Thermo-decompositional Analysis of Sawdust Blends of Invasive Alien Plants

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Abstract

This study examined the effect of blending two invasive wood species of distinct physical and chemical properties, maximum char yields and rates of decomposition, on their thermal behaviour towards sustainable production of energy. To evaluate their potential use for production of briquettes/pellets, an examination of the dynamic thermogravimetry of sawdust blends of bugweed, a low density, fast-growing fibrous invasive shrub with eucalyptus wood was conducted. Individual blends in ratios of 50:50 (BUG50), 30:70 (BUG30) and 70:30 (BUG70) were tested under a pyrolysis condition and also in oxidized atmosphere to examine their combustion behaviours at a constant heating rate. Results were compared to individual results of 100% bugweed sawdust (BUG100) and 100% eucalyptus sawdust (BUG0) as control. The pyrolysis test on the blended samples reveal an increase in maximum char mass yield of up to 17% from that observed in BUG100. Meanwhile, amongst all blends, BUG70 exhibited the least maximum char yield of 34.9% and the highest ash residue of 4.3%. The high ash residue in BUG70 was believed to distort its char combustion. The lowest maximum peak rate of volatilization achieved amongst all blends was 6.6%/min by BUG50 and that of the char decomposition was as low as 2%/min for BUG30. Remarkably, the peak and final decomposition temperatures of all three blends occurred at higher temperatures than those of BUG100, in the pyrolysis test. Results of their combustion tests conducted, reveal thermograms with profiles similar to those observed during the pyrolysis tests. However, there was a general decrease in the peak and final combustion temperatures from those observed during the pyrolysis test of the samples. BUG30 exhibited good char combustion stability across a wide temperature range and at higher combustion temperatures than BUG50 and BUG70. No significant differences were observed in the heating values of all samples tested.

Key words: Bugweed; Eucalyptus; Biomass blending, Wood fuel; Briquettes.

1. Introduction

Globally, wood undoubtedly remains one of the most essential and universally consumed material for domestic and industrial activities both as fuel and timber, and its demand is unending. In Africa alone, the annual consumption of wood is estimated at about 700 million m³. Approximately 89% of this total is consumed as fuel either in form of fresh firewood or charcoal and the rest as sawn wood [1]. This 89% is estimated by the International Energy
Agency (IEA) to be consumed by over 80% of householders in Africa who rely primarily on wood for cooking and space heating [1]. The use of wood fuel has been an age-long common practice in both developed and developing regions. Reportedly, in the United States, an estimated 2.5 million householders depend on wood as their primary fuel of choice for space heating and an additional 9 million households utilize it as an auxiliary heating fuel [2], [3]. A similar scenario is also obtainable with householders in other regions particularly in Europe and Asia [1].

Population growth is an obvious factor for the increased demand for wood energy as global population growth rate is reportedly directly proportional to 3 – 4% per annum rise in the consumption of wood fuels [4]. Ironically, this has been attributed to urbanization despite the expected use of modern cooking and heating technologies. Urbanization is perceived as a major contributing factor to the increased loss of forest wood for fuel. A larger percentage of wood is consumed in form of charcoal as the preferred domestic fuel by urban householders for space heating and cooking. This is owing to the fact that charcoal is light weight and hydrophobic (making it less expensive for transport and more convenient for storage), burns cleanly, exhibits a higher calorific value than fuel wood, and most importantly, is relatively cheaper than electricity and fossil-based domestic fuels [4]. Consequently, there has been an increased production of charcoal from raw wood usually sourced from large forest trees. Unfortunately, charcoal production is grossly inefficient. It is estimated that about 30 to 40% of the original weight of the raw wood feedstock obtainable as charcoal after its carbonization. Therefore, its increase in demand as well as the resultant surge in its production, continue to have a rippling effect on the sustainability of forest resources with impending impacts such as deforestation and loss of biodiversity. This is evident as the greater proportion of the aforementioned 89% of forest wood fuel consumed in Africa, is reportedly being channelled towards illegal charcoal production [5]. Moreover, the wood feedstock for commercial charcoal production is usually hardwood sourced from a small pool of tree species known for their high energy density and very low burning rates. One major drawback to this is the fact that such trees may become endangered due to the longer time it takes for them to regrow to full maturity after felling operations. This leads to loss of biodiversity and large-scale deforestation if not sustainably harnessed.

The above-mentioned environmental concerns have led to recent interests in the production of pellets and briquettes from industrial wood wastes and agricultural wastes, as feedstock for bioenergy production. Pelleting or briquetting involves the high strength compression of loose wood (or other biomass) waste particles into a uniformly dense and compact block with the aid of binders [6]. This therefore, serves as an alternative to the conventional use of forest wood fuels for domestic cooking and space heating as well as for industrial operations [2]. Despite achieving such high densities which optimizes wood combustion efficiency and residence time, the direct combustion of biomass remains most inefficient due to its low heating value [7]. Briquettes can also be pyrolysed or torrefied to increase its heating value. Promoting the use of briquettes and pellets also aids in preventing deforestation and loss of biodiversity by grossly minimizing the dependence on the limited forest reserves for fuelwood and charcoal.
With this recent global interest in briquettes and pellets, research has been focused mainly on the application of briquettes and pellets as feedstock for gasification and other thermochemical conversion processes; their production from various types of biomass waste as well as on their mechanical properties and durability during handling and storage [8]–[11]. However, with the use of sawdust particles as feedstock for briquetting, opportunities abound in utilizing other less-valuable, but fast-growing wood species which exhibit thermal properties too low to sustain combustion. Optimizing such species by blending them with those species renowned for their good combustion properties, could aid in further curtailing the overdependence on large forest trees for energy. Moreover, pellets and briquettes are often produced conventionally, from a mixture of sawdust wastes from different wood species piled up in sawmills, with little or no knowledge about their thermal behaviours and required mix ratios.

Against this background, this study reports the improvements in the final decomposition temperatures of three blends of bugweed and eucalyptus for potential use as feedstock for briquettes/pellets. An examination of the variations in the pyrolysis and combustion thermograms, char yield and other fuel properties of bugweed and eucalyptus in comparison with those of the three blends was conducted. Ideally, high char mass yield with low ash content and low thermal decomposition rate is desired in the use of briquettes/pellets as fuel.

The bugweed specie was selected for this study based on its high invasiveness and fast growth rate as well as its low energy density and high burning rate. Meanwhile, the choice of the eucalyptus wood for blending with bugweed was due to its much superior energy density, calorific value, fixed carbon and negligible ash content (as shown on table 1), which are beneficial to high char yield and low thermal decomposition rate. However, its properties such as high bulk density and lower volatile matter content are factors known to contribute to undesirable prolonged ignition time [12]. On the contrary, bugweed, though low in fixed carbon content and high in ash, is composed of higher amounts of volatiles which promote quick ignition of solid biomass fuels. Therefore, the blends of bugweed and eucalyptus in ratios of 30/70, 50/50 and 70/30 were examined for their proximate properties, higher heating values and derivative thermo-gravimetry (DTG), under inert and oxidized thermal conditions. Variations in the thermograms of the three blends were observed to ascertain any improvements in fuel properties from that of the unblended bugweed.

2. Experimental

2.1 Materials and sample preparation

The samples used for this study were offcuts harvested from the stems of bugweed and trunk of a eucalyptus tree sourced from the same grassland biome located in the Johannesburg area of South Africa.

To facilitate blending and maintain consistency in particle size, both wood samples were prepared by milling and the sawdust obtained was sieved using a Sigma-Aldrich no. 40 mesh sieve with nominal opening of 0.420 mm. The sawdust was air-dried prior to experimentation.
The Bugweed/Eucalyptus sawdust was blended in the following mix ratios designated by – BUG30 (ie. 30% bugweed/ 70% Eucalyptus), BUG50 (ie. 50% bugweed/ 50% eucalyptus) and BUG70 (ie. 70% bugweed / 30% eucalyptus). Samples of BUG100 (ie. 100% bugweed/ 0% eucalyptus) and BUG0 (ie. 0% bugweed/ 100% eucalyptus) were also prepared as control. For accuracy and simplicity, the individual species were measured in fractions totalling exactly 10 mg using a high accuracy Ohaus Pioneer Analytical PX224 weighing balance with readability of 0.0001 g. As shown in Fig. 1, all blends were mixed evenly by agitation in glass dram vials prior to testing.

![Figure 1: Unblended (BUG0 and BUG100) and blended (BUG30, BUG50, BUG70) samples](image)

### 2.2 Higher Heating Value (HHV), Proximate analysis and Thermogravimetric analysis

The higher heating values (HHVs) of the individual samples were determined experimentally using a Drycal Modular Oxygen Bomb Calorimeter.

Thermogravimetric and proximate analysis were carried out on the results obtained from the characterisation of the samples using the Universal V4.5A TA Instruments Data Analysis software. The experimental procedure was carried out by loading one gram of each sample onto an alumina sampling cup, placed onto a Q600 SDT thermal analyser (TA Instruments, USA). Each run was carried out in an inert atmosphere of nitrogen gas, flowing at 10 mL/min. Heating rate was set at 10 °C/min as the procedure ran from an initial temperature of 25 °C to a final temperature of 800°C and then held for 30 minutes. The same thermogravimetric procedure was also conducted in an oxygen flow of 10 mL/min and under the same heating rate and temperature limits. This was carried out to observe the combustion behaviors of the samples in an oxidized atmosphere. All experimental procedures were carried out in triplicate of each sample and results were averaged for accuracy.
3. Result and discussions

3.1 Higher Heating Value (HHV), Proximate analysis and Thermogravimetric analysis

In terms of their proximate composition, the volatile matter and fixed carbon contents, in particular were important parameters considered. This is due to their contribution to the ignition and combustion, char mass yield and heating values of solid fuels. For any solid fuel, its fixed carbon and ash are the main components of its char while the volatile matter contributes to its ignition.

Table 1: Comparison of the proximate properties, char yield and burnout of the primary wood samples and their blends.

| Blend | Proximate Composition | Max. Char Yield | Final Pyrolysis Temperature | Final Combustion Temperature | HHV |
|-------|-----------------------|-----------------|-----------------------------|-----------------------------|-----|
|       | MC (%) | VM (%) | FC (%) | Ash (%) | % | °C | °C | MJ/kg |
| BUG0  | 10.6  | 45.9  | 43.5  | 0.0   | 43.5 | 632.88 | 541.87 | 18.84 ±0.08 |
| BUG30 | 9.5   | 48.1  | 42.4  | 0.0   | 42.4 | 532.73 | 17.84 ±0.10 |
| BUG50 | 8.1   | 50.8  | 39.2  | 1.9   | 41.1 | 514.37 | 17.87 ±0.08 |
| BUG70 | 8.6   | 52.2  | 34.9  | 4.3   | 39.2 | 559.27 | 17.24 ±0.05 |
| BUG100| 9.6   | 54.3  | 34.6  | 1.5   | 36.1 | 493.43 | 17.58 ±0.07 |

Table 1. shows a general increase in the fixed carbon and decrease in volatile matter of all blended samples from those exhibited by BUG100. Interestingly, the ash content obtained in BUG50 (1.9%) and BUG70 (4.3%) were observed to be higher than those obtained in BUG0 and BUG100. A general increase of up to 17% in char mass yield was observed across all blended samples in comparison to that observed in BUG100. However, there were no significant differences in char yield observed amongst BUG30, BUG50 and BUG70.

Despite its low maximum char yield and high ash residue, the BUG70 also exhibited a final char decomposition temperature extending to 577°C, under pyrolysis conditions. The slow decomposition rate of BUG70 char could be as a result of the inert ash layer covering the carbon particles and hindering the char decomposition process. This therefore required increased temperatures to completely decompose the char. Increased ash content is also known to decrease the higher heating value of a solid fuel [13]. This effect of ash on HHV was evident with BUG70 as it was observed to exhibit the least HHV (17.24 MJ/kg) of all the blended samples including BUG100, which corresponded to its higher ash content. Its HHV was also slightly lower than
the minimum allowable HHV of 17.5 MJ/kg recommended by the German national standard for fuel briquettes/pellets [14]. However, there were no significant differences observed the HHV of the blends and those of BUG0 and BUG100.

3.2 Pyrolysis behavior

Figures 2A and 2B show the thermograms of the DTG of the BUG0 and BUG100 as well as those of the three blended samples. The thermograms show the thermal decomposition profiles of the individual samples in comparison to each other across the two important stages – volatilization (150°C – 350°C) and combustion (350°C – 650°C).

Figure 2A depicts a clear contrast between the thermal behaviours of bugweed and eucalyptus in the same dynamic thermogravimetric conditions. Between both samples, research have mostly been reported on the thermogravimetric decomposition of eucalyptus wood under varied experimental conditions [15]–[19]. The profile with double peaks observed on the eucalyptus (BUG0) DTG thermogram at P2 (287°C) and P3 (334°C) are similar to but significantly lower than those at 299°C and 363°C as reported in literature [15]. This can be attributed to variations in heating rates adopted in both studies, as well as differences in the structural compositions of the eucalyptus species used due to geographical and climatic factors. In this study however, the eucalyptus exhibited a more stable char decomposition at a higher average rate of 1.8 %/min at P5, which was much higher than that of the pyrolysis thermograms reported [15].

The pyrolysis thermograms of both BUG0 (eucalyptus) and BUG100 (bugweed), shows a similarity in temperatures of the volatilization peaks exhibited by BUG0 at P2 (287.15°C) and that of the single peak P1 (294.11°C) by BUG100. The double peaks P2 and P3 exhibited by the eucalyptus at the volatilization stage, were also observed at temperatures similar to those of hemicellulose decomposition (293°C) and cellulose decomposition (360°C), reported in literature [15], [20]. Therefore, the single peak P1 exhibited by BUG100 indicate the decomposition of its much dominant hemicellulose component. The high rate of volatility of its hemicellulose component explains the quick fire ignition usually exhibited by bugweed plants. Peak P4 (413.42°C) (with a shoulder at P5) was also observed at the char decomposition stage of BUG100. The occurrence of this shoulder at P5 can be attributed to a secondary char decomposition after the penetration of heat through the ash layer deposited on the char surface. As previously described, ash is known to hinder char thermal decomposition. The final decomposition of the BUG100 char at a much earlier temperature is as a result of its incapability of sustaining combustion for long periods after ignition. Meanwhile BUG0 exhibited a very gradual and stable char decomposition along P6 up to 632.88°C. This is an evidence of high char yield obtainable from eucalyptus and its ability to sustain combustion at higher temperatures.

A comparison of the DTG profiles of all three blended samples is shown in Fig. 2B. The thermograms of the blended samples reveal varying but significant reductions in peak rates of volatilization and char decomposition when compared to those of BUG100. Peaks P7, P8 and P9 all occurred at the same temperature mark of 299°C, slightly similar to that of BUG100 at P1. This is recognized as the decomposition of the bugweed fraction in each blend. Occurring at the
same temperature but in a sequential increase in rate of volatilization, P9, P8 and P7 are observed to be synonymous to the increasing fractions of bugweed in BUG30, BUG50 and BUG70. Moreover, the increase in peaks P11 and P10 of BUG50 (328.75°C) and BUG30 (331.97°C) occurred at a similar temperature to P3 (334.17°C) of the eucalyptus specie (BUG0). This increasing peaks are also observed to be synonymous to the increasing fraction of the eucalyptus from 50% in BUG50 to 70% in BUG30. This occurrence corroborates with a study, predicting the fractions of individual structural components in biomass from its DTG thermogram [21]. This phenomenon of increasing peak rates of volatilization of different thermograms occurring at the same temperature mark was also observed in literature [15]. In the study by Barneto et al. [15], it was observed that the thermogravimetric analysis of the three different eucalyptus species tested, generated thermograms with similar profiles and peaks with an increasing order of magnitude occurring at the same temperature mark. This same observation was made, when increasing the heating rate in the order of 5 C/min, 10 C/min and 15 C/min in the TGA experiment conducted on the same eucalyptus specie.

Furthermore, as shown in Fig 2B, multiple peaks were also observed during the char decomposition phase of all three blends. BUG50 and BUG70 exhibited similar char decomposition profiles with their first peaks intersecting at P12, with the same rate of 2.29%/min and temperature at 458.82°C. BUG50 and BUG70 also decomposed at the same final temperature of 559.27°C. BUG30 however, showed a much stable and different decomposition profile at higher temperatures along P14 curve, terminating at a final decomposition temperature of 591.46°C.

### 3.3 Combustion behavior

A comparison of the combustion DTG profiles of all samples is shown in Fig. 3A and 3B. The thermograms of the BUG0 and BUG100 in the oxidative environment as shown in Fig. 3A were similar to those exhibited under the inert conditions in Fig. 2A. The volatilization temperatures and rates of volatilization of their combustive decomposition peaks C1, C2, C3 also remained similar to the P1, P2, P3 peaks of their inert decomposition. However, there was a significant peak observed at C6 with a rate of 2.92%/min during the char combustion of BUG0 depicted in Fig. 3A. This is in contrast to the gradual P6 curve which showed no apparent peak in the pyrolysis char decomposition phase on Fig. 2A. The final char decomposition temperatures for both samples during combustion was also significantly lower than those of their pyrolysis process, due to the higher combustion reaction rate of the char in the presence of oxygen.

Meanwhile, comparison of the combustion thermograms for BUG30, BUG50 and BUG70 are shown in Fig. 3B. The thermograms in the volatilization phase of the combustion experiment showed similar profiles to those observed in the pyrolysis experiment in Fig. 2B. However, the peak volatilization temperatures of C9, C8 and C7 were equal at 291°C which is slightly below the 299°C observed in the pyrolysis experiment at P9, P8 and P7. Similar to the pyrolysis experiment (Fig. 2A), the increasing order of rates of volatilization in the combustion of C9 (5.6%/min), C8 (7.5%/min) and C7 (9.7%/min) (Fig. 3A), also conforms with the increasing percentage of bugweed in the BUG30, BUG50 and BUG70 blend samples. In the char combustion phase of the three blends, sharper peaks where observed, in contrast to the broader
Figure 2A. DTG thermograms of bugweed and eucalyptus wood samples; 2B: DTG thermograms of BUG30, BUG50 and BUG70 under pyrolysis conditions.
peaks observed in the pyrolysis results in Fig 2B. BUG70 generated the highest char combustion peak of at C12 (4.128%/min, 407.76°C). The multiple peaks however, were more sequential than those in the char pyrolysis phase in Fig. 2B. The char combustion peaks – C13, C14 and C15 of the BUG30 occurred at slightly higher temperatures that those of BUG50, while those of BUG50 also occurred at slightly higher temperatures than those of BUG70. However, there was a significant shift to lower final decomposition temperatures during the combustion of the three samples when compared to the pyrolysis decomposition results in Fig. 2B. Comparable to their pyrolysis thermograms, BUG50 and BUG70 were also observed to decompose completely at the same final temperature of 514.37°C while BUG30 decomposed at a much higher temperature of 532.73°C.

4. Conclusions

In this study, three blends of bugweed and eucalyptus were prepared in different ratios in order to investigate any improvements on their thermal decomposition profiles to maximize the use of bugweed for briquettes/pellets production. Parameters such as rates of volatilization and char decomposition as well as char yield which are vital for the efficient combustion of solid biomass fuels are significant to this study. There was an influence of a particular specie over the other at different stages of the run depending on their fraction in each blend. This occurrence was more evident during the volatilization and char decomposition phases of the pyrolysis and combustion
experiments. It was observed that the volatilization peaks of the bugweed fraction in each blend occurred at the same temperature across all blends while that of the eucalyptus occurred at a higher volatilization temperature. An evidence of this can be seen in Fig. 2A and 2B, whereby the first peaks P9, P8 and P7 observed on the thermograms of the samples occurred at the 299ºC which is similar to the peak temperature of BUG100 at P1 (294ºC). The same occurrence was also observed for the temperatures of peaks P10 (at 331.97C) and P11 (at 328.75C), which were similar to that of BUG0 peak P3 (at 334.17C). It is interesting to note that the first peaks rates of volatilization of peaks P9, P8 and P7 increased in a successive order of magnitude which corresponds to the increasing fraction of bugweed in BUG30, BUG50 and BUG70. This was in corroboration with previous studies.

While, all three blended samples exhibited similar char yields, the BUG50 and BUG70 decomposed completely at the same char final decomposition temperature in the pyrolysis and combustion experiment. Amongst all blends, only the BUG30 decomposed at a higher final decomposition temperature. The char final decomposition temperatures for all blends were however, much higher than that of BUG100, but lower than that of BUG0. The high ash residue of 4.3% generated by BUG70 with the lowest FC of 34.9 % and high VM of 52.2% could be a preliminary indication of its poor combustion efficiency likened to that exhibited by BUG100. High ash percentage and low fixed carbon are impeding factors to the sustenance of combustion by a solid fuel.

The above thermal behaviours of the blends indicate the influence of bugweed dominant during the volatilization phase and that of eucalyptus dominant during the char decomposition phase. This supports the aim of blending the two species whereby the bugweed supports ignition due to its superior volatilization property while combustion to higher temperatures is sustained by the superior thermal stability of the eucalyptus. Considering the improvements observed in the proximate properties and thermal degradation behaviours by the blends, BUG30 and BUG50 were considered as the most suitable out of the three blends as possible feedstock for briquette/pellets production. The similarities in the heating values of all blends however, indicates that there was no influence on the fractions of either the bugweed or the eucalyptus on the HHV of the samples. Further investigations into their flammability properties and other fuel parameters is needed to further validate the findings of this study.

Acknowledgements

The authors wish to acknowledge the financial support offered by the National Research Foundation of South Africa (NRF), in the actualization of this research work for publication.

Reference

[1] Global Environment Fund (2013). Africa will import-not export-wood. Online Report. Available: http://www.criterionafrica.com/wp-content/uploads/2017/06/Africa-will-Import-not-Export-Wood.pdf. [Accessed: 30-Mar-2019].

[2] Antwi-Boasiako, C. & Acheampong, B. (2016). Strength properties and calorific values
of sawdust-briquettes as wood-residue energy generation source from tropical hardwoods of different densities,” Biomass and Bioenergy, vol. 85:144–152.

[3] U.S. Energy Information Administration, EIA (2014). Increase in wood as main source of household heating most notable in the Northeast. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=15431. [Accessed: 10-Feb-2019].

[4] Girard, P. (2002). Charcoal production and use in Africa: what future?. Vol. 53:30–35.

[5] Seidel, A. (2008). Charcoal in Africa Importance, Problems and Possible Solution Strategies Charcoal in Africa: Importance, Problems and Possible Solution Strategies. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ). Retrieved from: http://www.cocinasmejoradasperu.org.pe/Publicaciones/Charcoal_in_Africa_Importance_Problems_and_Possible_Solution_Strategies.pdf. [Accessed: 4-Jan-2019].

[6] Nasrin, A. B., MA, A. N., Mohamad, S., Choo, Y.M. Rohaya, M. H., Azali, A. (2006). Production of palm-based biomass briquettes. *MPOB Inf. Ser.*, ISSN: 1511-7871.

[7] Pattanotai, T., Watanabe, H., Okazaki, K. (2014). Gasification characteristic of large wood char with anisotropic structure. FUEL, 117:331–339.

[8] Ruoppolo, G., Miccio, F., Brachi, P., Picarelli, A., Chirone, R. (2013). Fluidized Bed Gasification of Biomass and Biomass / Coal Pellets in Oxygen and Steam Atmosphere. Chemical Engineering Transactions, 32:595–600. http://dx.doi.org/10.3303/CET1332100.

[9] Hongrapipat, J., Saw, W. L., Pang, S. (2015). Co-gasification of blended lignite and wood pellets in a dual fluidized bed steam gasifier: The influence of lignite to fuel ratio on NH3 and H2S concentrations in the producer gas. FUEL, 139:494–501. http://dx.doi.org/10.1016/j.fuel.2014.09.030

[10] Erlich, C. & Fransson, T.H. (2011). Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental study. Applied Energy, 88:899–908. http://dx.doi.org/10.1016/j.apenergy.2010.08.028.

[11] Peng, J. H. (2012). A study of softwood torrefaction and densification for the production of high quality wood pellets. Ph. D Thesis, p. 260.

[12] Okoye, N. H., Eboatu, A. N., Arinze, R. U., Prisca, I., Umedum, N. L., Ogbonna, O. A. (2014). Effect of Density on Flame Characteristics of Some Tropical Timbers. J. Appl. Chem., 7(6):104–111. http://dx.doi.org/10.9790/5736-0761112114.

[13] Ijagbemi, C. O., Olusegun, A. S., Ademola, K. (2014). Evaluation of combustion characteristic of charcoal from different tropical wood species. J. Appl. Eng., 4(4):50–57.
[14] Hielg, W. & Janssen, R. (2009). Advancement of pellets-related European standards. European Pellets Standards, p. 26. Retrieved from: https://pelletsatlas.info/wp-content/uploads/2015/09/D75_Standards_WIP_HFA_Final091116.pdf.

[15] Barneto, A.G., Hernández, R.B., Berenguer, J.M. (2011). Thermogravimetric characterization of eucalyptus wood. *O Pap.*, vol. 72(7):53–56.

[16] Cai, Z., Ma, X., Fang, S., Yu, Z., Lin, Y. (2016). Thermogravimetric analysis of the co-combustion of eucalyptus residues and paper mill sludge. *Appl. Therm. Eng.*, 106:938–943. http://dx.doi.org/10.1016/j.applthermaleng.2016.06.088.

[17] Grotkjær, T., Dam-Johansen, K., Jensen, A.D., Glarborg, P. (2003). An experimental study of biomass ignition. *Fuel*, 82(7):825–833. http://dx.doi.org/10.1016/S0016-2361(02)00369-1.

[18] Franco, C., Pinto, F., Gulyurtlu, I., Cabrita, I. (2003). The study of reactions influencing the biomass steam gasification process. *Fuel*, 82(7):835–842. http://dx.doi.org/10.1016/S0016-2361(02)00313-7.

[19] Alzate, C. A., Chejne, F., Valdés, C. F., Berrio, A., La Cruz, J. D., Londoño, C. A. (2009). CO-gasification of pelletized wood residues. *Fuel*, 88:437–445. http://dx.doi.org/10.1016/j.fuel.2008.10.017.

[20] Chen, W., Peng, J., Bi, X. T. (2015). A state-of-the-art review of biomass torrefaction, densification and applications. *Renew. Sustain. Energy Rev.*, 44:847–866. http://dx.doi.org/10.1016/j.rser.2014.12.039.

[21] Awosusi, A. A., Ayeni, A. O., Adeleke, R., Daramola, M. O. (2017). Biocompositional and thermodecompositional analysis of South African agro-waste corncob and husk towards production of biocommodities. *Asia-Pacific J. Chem. Eng.*, 12(6):960–968. http://dx.doi.org/10.1002/apj.2138.