99	0.18
		3.0	0.74	0.09
		0.8	0.54	0.05

findings of Miaoa et al. (2011) that distribution of grounds after size reduction for some biomass does not always follow lognormal distribution only as found by Mani et al. (2004) rather they may deviate to form normal or skewed normal distribution.

Figures 6 and 7 illustrate the bulk and particle densities of the palm kernel and groundnut shell grinds. For the same hammer mill screen size, the geometric mean particle diameter of palm kernel shell was slightly different from that of the groundnut shell. The larger the screen opening, the lower the bulk and particle densities for groundnut shells, while for palm kernel shells, the particle densities did not change significantly. Grounds from the smallest screen size (0.8 mm) produced higher bulk density for groundnut shells of 267.6 kgm^{-3}. Bulk and particle densities of palm kernel shells are higher than that of groundnut shells. The particle and bulk density of the two materials can be described according to a polynomial relationship of the second degree of the form $\rho = ax^2 + bx + c$. Where, ρ is the particle or bulk density; x is the screen size; and a, b, and c are regression coefficients. However, the result is contrary to the results obtained by Miaoa et al. (2011) in the grinding of *Miscanthus*, switch grass and willow, where they expressed the screen aperture with particle and bulk density with a power- law of the form ax^b. The variations may be attributed to the nature of the material and probably the type of milling mechanism and shape of screen aperture coupled with the fact that the biomass underwent double size reduction (chopping and grinding). At the same screen aperture, palm kernel shell exhibited both higher particle and bulk density than groundnut shell and this is mainly attributed to the initial physical properties of the material.

Figure 8 shows the effect of geometric mean diameter of the grounds on bulk and particle densities. The geometric mean particle diameter of the grounds increased with the bulk and particle density according to

Figure 6. Bulk and particle density of grinded palm kernel shell.

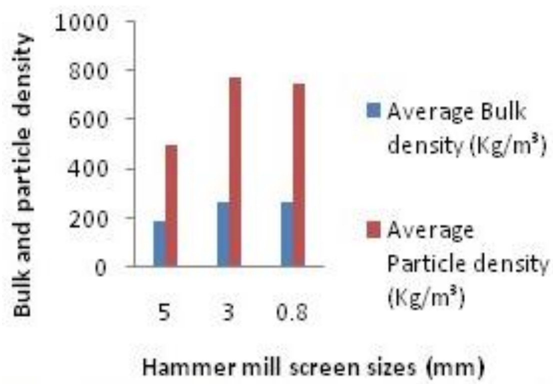

Figure 7. Bulk and particle density of grinded groundnut shell.

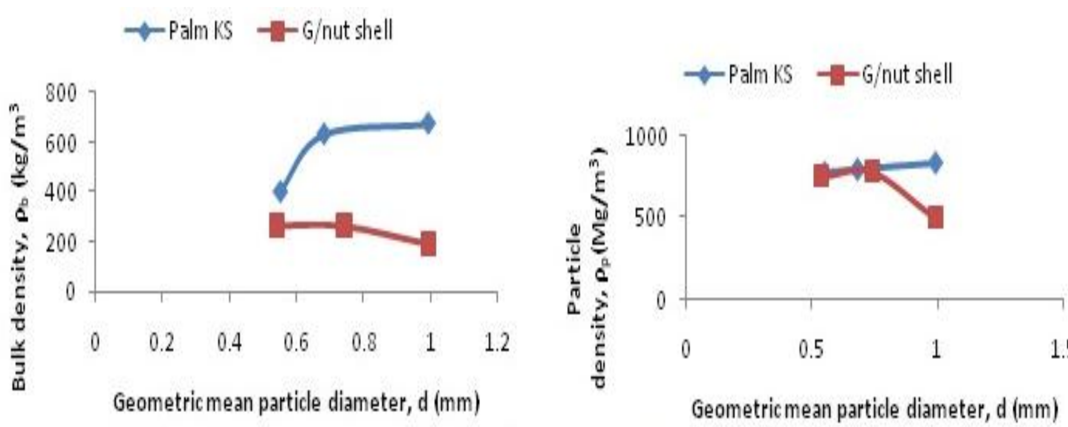

Figure 8. Effect of geometric mean particle on bulk and particle density of palm kernel and groundnut shell.

a third order polynomial of form $ax^3 + bx^2 + c$, where x is the geometric mean of the material. While the bulk and particle density of groundnut shell decreased with increased geometric mean diameter; that of palm kernel

Table 6. Relationship between geometric mean, particle size and bulk and particle densities of biomass grinds.

Biomass grind	Model	R^2
Palm shell	$\rho_b = -17548d^3 + 35216d^2 - 21546d + 4517$	1.00
	$\rho_p = -63.72d^2 + 232.2d + 671.5$	1.00
G/nut shell	$\rho_b = 2337d^3 - 5926d^2 + 4676d - 897.9$	1.00
	$\rho_p = -2822d^2 + 3762d - 458.7$	1.00

shell increased with geometric mean. For example, the bulk density of groundnut shell grinded decreased by 39.4% as geometric mean particle diameter increased by 45.45%. In the case of groundnut shell, because of the bulky nature of the layer ground particles and the shape formation of layers inside the beaker, they occupied more pore volumes than smaller particles which led to decrease in bulk density. Although, Chung (1998) and Mani et al. (2004) stated that the porosity within the ground particle is reduced further when the ground particle size was reduced, this lowers the bulk or particle density. Mani et al. (2004) also stated that this was due to a certain particle diameter. However, the contrary was observed in palm kernel shell ground where the bulk and particle density decreased with geometric mean particle diameter. It was noticed that the layer formation when the two materials were poured inside the measuring beaker and tapped slightly during bulk and particle density measurement of groundnut shell and palm kernel shell were different at various geometric particle diameter (from different sieve sizes). While the ground groundnut shell tends to lay on top of one another at all geometric diameter from all screen aperture, there was a serious compact rearrangement for palm kernel shell at higher geometric particle diameter. The reverse was observed for palm kernel shell at lower geometric length and this may have accounted for the differences in bulk and particle density behaviour for the two materials. Nevertheless, the sensitivity of bulk and particle density behaviour was not clear as observed in Figures 5 and 6 (Mani et al., 2004) for wheat straw, barley straw, corn stover and switch grass, respectively because even though the line of best fit was drawn through the plotted points, the actual points were irregular. Although, Miao et al. (2011) stated that aperture shapes and sizes of milling screens, the machine types, motor speed and material feeding method were key variables determining particle size, particle size distribution and bulk density; however, the nature of the material was also a key variable.

A third-order polynomial (Table 6) was developed for palm kernel shell and groundnut shell grounds to relate the bulk density and geometric mean diameter, with R^2 values of 1.00, respectively. For particle density of groundnut and palm kernel shell grounds, quadratic relationships were established with respect to the geometric mean particle diameter to the geometric mean particle diameter of the ground with coefficient of determination (R^2) value of 1.00. To further confirm the fitness of the data, analysis of variance was performed for each regression model using the average values of bulk and particle densities data. The regression models were significant at 95% confidence level. This is similar to the results obtained by some researchers [5] while Miao et al. (2011) obtained a power law relationship. The estimated surface area per mass (cm^2/g) and the number of particle in a charge was determined by Equations 7 and 8. The shape of the grinds was assumed to be spherical because of the round aperture of the screens. Therefore, the equation was applied with its factors for a spherical shape. Figure 9 presents the relationship between screen apertures and total surface area and also number of particle in a charge. The figure shows the sensitivity of the two parameters to the screen aperture sizes. While the number of particles decreased with increased screen aperture, the specific surface area increased with aperture size. This is in tune with the results of Miao et al. (2011), although the result in terms of surface area is inconsistent with milling screen apertures because they reported a higher specific surface area in screen sizes of 4 and 12.7 mm than 1, 6 and 8 mm in *Miscanthus*. They also showed the same scenario in switch grass grinding. Although, the results contradicts the expected trends, they stated that based on S319.4 standard, it is possible for larger particle specific surface area estimation to be lower than the smaller particles. Therefore, they suggested the need to improve the existing standard based on material properties. While the materials showed a higher surface area at 5 mm screen aperture, they showed a higher number of particles in smaller milling screens of 0.8 mm.

Generally, the economics and efficiency of downstream bioenergy production success has been linked by some researchers to particle shape, size distribution and comminution energy consumption (Djantou et al., 2007; Hess et al., 2009; Zhu et al., 2009). The authors have proposed different particle sizes and distributions which can be adequate for several downstream applications which include combustion using fluidized bed combustion (FBC) systems, electricity generation, hydrothermal conversion, biochemical pyrolysis, hydrolysis, fermentation, transportation and storage of biomass. The above proposals are mainly for biomass produced or

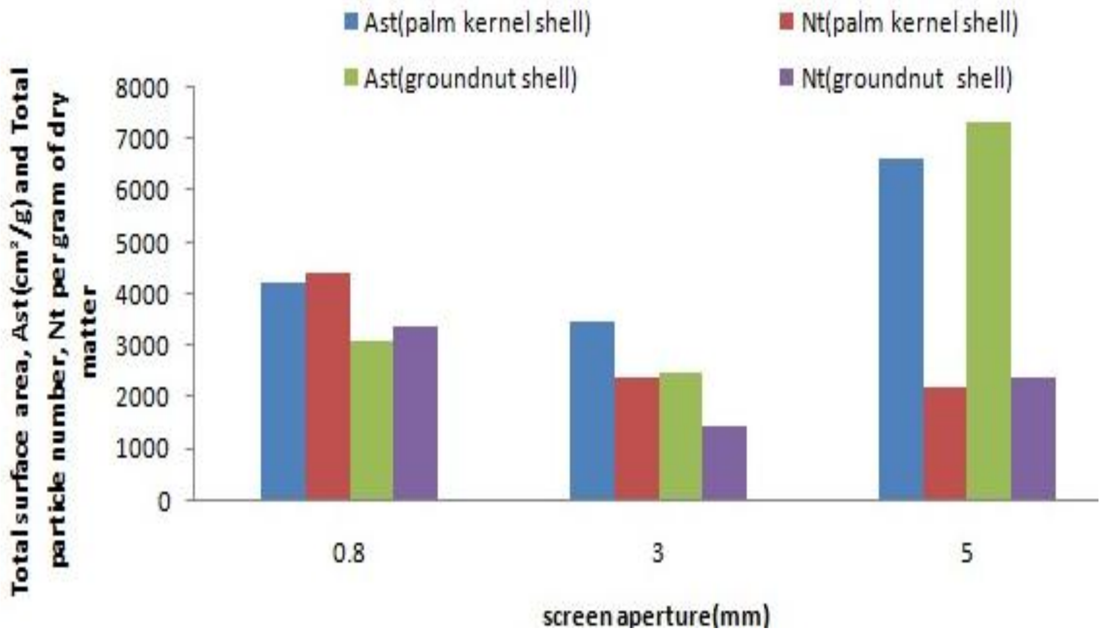

Figure 9. Total surface area, Ast (cm^2/g) and total particle number, Ntper gram of dry matter.

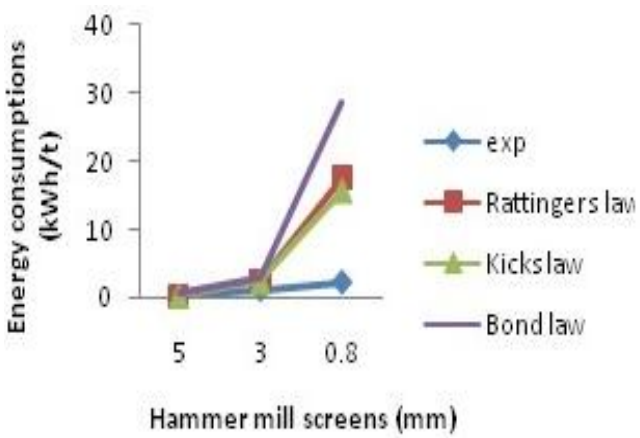

Figure 10. Result of fitting grinding data with grinding laws for palm kernel.

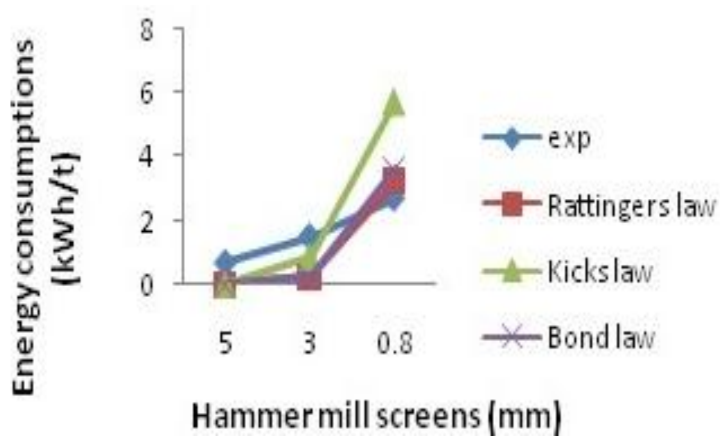

Figure 11. Result of fitting grinding data with grinding laws for groundnut shell.

generated from developed countries which have advanced the integration of bioenergy in their energy system. This is lacking in developed countries like Nigeria where available raw material for bioenergy generation has not been standardized.

Conclusion

This study estimated the amount of energy required for grinding palm kernel and groundnut shells using laboratory hammer mill and also characterizes the ground physical properties. The material type and hammer mill screen aperture significantly influenced the energy requirement for grinding the two materials. For a given screen aperture size, groundnut shell consumed more energy than palm kernel shell. The energy relationship with hammer mill screen exhibited a second order polynomial form. Within the same hammer mill screen aperture range, the energy requirements for palm kernel and groundnut shells are considerably lower than most grass-based biomass or straw. The bulk and particle densities of groundnut shell decreased with increased geometric mean diameter while that of palm kernel shell increased with geometric mean. The two materials exhibited a lognormal particle size distribution at hammer mill screen of 5 and 3 mm while 0.8 mm screen aperture exhibited a normal size distribution. The total particle and surface area estimate in a charge is sensitive to the screen sizes. Rattingers, Kicks and Bond's energy equations was used to investigate the results of the biomass comminution with Rattingers equations showing a higher R^2-value for palm kernel shell, while Kick's equation showed a higher R^2-value for groundnut shell.

Conflict of Interests

The authors have not declared any conflict of interests.

REFERENCES

ASAE (2001). ASAE Standards (47th ed.), S319.3 Method of determining and expressing finess of feed materials by sieving. St Joseph, M. I.: American Society of Agricultural Engineers pp. 3-6.

Badger PC, Fransham P (2006). Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs - a preliminary assessment. Biomass Bioenergy 30:321-325.

Bitra VSP, Womac AR, Chevanan N, Miu PI, Igathinathane C, Sokhansanj S, Smith DR (2009). Direct mechanical energy measures of hammer mill comminution of switch grass, wheat straw, and corn stover and analysis of their particle size distributions. Powder Technol. 193:32-45.

Bridgeman TG, Jones JM, Williams A, Waldron DJ (2010). An investigation of the grindability of two torrefied energy crops. Fuel J. 89:3911-3918.

Cadoche L, Lopez GD (1989). Assessment of size reduction as a preliminary step in the production of ethanol from lignocellulosic wastes. Biol. Wastes 30:153-157.

Chung CS (1998). Measuring density and porosity of grain kernels using a gas pyrometer. Cereal Chem. 65(1):13-25.

Cundiff JS, Grisso RD (2008). Containerized handling to minimize hauling cost of herbaceous biomass. Biomass Bioenergy 32:308-313.

Datta R (1981). Energy requirement for lignocelluloses: pre-treatment processes. J. Biochem. 5(4):16-19, 42.

Djantou EB, Mbofung CM, Scher J, Desobry S (2007). A modelling approach to determine the effect of pre-treatment on the grinding ability of dried mangoes for powder production. J. Food Engineer. 80:668-677.

Esteban LS, Carrasco JE (2006). Evaluation of different strategies for pulverization of Forest biomass. Powder Technol. 6:139-151.

Fortsch DS (2006). Ball Charge Loading–Impact on specific power consumption and capacity IEEE-IAS Cement Industry committee paper. New York, Academic Press.

Hess JR, Kenney KL, Ovard LP, Searcy EM, Wright CT (2009). Uniform-format solid feedstock supply system. National Laboratory Bioenergy Program, London, Academic Press.

Hill B, Pulkinen DA (1988). A study of pellet durability and pelleting efficiency in the production of dehydrated lfafa pellets. Saskatchwan Dehydrators Association. New York, Springer.

Himmel M, Tucker M, Baker J, Rivard C, Oh K, Grohmann K (1985). Comminution of biomass: hammer and knife mills, Biotechnology and Bioengineering Symposium, Darka 15:39-58.

Kumar P, Barrett DM, Delwiche MJ, Stroeve P (2009). Methods of pre-treatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. Ind. Chem. Engineer. Res. 48:3713-3729.

Mani S, Tabil LG, Sokhansang S (2004). Grinding performance and physical properties of selected biomass. Biomass Bioenergy 27(4):339-352.

McCabe WL, Smith JC, Harriott P (2005). Unit operations of chemical engineering. 7th ed. McGraw-Hill international, New York pp. 984-1000.

Miaoa Z, Grift TE, Hansen AC, Ting KC (2011). Energy requirement for comminution of biomass in relation to particle physical properties. Ind. Crops Prod. 33:504-513.

Paulrud SJE, Mattsson CN (2002). Particle and handling characteristics of wood fuel powder: effects of different mills. Fuel Process. Technol. 76:23-39.

Repellin V, Alexandre G, Mathieu R, Rene G (2001). Energy requirement for fine grinding of torrefied wood. Biomass Bioenergy 34(7):923-930.

Samson P, Duxbury P, Drisdelle M, Lapointe C (2000). Assessment of pelletized biofuels. Available at: http://reap.ca/Reports/pelletaug2000.html.

Schnatz R, Knobloch O, Beckum I (2000). Influence of the ball filling factor on the power consumption and throughput of ball mills in combined grinding plants. ZKG International 5(8):438-447.

Searcy E, Flynn P, Ghafoori E, Kumar A (2007). The relative cost of biomass energy in transportation. Application of Engineering in Agriculture. pp. 136-140, 639-652.

Song SH, Myeong GL, Hyong JL, Won BY (2014). Analysis of grinding kinetics to control the effect of rice flour particle size on the yield of alcohol and glucose during fermentation. Int. J. Food Sci. Technol. 49:2703-2710.

Wu X, Zhao R, Bean SR, Seib PA, McLaren JS, Madl RL, Tuinstra M, Lenz MC, Wang D (2007). Factors impacting ethanol production from grain sorghum in the dry-grind process. Cereal Chem. 84:130-136.

Zhu JY, Wang GS, Pan XJ, Gleisner R (2009). Specific surface to evaluate the efficiencies of milling and pretreatment of wood for enzymatic scarification. Chem. Eng. Sci. 64:474-485.