Densification of Tropical Wood Residues for the Development of Solid Fuels

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Abstract
Densification of materials through pelletisation, briquetting and cubing to form strong and durable bonding products with greater structural homogeneity, better handling and durability properties has attracted the attention of researchers in recent past. The present work focused on conversion of residues of some tropical wood species to energy fuel through pelletisation. The woody-biomass species studied were *Apa (Afzelia Africana, AA), Iya (Daniella oliveri, DO)* and *Arira (Detarium microcarpum, DM)* which were sourced in Nigeria. The samples were prepared in different sizes of less than 0.50 mm, 0.50 - 1.00 mm and 1.00 - 1.70 mm after drying in a laboratory environment. The different particle sizes were forced into a prepared die using gelatinised starch as binder. Higher heating value (HHV), impact resistance index (*IRI*) and water resistance test were obtained for all samples with and without binder. The average HHV of pellets produced from *DM* was found to be 26.53 MJ/kg without binder, which is the highest among the three samples, showing that DM may have higher lignin content. However, pellet samples AA produced with binder has average HHV of 25.41 MJ/kg which is highest among the three samples. Result showed that *IRI* increases as particle size decreases for pellets produced without binder, while for pellet with binder, *IRI* increases as the particle size increases. Result of water resistance test showed that the disintegration time increases as particle size decreases. The basic physical properties that enhance handling and transportation operations of wood pellets have been achieved when compared with standard.

Keywords: Densification, Biomass, Residues, Higher heating value, Impact resistance index

1. INTRODUCTION

The desire to increasingly provide sustainable and renewable energy fuels has continued to gain global concerns and renewed interests due to the yearning for reduced fossil fuel utilisation. Among the renewable energy sources, biomass is a promising alternative, which has been playing a major role in affordable and sustainable energy supply since the beginning of civilization (Medic, Darr, Shah, Potter, & Zimmerman, 2012; Wei-Hsin & Kuo, 2010). In recent times, biomass is becoming one of the widely utilised renewable energy sources, second only to hydropower in electricity generation (Ajimotokan, 2014; Jiang et al., 2016). It is such a broadly exploited energy source, perhaps as a result of its cost effectiveness and indigenous nature, which makes it account for nearly 15% of the total energy supply in the world and as much as 35% in developing countries, used customarily for cooking and heating (Tokan, Sambo, Jatau, & Kyauta, 2014).

Woody biomass residue as a source of energy fuel has continued to gain significant interest and attention, because of its renewability, greenish and global availability (Soponpongpipat & Sae-Ueng, 2015). However, some inherent properties of woody biomass residues make them not readily available as an excellent source of energy fuel. These characteristics need to be improved upon to enhance the combustion, transportation and handling properties of the woody biomass, especially as an alternative source of fuel through densification (Balogun, Lasode, & McDonald, 2018). Densification through pelletisation process is one of few methods used to enhance the aforementioned properties of biomass, which also reduces the microbial activities causing its incessant decay (Chew & Doshi, 2011). The end product of the pelletisation process of woody biomass residue is known as bio-pellets. The wood pellets have been considered as a high quality biomass feedstock, which is suitable for many industrial and residential applications, through processes like combustion, pyrolysis and gasification (Lasode, Balogun, & Aremu, 2011; Li et al., 2012).

Pelletisation is a process of increasing the bulk density of materials by application of mechanical force through a prepared die and roller like piston (Stelte et al., 2011a). It is a mass and energy densification of materials that possess low bulk densities such as sawdust, straw and other herbaceous energy crops (Mania, Tabilb, & Sokhansanj, 2006; Yang, Sarkar, Kumar, Tumuluru, & Raymond L. Huhnke, 2014). This densification process has proven to significantly reduce the cost of handling, transportation and storage facilities (Stelte et al., 2011a). Wood products, by-products, plant and crop residues generally possess low densities due to their porous inter-particles structure. Their densities range from 40 - 150 kg/m^3 for grass type biomass, and 320 - 720 kg/m^3 for most types of dried hard and softwoods (Stelte et al., 2011b). The typical bulk density of biomass chips is less than 150 kg/m^3 while those of wood pellets is typically over 600 kg/m^3 (Gilbert, Ryu, Sharifi, & Swithenbank, 2009). Generally, pellets have bulk densities that are significantly greater than the parental wood species, which typical unit densities can be as much as 1,000 - 1,400 kg/m^3 (Stelte et al., 2011b) , and bulk densities of about 700 kg/m^3 (Mania et al., 2006).

The application of densified biomass wastes in place of fossil fuels would result in low emissions of greenhouse and acid gases. In order to make the biomass wastes available for a variety of applications in residential and industrial applications, the challenges with the use of the residues in their original form must be resolved (Chew

& Doshi, 2011). For instance, high moisture content, irregular shape and sizes, and low bulk density have tremendously limited the use of raw woody biomass residues in co-combustion in industrial boiler with coal for production of steam, direct combustion for the provision of heat energy, and in thermal gasification plant (Mania et al., 2006; Yang et al., 2014)**.**

In this study, the utilisation of woody biomass residues in form of tropical wood wastes in different particles sizes, moisture content and bonding mechanisms are examined. The overall goal is to provide an insight into the conversion of tropical wood residues to energy fuel through densification technology, and to optimise the process condition under varying pelletising process conditions.

2. MATERIALS AND METHODS

2.1 Material preparation and characterisation

The tropical wood species used in this study and their respective growth location are *Apa (Afzelia africana) (AA):* 8.19153 ^{o}N 5.21541 ^{o}E *, Iya (Daniella oliveri) (DO):* 8.19102 ^{o}N 5.21515 ^{o}E and *Arira (Detarium microcarpum) (DM):* 8.19089 ^{o}N 5.21507 ^{o}E sourced at altitude 466 m, 460 m and 448 m respectively. The residues of the woody biomass were collected during milling operations and characterised under different particle sizes of less than 0.50 mm, 0.50 - 1.00 mm and 1.00 - 1.70 mm. These materials were stored under atmospheric conditions for about three months in the Faculty of Engineering and Technology wood work Laboratory, University of Ilorin, Ilorin, Nigeria before the experiment.

2.2 Procedure for development of pellet rigs

A closed-end die was designed in cylindrical shape of internal diameter of 10 mm and 40 mm height, a piston of 75 mm in length for ramming the pellets. It is fabricated with mild steel and side hole to accommodate thermocouple probe for measuring the pellet temperature generated as a result of frictional force between die wall and pellet material. Universal testing machine was used to develop the required force to generate the pellet. The pellet was built in sequential layers and a limit speed rate was set on the universal testing machine and the pressure for compressing each sample, which is recorded when the piston reaches this limit. A thermocouple was connected to the die to determine the temperature at which pellets were produced.

2.3 Pellet produced without binder

Pellets were produced without binder to serve as control pellet model. The lignin content present in the samples was heated up due to friction generated during pelletisation between the die wall and the biomass material which acts as binder for the pellets. Approximately, 0.8 g of biomass was weighed on an AQM series OIML-R76 digital weighing balance and fed into the die for each run to produce a single pellet of 10 mm average height, closed with backstop plate at the other end. These samples were prepared in triplicate for each pellet sample at a particular particle size.

2.4 Pellet produced with binder

The gelatinised starch obtained from cassava tuber was used as the binder. Approximately, 0.5 g (62.5%) of biomass and 0.3 g (37.5%) of gelatinised starch was weighed on a digital weighing balance and fed into the die for each run to produce a

single pellet of 10 mm average height, closed with backstop plate at the other end. Each particle size was prepared in triplicate for adequate analysis.

2.5 Determination of moisture contents

Moisture content was determined using Radwag USA L.L.C. PMX 50/1 moisture analyser with 5 g of each sample placed on a tarred sample dish and the lid is closed to start the drying process. The moisture analyser determines the accurate and precise moisture contents of samples, which operates on loss of weight on drying according to ASTM D4442-16 (2003). Afterwards, the sample is weighted, heated to evaporate all moisture and when the process is completed, the moisture content of the original sample is calculated based on the weight lost, using halogen, infrared or glass, free metal heaters positioned above a precision balance.

2.6 Determination of calorific value of samples

The P.A. Hilton C200 bomb calorimeter (S/N. C200/00534, Hampshire, SO20 6PX, England) was used to determine the gross calorific value tests using method recommended by ASTM E870-82 (Akhator, Obanor, & Ugege, 2017). 0.8 g of pellet sample was place in a nickel crucible attached to a thread and burned in the bomb calorimeter, which was filled with 2 litres of water. The attached thread was ignited to combust the sample in the presence of oxygen gas, which gives a rise in temperature to the surrounding water and the rise in temperature is measured by the temperature sensor. The difference between the maximum and minimum temperatures obtained was used to compute the gross calorific values of the biomass materials as follows;

$$Q = \frac{(\varepsilon \times \theta) - Q_{fuse} - Q_{ign}}{M_f} \qquad (1)$$

where Q is the calorific value of sample (MJ/kg), M_f is the mass of fuel sample (kg), Q_{fuse} is the heat contribution from the cotton threads (MJ), Q_{ign} is the heat contribution from the nichrome ignition wire (MJ), θ is the corrected temperature rise of the calorimeter vessel (K) and ε is the effective heat equivalent of the calorimeter (MJ/K).

2.7 Determination of impact resistance index

The impact resistance test was carried out using ASTM D 440-86 to investigate the strength and hardness of the briquettes by shattering the prepared pellet (Ø10 mm by 10 mm height) at a distance of 1 m above the ground level against a concrete surface. The was done repeatedly, and the impact resistance index was then calculated in accordance to Richards (Richards, 1990):

$$IRI = \frac{(100 \times N)}{n} \qquad (2)$$

where N is the number of drops, and n is the total number of pieces after N drops as illustrated in the work of Kaliyan and Morey (2009).

2.8 Water resistance test

Water resistance test was conducted to determine the rate of water absorptivity resistance of the pellet samples, before the disintegration. Thirty-five centilitres (35 *cl*) of water at 15 ^{o}C was poured into a jar, while each pellet was placed in the water and a stopwatch was used to count the time of complete disintegration of pellet sample in the water. The longer the disintegration time of pellet, the better the quality of the pellet (Jandacka, Nosek, & Holubcik, 2011).

3. RESULTS AND DISCUSSION

3.1 Moisture content and heating value

The moisture content of sample DM is the highest as 10.6%, follow by sample AA as 10.55% while sample DO as 10.37% which are in accordance with the work of Li and Liu for quality pellets production. They showed in their work that the production of high quality pellet was a function of moisture content of the wood sawdust which were found to be in the range of 6 - 12% (Y. Li & Liu, 2000). Figure 1 shows the variation of calorific values of different woody biomass residues of African origin. It shows that *Arira (Detarium microcarpum) (DM)* without binder has highest calorific value of 26.53 MJ/kg among all the three samples. Sample *Apa (Afzelia africana) (AA)* without binder has lowest energy value of 17.14 MJ/kg, which shows that the composition of lignin content in its lignocellulosic morphology is very low since lignin has a low degree of oxidation and a considerably high combustion heat as illustrated in the work of Garcia-Maraver, Rodriguez, Serrano-Bernardo, Diaz, & Zamorano (2015). However, sample *AA* with binder has 25.41 MJ/kg and sample *Iya (Daniella oliveri) (DO*) with binder has 20.36 MJ/kg, depicting a common trend that these samples *AA* and *DO* have higher calorific values than those samples without binder. Sample *DM* with binder has the lowest calorific value of 17.56 MJ/kg among all sampled pellets, depicting that addition of external binder weakens the lignin content, thus slackening its composition.

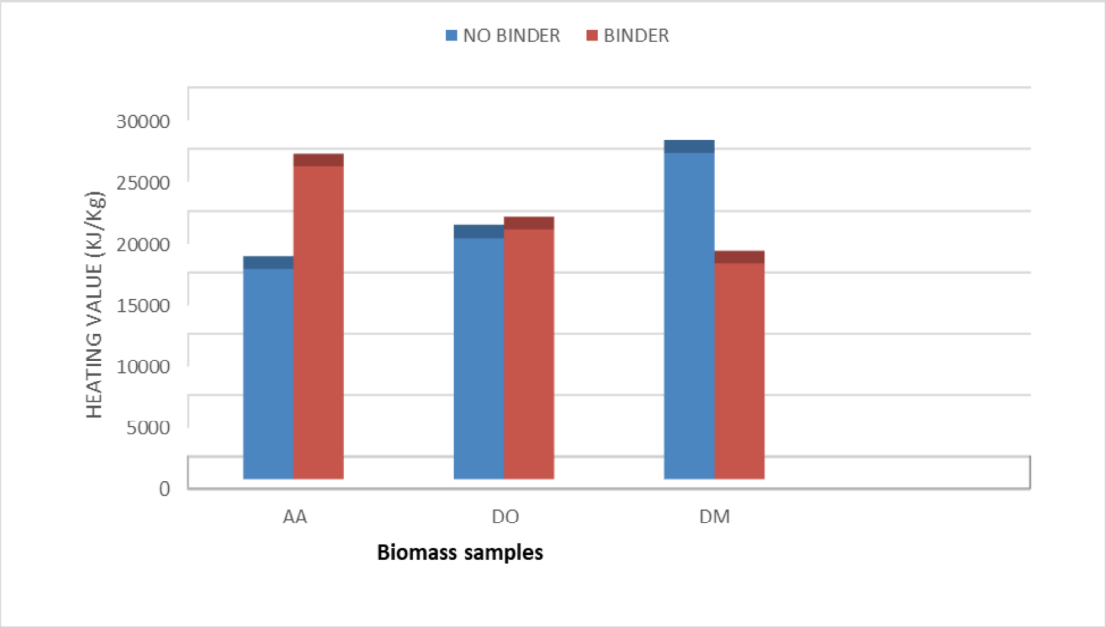

Figure 1: Calorific values of different pellets samples produced with binder and without binder

3.2 Impact resistance index

Figure 2 shows impact resistance index (IRI) for pellet produced without a binder. It indicates that the IRI increases as the particle size decrease, showing that the pellets produced from residues of less than 0.50 mm have better impact resistance property regardless of the species of the wood samples prepared without binder. Figure 3 shows impact resistance index for pellet produced with binder. Figure 3 reveals that the IRI increases as the particle size increases. It is observed that the binder has better

adhesive property on the larger particle size than the smaller particle size. Generally, sample *DO* has the highest IRI without binder at less than 0.50 mm particle size as 200 IRI and with binder at 1.00 - 1.70 mm particle size of also at 200 IRI. The higher the value of IRI the better the hardness and shear resistance of the pellets (Li & Liu, 2000; Rajaseenivasan, Srinivasan, Qadir, & Srithar, 2016).

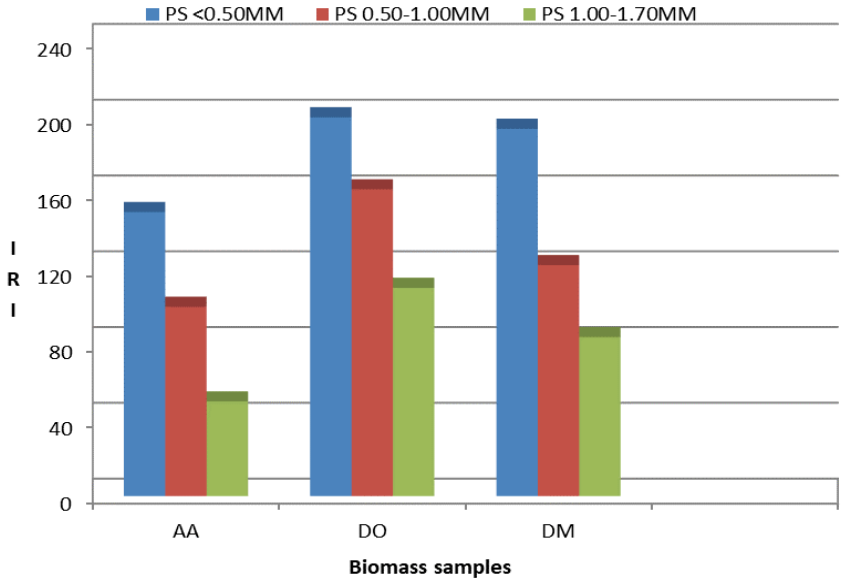

Figure 2: Impact resistance index (IRI) for pellet samples produced without a binder

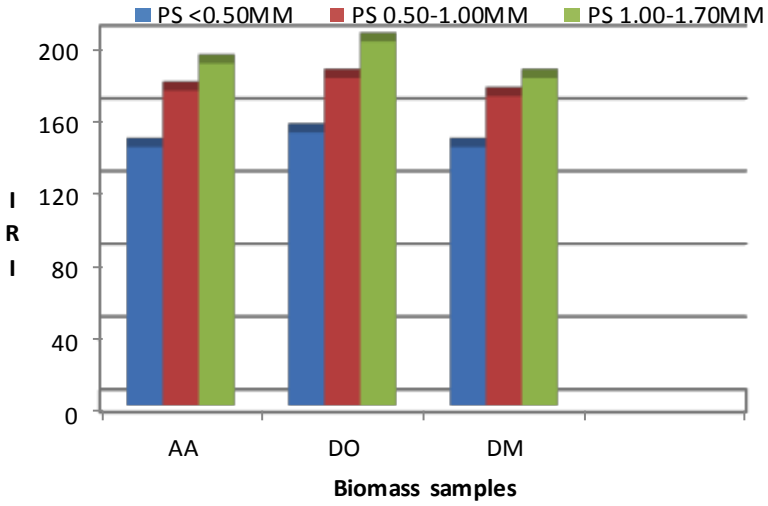

Figure 3: Impact resistance index (IRI) for pellet samples produced with a binder

3.3 Water resistance test

Figures 4 and 5 show the hydrophobicity test of different pellet samples for various particle sizes produced without binder and with binder respectively. Figures 4 and 5 show that the pellet samples with the smallest particle size have the highest disintegration time when dropped into the water. Sample *AA* tends to remain under water longer than samples *DO* and *DM*. However, samples produced with binder seemed to be more hydrophobic than the samples without binder. This can be attributed to the adhesive property induced by the presence of the binder in the crystal of the samples particles which makes it less porosity for penetration of the water

molecules into the pellet particles, thus enhancing the durability and strength of the pellets (Birwatkar, Khandetod, Mohod, & Dhande, 2014).

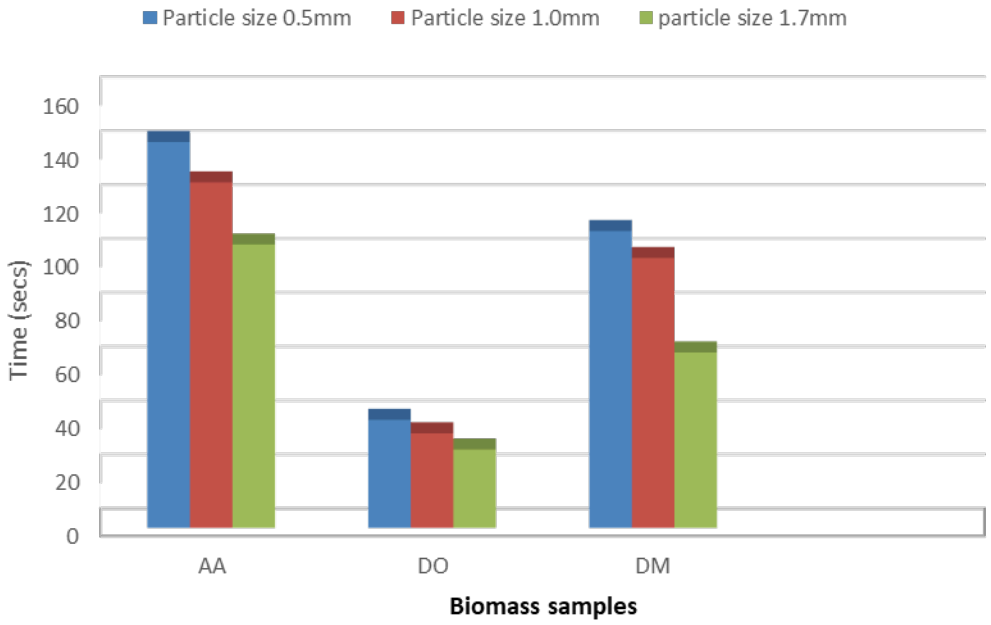

Figure 4: Water resistance test on pellet samples of different particle sizes produced without binder

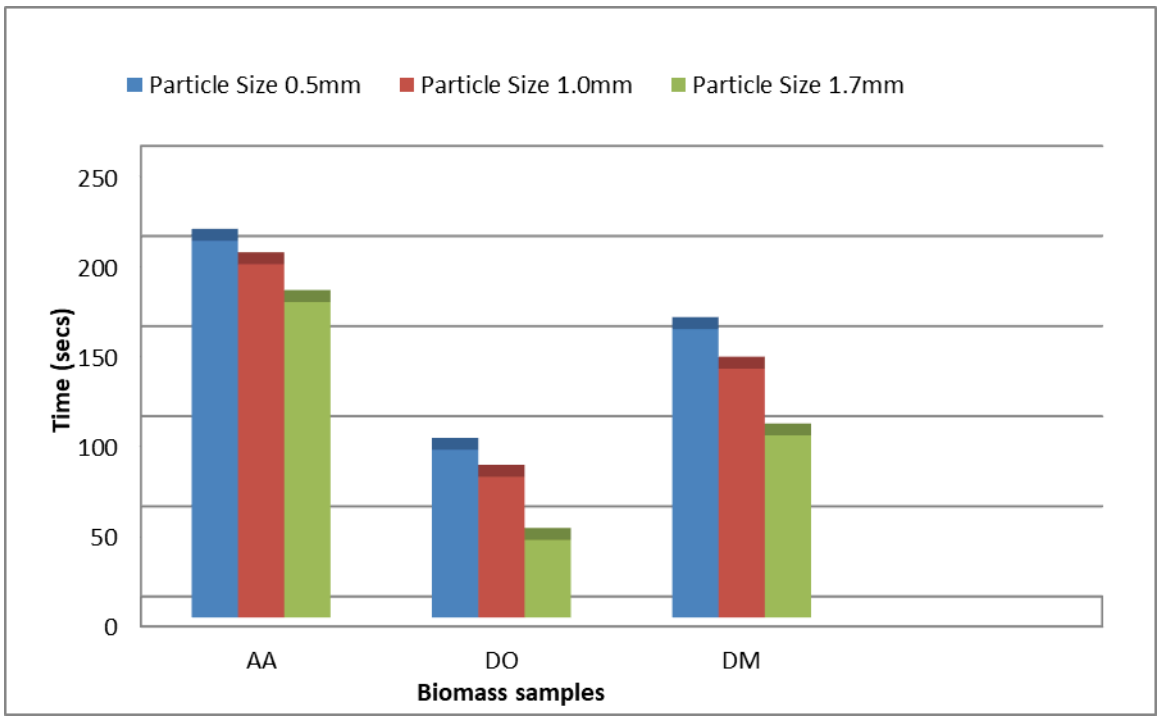

Figure 5: Water resistance test on the pellet samples of different particle sizes produced
with binder

4. CONCLUSION

The study concluded that the addition of binder during pelletisation has influence on the formation of the pellets and its properties. For instance, the calorific values of some specific pellet such as samples *Arira (Detarium microcarpum) (DM)* were higher without binder because of some inherent composition of the lignocellulosic morphology, while pellets samples *Apa (Afzelia africana) (AA)* and *Iya (Daniella oliveri) (DO*) exhibited better heating values with binder. The impact resistance index (IRI) decreases as particle size increases for samples without binder, and increases as the particle size increases for samples with binder. Water resistance test on the pellet samples produced with binder and without binder tend to behave with the same trend as the disintegration time increases as particle size decreases. The basic physical properties that enhance handling and transportation operations of wood pellets have been examined, thus some fundamental facts have been established concerning conversion of wood residues to wood fuel.

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