

PROMOTING SUSTAINABILITY THROUGH INNOVATION: CONVERSION OF WOOD WASTE TO PELLETS

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Abstract: Sustainability could be achieved by applying technological innovation to scientific principles. Applying knowledge-based capacity in creatively solving societal problems and as such provide economic empowerment. In this study, wood wastes (sawdust samples) *Cetis africana* (Ita white); *Cordina millenni* (Omo Sheda), and mixed sawdust (unclassified) were characterized for optimum condition and made into pellets. An in-house pelletiser of shape factor 2.78 was fabricated for this production. The particle size, binder modification, combustible properties, and calorific value showed that a sample with $x \leq 600 \mu\text{m}$, 30% w/v binder concentration at a compressive pressure of 6.2Nm^{-2} gave the best result. The mixed sawdust sample gave results that were not consistent, requiring a proper initial understanding or sorting out. *Cetis africana* was observed as the best sample with good pellet quality that can be used in different heating systems. Meeting societal problems such as effective waste management aimed at curbing the negative impact of greenhouse gas emission on the environment and power generation in distributed form can be fast-tracked through innovative research and development which must be commercialised thus financially empowering the society at large.

Keywords: Sustainability, Technological innovation, Waste to wealth, Commercialisation

INTRODUCTION

Sustainability can only be achieved by mainstreaming innovation and mentoring upcoming Engineers and Scientists to think innovatively. This goes beyond departmentalisation but exposing students to an interdisciplinary way of handling issues as students and in preparation for life after school. Technopreneurship is a system of mainstreaming technological innovation towards achieving sustainability in various sector and economies of the world (Rajalingam, 2014; Okorie et al., 2014). This involves capacity building, networking, marketing, project teams, and interdepartmental learning that will produce citizens that are entrepreneurial and have a competitive edge. This will equip even students to be proactive, looking out for ways of using their knowledge-based capacity to solve societal problems.

According to Steven Sutanro, as reported by McClure (2015), innovation is about applying technology to empower young people to become lifelong learners who are agents of change. One such innovative works is seeking to convert waste to wealth by turning sawdust to pellet for both industrial and domestic energy use. The research will no longer end only in publications that will in turn end on the shelves but be target-oriented in meeting societal needs. Graduates will no longer come out and be job seekers but problem solvers and employers of labour through various innovations (Rajalingam, 2014).

European Union presented some climate and energy targets to be achieved by the year 2030 which gave room for the contribution of renewable energy to the energy mix around the world and the increase in the demand for pellets (Whittaker and Shield, 2017). Biomass stands out among the renewable energy sources that are available for the achievement of these goals. Densification of biomass is crucial in minimizing the disadvantages associated with the use of biomass such as low density, high moisture content, handling, and storage (Malik et al., 2015; Tumuluru. 2014). This can be achieved through briquetting, pelletizing, or agglomeration (Mitchual, 2014). The interest in pelletizing has increased over the years between 2006 and 2012. Pellet production worldwide grew from 7 to 19 million tons with Europe and North America being the highest producer and consumer of these classified products. These have given rise to the introduction of new materials as feedstock and the development of quality standards that will help to guarantee

the right use of different types of pellet in combustion equipment with the introduction of new classification (Miranda *et al.*, 2015).

A wide range of study has been done on the densification of materials due to high availability of different types of biomass and the need to adapt them to specific uses. Pelletisation helps to produce biofuels with lower moisture, dense and relatively uniform shape, having higher effective heating value, with clear burning and reduced ashes when compared with raw biomass (Ungureanu *et al.*, 2018). This process produces pellets which can be used in different energy conversion units such as boilers, engines, and gas turbines even fuel cells (Koukouzas *et al.*, 2008). To produce quality pellets, two things must be considered; the characteristics of the raw materials to be used as feedstock and the operational variables in the densification process (Garcia- Maraver and Carpio, 2015; Harun 2018). These parameters include biomass type, moisture content, particle size, operating conditions, pelletiser type, die diameter, shape factor (L/D), and a binding agent (Stahl *et al.*, 2012; Garcia- Maraver and Carpio, 2015; Tumuluru, 2014; Whittaker and Shield, 2017; Lisowski *et al.*, 2018).

Lignocellulosic biomass is the major raw material for pellet production (Malik *et al.*, 2011). It can also be soft or hardwood species, red or white in colour. The choice of biomass wood waste such as sawdust as feedstock would mitigate the problem of deforestation. The physical and chemical compositions of the biomass type (raw material) affect greatly the quality of the pellets (Malik *et al.*, 2015 Liu *et al.*, 2014; Garcia - Maraver and Carpio, 2015). They include moisture content, ash content, mineral analysis, particle size, shape, and calorific value. All these variables and as well as the intended use of the pellets influence the choice of wood species for pellet production (Mitchual, 2014). Whittaker and Shield (2017) in their review concluded that softwood is believed to give higher quality pellets than hardwood due to its high lignin content but with binders supplying additional lignin, good quality hardwood pellets can be formed.

Particle size is an important parameter in determining the hardness of pellets and this must be considered (Whittaker & Shield, 2017; Adapa *et al.*, 2013). It affects the total surface area; pore size and number of contact points for interparticle bonding that is necessary to produce good quality pellets (Ungureanu *et al.*, 2018). Many researchers have worked on identifying the optimum particle sizes for different biomass materials to produce the best quality pellets (Miranda *et al.*, 2015).

Samples with low ash content, and relatively high bulk densities are preferred (Khan *et al.*, 2017). The moisture content is an important factor in determining the quality and burning characteristics of pellets (Kitimbo *et al.*, 2014). It is required at the lowest optimum. The colour of the wood sample also influences the choice of wood. *Cetis africana* (*Ita white*) is white in colour and *Cordina milleni* (*Omo Sheda*) is a redwood sample.

The target of the pellets in this work is to serve as feedstock for a gasification operation in a downdraft gasifier to generate gaseous fuel. Three out of eight wood species of sawdust samples studied previously (under review) were selected for this work, with a conclusion that lignocelluloses wood waste materials are made up of different chemical properties even within the sample of same species is in agreement with Garcia- Maraver and Carpio, (2015). The selection favoured majorly the hardwood sawdust and the mixed sawdust. Mixed sawdust here refers to mixtures unclassified (mixed without intension), which is the most common state available on site.

MATERIALS AND METHODS

Feedstock Preparation

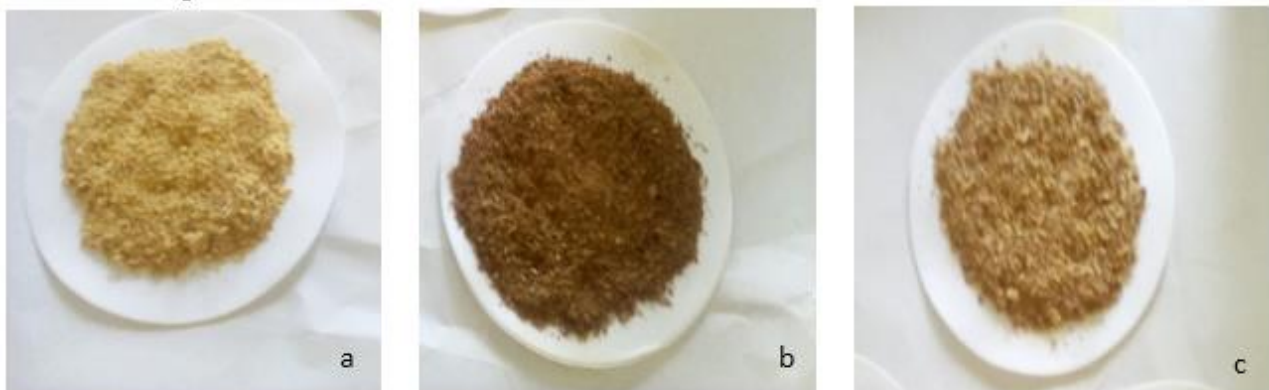


Figure 1. Images of the feedstock (a) *Cetis africana* (*Ita white*); (b) *Cordina milleni* (*Omo Sheda*); (c) Mixed sawdust. Fresh wet sawdust samples of *Cetis africana* (*Ita white*); *Cordina milleni* (*Omo Sheda*) and Mixed sawdust samples were sun-dried for three days to reduce moisture. The dried samples were sieved using an Octagonal sieve shaker using a set of 5 sieves screen. Sample retained in 600 μ m and 850 μ m were selected for pellet making and others were treated as undersize and oversize materials. These were store in an airtight ziploc bag for further analysis.

Pellet Formation

The pellets were made in an in-house constructed pelletiser designed specifically for this work. The pelletiser is a manually operated extruding press with a die of diameter 37mm and length of 103 mm, operating at an average of 177.6 rpm. The rpm was determined using a non-contact digital tachometer (Model T445019). The two-particle sizes for the three sawdust samples of known mass were mixed manually with the binder at different concentrations (20, 25, 30, 35, 40% w/w) selected for the process. The mixture is fed in and extruded through the machine and the pellets made by cold compression (Mitchal, 2014). The freshly formed cylindrical pellets were made to dry in ambient temperature uniformly and effectively for 48hrs to avoid cracks. Pellets were kept for about two to three weeks at a temperature of 27°C and a humidity of 50% (Liu et al., 2014) to achieve a stable parameter before further analysis. The optimum moisture content of the pellet made was determined and the pellets stored in a vacuum container. Pellets were randomly selected from each trial for further analysis.

PELLET CHARACTERISATION

Pellet Dimensions

The dimension, average length (L) and average diameter (D) of the randomly selected pellets were determined with three pellet sample each of the 23 selected concentration of binders by using a vernier calliper according to the work done by Liu et al., (2016). The ends of the randomly selected pellets were treated with an abrasive to give them a smooth cylindrical edge before measurements were taken. The length was taken in accordance with the Handbook of Biomass Gasification as recorded by Brandin et al., (2011) and Tumuluru (2014). The mass of each pellet was determined by weighing in a precision digital balance. This was repeated for three sawdust sample.

The Shape correlation factor given by the ratio of length to diameter (L/D) was determined according to the method described by Biswas and Umeki, 2005; Garcia- Maraver and Carpio, 2015.

Pellet Density

The unit density ($P \text{ km}^{-3}$) of the pellet was determined; this was done randomly for each concentration of binder and experiment repeated in triplicate following Tumuluru (2014).

Bulk density

Bulk density $P_b(\text{km}^{-3})$ was determined according to Liu et al., 2014.

Compressive Strength

The mechanical strength of the pellets was analyzed by conducting the compressive test for the two different particle sizes at different concentration. The randomly selected pellets from similar texture were cut to obtain a flat surface with an averagely uniform length. The die-diameter of 35mm and 98mm length was used for the test. Twenty three pellet samples were tested and the experiment was carried out in triplicates. Compressive strength of the pellets was plotted against the various concentrations for the 3 samples at selected particle sizes. The ultimate compressive strength was plotted for the best pellet strength.

Combustion Test

The combustion test of the pellets was conducted using a household eco-stove as described by Jindaporn and Charoenporn with modifications. Five (5) pellets each were arranged in the stove such that air passage is not blocked. The heat generated was used to boil two (2) litres of water. The temperature of the system was monitored with a thermocouple which was calibrated with chemicals of known melting point. The smoke emission of the pellet fuels was observed during the process. The overall efficiency of the process was reported. This was observed for the three (3) selected concentrations (20, 30, 40) for the three (3) types of pellet source. The particle size used was 600 μm retained.

$$\text{Ignition Time, } t_2 = t_1 - t_0 \quad (1)$$

$$\text{Water boiling Time} = [t_3 - t_2] \quad (2)$$

$$\text{Total Duration} = [t_4 - t_1] \text{ min} \quad (3)$$

Where t_1 = time the pellet stabilized for use (min), t_0 = time the pellet stove was lighted (min)

Where t_2 = Ignition time (min), t_3 = time the water boils (min)

Where t_4 = Pellet burn out time (min), t_1 = time the pellet stabilized for use (min).

Surface Analysis

The morphological changes during pelletizing and the effect of binder concentrations on the binding structure of the pellets were investigated using a scanning electron microscope (SEM). From the result of the compressive strength of the sample, the concentration with the best compressive strength (XA3) was studied and compared with two others – the raw sample (XA0) and the sample with the least binder concentration (XA1).

Calorific Value

The heat value for the pellets was determined using an oxygen bomb calorimeter model E2K – Bomb Calorimeter. The determination was done for the two (2) types of pellet sources and particle size $X = 600 \mu\text{m}$ retained. A= *Cetis africana* (Ita white), B= *Cordina milleni* (Omo Sheda) (XA, XA3, XA4, XA5) and (XB, XB3, XB4, XB5). The determination

was done for the raw wood waste sample and the pellets at different binder concentration. The result was compared with the computed calorific value of the raw sample.

Statistical Analysis

The statistical analyses for the results were done using statistical package for Social science IBM SPSS version 23. The results obtained from different pellet produces were compared using one-way analysis of variance (ANOVA). The means were compared using Duncan Multiple Range Test. Results were expressed as mean ± standard deviation with values of p < 0.05 considered as significant.

RESULTS

Raw Materials

Figure 1 shows the images of the raw samples of the selected lignocelluloses wood waste. Table 1 shows the physico-chemical properties of the sample.

Table 1. Property of Raw materials before Pellet Formation

Sample	Moisture (%db)	Content	Bulk Density (kg/m ³)	Ash Content (% db)	Fixed Carbon	Volatile Matter	Particle size (µm)
A	10.85± 2.24		234.00 ^f ±3.0	1.93 ^d ±0.15	9.70 ^e ±0.17	88.37 ^e ±0.06	X ≤600 Y ≤ 850
B	11.28±0.57		199.70 ^e ±1.5	1.33 ^b ±0.23	10.50 ^d ±0.30	88.17 ^d ±0.15	X ≤600 Y ≤850
C	9.97±2.24		163.70 ^d ±24.50	1.53 ^c ±0.32	9.78 ^c ±0.35	88.70 ^f ±0.10	X ≤600 Y <850

Note: A = *Cetis africana*(Ita white); B = *Cordina milleni* (Omo Sheda) ;C = Mixture

The particle size range of X ≤600 µm and Y ≤ 85 µm agreed to the recommended sizes range for quality pellets (Khan et al., 2017; Whittaker and Shield, 2017). The initial moisture content (MC) of the samples (sample A has MC as 10.85± 2.24, B as 11.28 ± 0.57 and C as 9.97± 2.24). This was determined prior to pelletizing the operation to get the optimal moisture content range of 10% - 15% for pellet making (Ajobo, 2014; Lu et al., 2014; Ungureanu et al., 2018). This is vital in ensuring pellet quality (Arzola et al., 2012; Kitimbo et al., 2014; Whittaker and Shield, 2017; Harun et al., 2018). The optimal moisture content needed to be determined and maintained because above this optimal, combustion heat will be partially lost in evaporating water from pellet in the combustion chamber and the shelf life of the pellets will be hindered with a high rate of degradation as was observed (Fig 2) and below its reaction between the particles will be hindered.

Pellet Properties

Figure 3 and 4 show various pellets produced at different binder concentration and at different particle sizes. Table 2 shows the mean value of the properties of the pellets.



Figure 3: Pellets from different Species at 600 µm and properly dried



Figure 4: Pellets from a Specie at 850 µm particle size with degradation as a result of moisture not drying effectively to the desired optimal.

Table2. Pellet Properties

Pellet Property	Length (mm)					
	Binder Conc (% w/w)	20	25	30	35	40
AX		98.17± 0.76a	98.17±0.76a	96.00±1.32 ^a	97.70± 1.93 ^a	97.33± 3.21 ^a
AY		98.10±0.96 ^{ab}	95.83±3.33 ^{ab}	95.67± 1.15 ^b	99.57± 0.93 ^a	98.37± 2.12 ^a
BX		95.50± 0.87 ^a	95.33± 1.53 ^a	95.63 ± 0.32 ^a	97.17 ± 1.04 ^a	95.80±0.75 ^a
BY		96.50±1.00 ^{bc}	95.33± 2.02 ^c	100.17 ± 0.76 ^a	95.17±1.04 ^c	98.00± 0.50 ^b
CX		-	-	98.33 ± 1.04 ^b	96.93± 1.75 ^b	101.17 ± 2.75 ^a

Pellet Property	Diameter (mm)					
	Binder Conc (% w/w)	20	25	30	35	40
AX		36.17± 0.29 ^a	34.93 ± 0.12 ^b	33.67 ± 0.58 ^c	35.17 ± 0.29 ^b	36.07 ± 0.12 ^b
AY		36.17 ± 0.58 ^a	35.47± 0.55 ^a	36.67 ± 0.29 ^a	35.70±0.72 ^a	34.87 ± 0.32 ^a
BX		35.17± 0.29 ^a	35.00± 0.50 ^{ab}	34.50± 0.87 ^{ab}	34.83± 0.29 ^{ab}	33.90± 0.66 ^b
BY		34.97± 0.58 ^a	34.60± 0.70 ^a	34.33± 0.29 ^a	34.03±1.36 ^a	35.00±0.00 ^a
CX		-	-	36.17± 0.29 ^b	37.00 ± 0.87 ^a	34.67± 0.29 ^c

Pellet Property	Shape factor L/D					
	Binder Conc (% w/w)	20	25	30	35	40
AX		2.71± 0.36 ^b	2.81± 0.17 ^{ab}	2.85 ± 0.87 ^a	2.78 ± 0.50 ^{ab}	2.75 ± 0.99 ^{ab}
AY		2.75 ± 0.35 ^a	2.70± 0.11 ^a	2.64± 0.05 ^b	2.79 ± 0.06 ^a	2.82 ± 0.04 ^a
BX		2.71 ± 0.05 ^b	2.72 ± 0.06 ^{ab}	2.77 ± 0.07 ^{ab}	2.79 ± 0.01 ^{ab}	2.83 ± 0.55 ^a
BY		2.76 ± 0.03 ^a	2.75± 0.03 ^a	2.80 ± 0.09 ^a	2.80 ± 0.08 ^a	2.80± 0.01 ^a
CX		-	-	2.72 ± 0.04 ^b	2.62± 0.09 ^b	2.94 ± 0.11 ^a

Pellet Property	Mass (g)					
	Binder Conc (% w/w)	20	25	30	35	40
AX		48.99 ± 1.60 ^c	49.76 ± 0.15 ^c	55.30 ± 0.54 ^b	57.68 ± 0.71 ^b	64.28±2.32 ^a
AY		44.47 ± 0.74 ^{ab}	47.78± 1.8 ^b	55.29 ± 1.15 ^{ab}	59.85 ± 1.09 ^{ab}	62.49 ± 1.61 ^a
BX		43.86 ± 0.23 ^c	49.68 ± 1.44 ^d	51.80 ± 0.13 ^c	53.87 ± 0.21 ^b	59.87± 0.9 ^a

BY	43.38± 0.61 ^c	44.90± 2.81 ^c	55.29± 1.15 ^b	58.19 ± 3.69 ^b	62.49± 1.61 ^a
CX	-	-	46.72± 1.39 ^b	52.00 ± 0.86 ^a	53.87± 2.05 ^a

Pellet Property Binder Conc (%w/w)	Density (kg/m ³)				
	20	25	30	35	40
AX	486.17± 21.80 ^c	528.83± 8.67 ^c	647.27± 17.02 ^a	608.03± 16.57 ^b	684.57± 42.34 ^a
AY	441.50 ± 17.43 ^{ab}	504.97 ± 20.92 ^{ab}	547.67 ± 26.08 ^{ab}	601.23± 33.77 ^{ab}	665.33± 11.93 ^a
BX	472.87 ± 4.80 ^c	542.03 ± 28.05 ^b	579.93 ± 26.11 ^b	581.93 ± 17.55 ^b	692.80 ± 27.52 ^a
BY	468.00± 3.50 ^c	502.80 ± 61.61 ^{bc}	596.23± 16.21 ^{ab}	676.87 ± 101.3 ^a	662.73 ± 19.78 ^a
CX	-	-	462.50 ± 15.74 ^c	499.53± 28.99 ^b	564.60 ± 33.97 ^a

Values are mean ± SD of 3 determinants. Values with different superscript across the row indicate significant difference (p< 0.05) Where: *Cetis africana (Ita white)*; *B = Cordina milleni (Omo Sheda)*; *C = Mixture*. Particle Size X =600 µm; Y =850µm

The length in Table 2a varied between 95.17 and 101.17 mm. This length values are larger than the regular commercial pellets (11-17) and diameter (8-10 mm) (Tumuluru, 2014; Biswa and Umeki., 2015). In this work, the in-house pelletiser has a die diameter of 37mm and length of 103, and in turn a shape factor (length to diameter ratio) of about 2.78. This will help increase the pressure needed for the pelletizing process. The pellets showed an increase in length as concentration increased and since the pelletiser has no cutter attached to it thus the length of the pellets formed varied slightly (Stahl et al., 2012). This affected the production rate and the number of pellets in each batch. These process variable was designed to give a small die diameter and a high die length/diameter ratio, that in turn produce pellets with high compressive strength and quality as was observed. This agreed with the recommendations of Tumuluru et al., 2011, Malik et al., 2015 and Whittaker & Shield, 2017).

The pellet produced in this work has a length (L) and diameter (D) ratio ≤ 4 (L/D ≤ 4). The diameter ranged between 33.67mm – 37.00mm. The mass of the pellets ranged between 43.38 – 64.28 kg. The shape correlation factor which is the ratio of length to the diameter of pellets ranged between 2.6 – 2.94. The ratio is a good metric for the degree of compression experienced by the raw material during pelletizing. Pellet dimension (diameter, length, and or diameter/length ratio) will help determine the pressure required for the process (Garcia-Maraver and Carpio, 2015). The L/D ratio influences the unit density of the pellets as reported by Biswas and Umeki (2015).

Density

The unit density of the pellets varies between 441 and 692 kgm⁻³. Both unit and bulk density is greatly influenced by the raw material moisture content and its particle size in addition to the concentration of the binder. As can be seen in the table, with a high L/D ratio above 2.50, the density of unit pellets were relatively high above 500 kgm⁻³ except for AX1, AY1, BX1, and BY1 with binder concentration 20%w/v. This confirms the influence of binder concentration on the density of pellets formed. For both samples A and B, density increased as binder concentration increased. Particle size X, 600 µm had the highest density when compared with Y, 850 µm, for both samples AX5 (684.51 ± 42.34kg/m³) > AY5 (665.33 ± 11.93kg/m³), BX5 (692.80 ± 17.55 kg/m³) > BY5 (662.73 ± 19.78 kg/m³). This implies that pellet density decreases as particle size increases. Higher density represents high energy per unit volume of material. (Mirande et al, 2015; Adapa et al., 2015). The bulk density is lower than expected because of the peculiarity of the pellet dimension which is a little bigger than a regular pellet but less than a briquette (Tumuluru; 2014). The density of the pellets also increased with an increase in the amount of binder used. This increase is independent of the variety of binder used as was reported by Stahl et al., 2012 as they compared various varieties of starch.

Compressive Strength

This provides a quick measure of the quality of pellets. It is the impact resistance that shows the maximum crushing load a pellet can withstand before cracking or breaking (Garcia – Maraver and Carpio, 2015). It determines the stability and durability of densified materials and is largely affected by the particle size of the feedstock (Onukak et al 2017). The plot of compressive strength against binder concentration showed that for all samples, particle size X=600 µm retained gave higher strength when compared with Y=850 µm (Fig 5).

Binder concentration 30% w/v from the graph gave the highest strength and it showed that further binder addition tends to a negative or a waste of material. It was observed that the binder concentration of less than 20% had very low mechanical strength was not reported. The Ultimate comprehensive of the samples at 30% w/v was plotted which showed that sample B *Cordina milleni* (Omo Sheda) had the best strength (Fig 6).

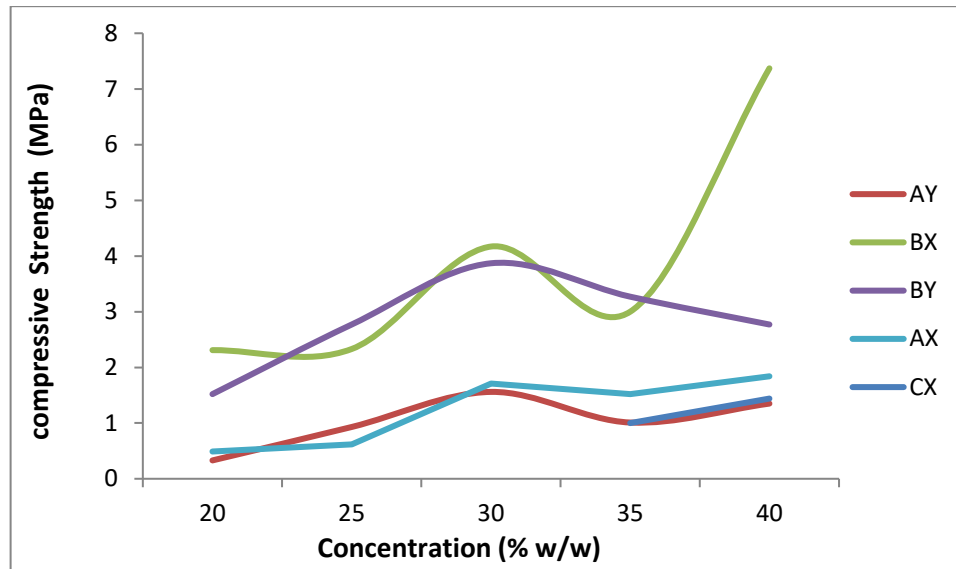


Figure 5. Compressive Strength of the samples at different concentrations

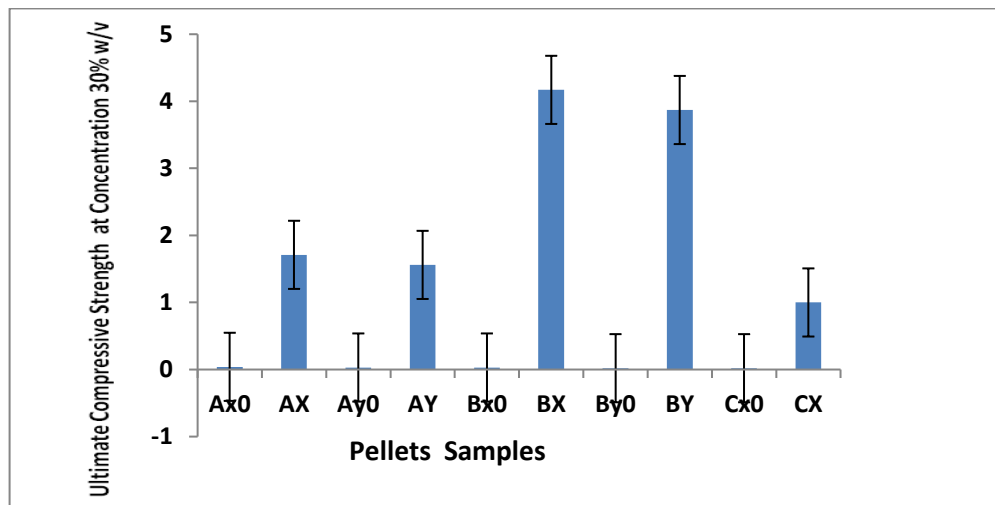


Figure 6: Ultimate Compressive Strength at the Concentration of 30% w/v.

Combustion Test

It was observed that each of the five (5) pellets used weighed differently depending on the concentration of the binder and wood type as recorded in table 5a and 5b, the weight ranged between 0.28 kg – 0.40 kg. The flame temperature gradually increased from ambient temperature and starts decreasing as the water boils. The maximum flame temperature has its range between 601°C – 306°C. The ignition time was the same as all wood samples. Pellet with binder concentration 40% w/v having higher density had longer burnout time for all three samples [Acda and Devera, 2014] with sample B (*Cordina milleni*) having the longest burnout time and duration but gave the highest smoke emission compared to the other samples. Pellets with a lower concentration of binder (20%w/v) burns off faster and have a shorter duration for burning (Onukak et al., 2017). It was observed that sample C (mixed sawdust) required more pellets to sustain the flame having the shortest duration and burnout time (Liu et al., 2014).

The efficiency of combustion of densified materials such as pellets and briquettes depends on the moisture content, the chemical composition which is a function of the biomass type, and the density of the material (Aashosh and Summet, 2014). Particle size 600 μm was selected for the test because it had a higher density. The calibration of the

thermocouple as recorded in Table 3 showed the melting point of known chemicals in agreement with the thermocouple reading.

Table 3: The calibration test for the thermocouple

Standard Chemicals	Melting point (°C)	Type k Thermocouple (°C)	Observations
Environment	28	28	Warm Day
Benzoic Acid	128	128	White powder turned clear
Solder (alloy of Pb & Sn)	430	423	Melted
Zinc granules	500	500	Melted into ashes
Melting Point glass	560-570	560	Bent
Magnesium ribbon	651	648	Deflagrated with a blinding

Table 4. Combustion Test *Cetis Africana* (Ita white)

Pellet Sample								<i>A =Cetis Africana (Ita white)</i>	
Binder Conc (% w/w)	No of Pellets	Volume of water (l)	Ignition Time $t_2=[t_1-t_0]$ (min)	Boiling Time $[t_3-t_2]$ (min)	Total Duration $[t_4-t_1]$ (min)	Smoke Emission	Boiling Temperature (°C)		
20	5	2	6	12	37	Low	97		
30	5	2	6	11	40	Low	97		
40	5	2	7	9	47	Very low	97		

Particle Size X =600 μm; Ambient Temperature = 27 °C

Table 5.Combustion Test *Cordina milleni* (Omo Sheda)

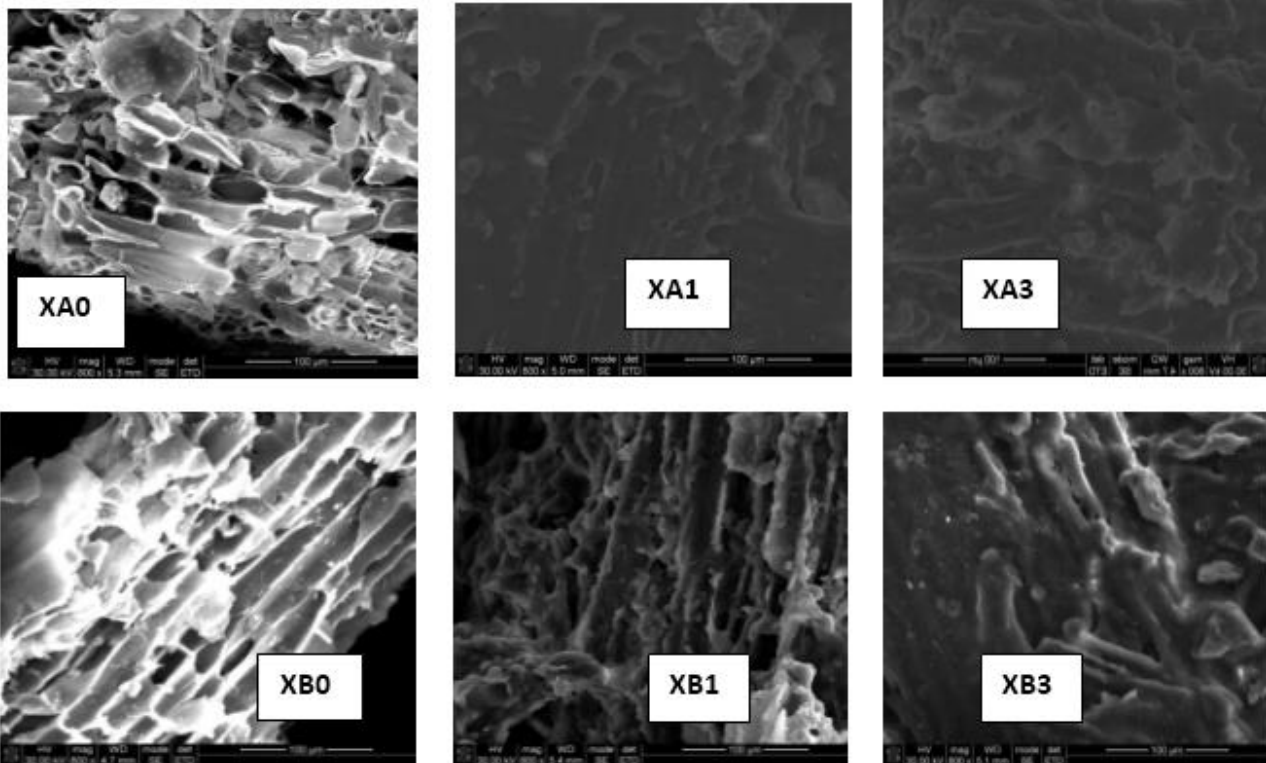
Pellet Sample								<i>B =Cordina Milleni (Omo Sheda)</i>	
Binder Conc (% w/w)	No of Pellets	Volume of water (l)	Ignition Time $t_2=[t_1-t_0]$ (min)	Boiling Time $[t_3-t_2]$ (min)	Total Duration $[t_4-t_1]$ (min)	Smoke Emission	Boiling Temperature (°C)		
20	5	2	6	16	39	Very high	97		
30	5	2	6	14	44	High	97		
40	5	2	6	13	49	Moderately high	97		

Particle Size X =600 μm; Ambient Temperature = 27 °C

Surface Analysis

It was observed that the raw sample had more pores when compared with XA1 and XA3. XA3 showed more binder cementing when compare to the others XA3 > XA1 > XA0. This was also observed for the other samples B and C such that XB3 > XB1 > XB0. Comparing the particle sizes Y (850 μm retained) and X (600 μm retained) for samples A and B. It was observed that X (600 μm retained) had more cementing and better binding than Y (850 μm retained).

This confirms that binders help to cement particles of the feed materials used for pellets formation in agreement with Qiang et al., 2015. This effect is increased when particle size is reduced and as binder concentration is increased and in turn, the compressive strength is increased. The result also confirms that the pellets formed had a good mechanical property that reduces the risk of breakage during handling, transportation, and storage. These pellets will be efficient for use in pellet stoves and have the good potential not to disintegrate and cause system blockage when used in high-temperature furnaces such as a gasifier.



Calorific Value

The energy value of the raw wood waste and pelletized wood waste made at different binder concentration as determined using a bomb calorimeter and result presented in Table 5 showed that binder concentration does not really have significant effect on the calorific value of the pellets owing to the overall low percentage content of the binder to the water and the sample (Kuokkanen *et al.*, 2011). Pelletisation affects moisture content but not the energy density on a dry basis. It does not affect the energy content. So, the mass-energy density of pelletized wood is the same as the feed wood as-received but the volume energy density is not the same (Basu, 2013).

Table5: Calorific Value of Raw and Pelletized wood waste

Binder Conc (% w/w)	Sample Code Particle size X =600 μm	A = <i>Cetis Africana</i> Calorific Value (MJ/Kg)	B = <i>Cordina Milleni</i> Calorific Value (MJ/Kg)
0	XA , XB (Raw)	17.227	17.202
0	Calculated (Raw sawdust)	15.700	16.960
30	XB3 , XA3	16.106	17.251
35	XA4 , XB4	16.277	16.232
40	XA5 , XB5	16.357	16.554

Effect of Biomass Type on Quality of Pellets.

For the samples selected for work, the major constituents are as shown in Table 6.

Table 6: Chemical composition of the pellets

Samples	Cellulose	Hemicelluloses	Lignin
A	36.80±3.76	31.00±1.41	22.00±2.63
B	35.95±0.26	32.00±2.83	18.54±2.35
C	37.94±3.73	28.50±2.12	25.13±2.42

Adapa *et al.*, 2013 pointed out that biomass type is the most significant factor that affects the quality of pellets. Moisture plays a major role in determining pellet property (Onukak *et al.*, 2017; Garcia Maraver A and Carpio M., 2015). High moisture content reduces the binding strength as well as the density. This was observed as sample A with MC% of 10.85 ± 2.24 had higher density when compared with sample B with MC% of 11.28 ± 0.57 . Sample B is also a dark wood, it produced more emission and odour during the combustion test. The wood with more odour, has more volatile

compound present. The darker or richer the colour of wood, the more extractives present in the wood (Reeb and Milota, 1997). Colour of wood sample helps us to give an estimation of the properties and quality of pellet fuels such as the heating value (Lam and Sokhansanj, 2014)

Sample C which is the mixed sawdust gave varying results. It requires more pellets to burn and it has a short burn out time. (Liu *et al.*, 2014). This confirms that pellets should be made from single wood species per time or mixed on purpose after carefully understanding the characteristics of the individual raw material. This agreed with the report of Link and his team in 2013 that the interaction between the chemical properties of different biomass fuel gives problematic results even to the end product and use of the pellets except there is sufficient investigation of the individual samples before the combination (intentional mixing).

Effect of Particle size on quality of Pellets

As was observed, drying and sieving were the only pretreatments done on the sample of sawdust selected for this work since the extent of grinding depends on the feedstock (Whittaker and Shield, 2017). The selected particle size as seen in the table ($x \leq 600 \mu\text{m}$) and ($y \leq 850 \mu\text{m}$) was the recommended particle size for a good densification process (Khan *et al.*, 2017; Onukak *et al.*, 2017). Arzola *et al.*, 2012 concluded that particle size had a greater influence on pellet quality than binding agent content or concentration. The results presented showed that particle size $X = 600 \mu\text{m}$ retained had higher density, higher compressive strength for the three (3) sawdust samples (AX, BX, and CX), when compared to $Y = 850 \mu\text{m}$, retained (AY, BY, and CY). Particle size has a strong influence on the pellet density of both wood and non-wood biomass (Harun *et al.*, 2008; Miranda *et al.*, 2015).

Results for CY (mixed samples with $850 \mu\text{m}$ particle size) were not reported because the pellets were coarse and had cracks and fractures. This confirms that large particle size causes cracks and fracture on pellets as well as low fusion point as reported by (Onukak *et al.*, 2017; Malik *et al.*, 2015). This is worse especially when proper cooling is not achieved as was observed. There will be stresses appearing between the inner (warm or wet) and the outer (cold/dry) part of the pellets. (Malik *et al.*, 2015; Whittaker and Shield, 2017). All this invariably affects the mechanical strength and ultimately the quality of the pellets formed.

With finer the particle size, the compaction process is made easier, and the larger the surface area for bonding. (Onukak *et al.*, 2017; Whittaker and Shield, 2017). This confirms the need for pre-treatment such as drying, grinding, and/or sifting before pelletizing operation for high-quality pellets (Miranda *et al.*, 2015, Adapa *et al.*, 2013; Katimbo *et al.*, 2014; Malik *et al.*, 2015). The combustion property of particle size of $850 \mu\text{m}$ was not considered. The denser particles were observed to be the $600 \mu\text{m}$ and they also had longer burn out time.

CONCLUSION

Biomass waste conversion to pellet fuel is an innovative project. It was concluded that the higher the concentration of the binder, the cementing of the sawdust particles and the higher the density of the pellets but the compressive strength showed that there is an optimal point where an increase in concentration does not amount to strength but waste of resources as can be seen from the graph of compressive strength against concentration, 30% w/v gave the highest strength and energy at break for samples, A and B but C energy was not highest at 30%.

For both types, density increased as the binder concentration increased with sample A particle size $600 \mu\text{m}$ (AX5 = 40% w/v) and BX5 having 684.5 and 692.80 kg/m³ respectively as the highest densities though it may not be the strongest compacted as shown by the compression strength. Also for both sample type A & B, particle size (X) $600 \mu\text{m}$ retained had the highest density when compared with (Y) $850 \mu\text{m}$ retained. This also affects the combustion properties of the pellets.

From the ultimate compressive strength sample B *Cordia milleni* (Omo Sheda) had the highest strength but considering the result during combustion test and having the issue of environmental friendliness as part of the central reason for this research, Sample A will be preferred to B. Sample A which is *Cetis africana* (Ita white) at the optimal concentration of 30% and the best particle size of $600 \mu\text{m}$ retained gave the best shape factor of 2.80, and the highest density of 647 kg/m³ having less smoke when compared with Sample B *Cordia milleni* (Omo Sheda). Sample C which is the mixed wood gave results that did not agree with the other individual and this cannot be depended upon. This helps to conclude that to get a good result and high energy for pellets and other densified materials saw millers must be advised to separate their waste.

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