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Impact of Torrefaction Process in Elevating the Fuel Properties of Selected Herbaceous Biomass Solid Waste

Imuekemhe Hassan[1], *Oginni Olarewaju Thomas*[2], *Fadiji Adegoke Ezekiel*[2], *Adache Linus Adache*[3], *and Taye Stephen Mogaji*[1,*]

[1]Department of Mechanical Engineering, School of Engineering and Engineering Technology, Federal University of Technology, P. M. B. 704, Akure, Ondo State, 340106, Nigeria

[2]Department of Mechanical Engineering, Bamidele Olumilua University of Education, Science and Technology, Ikere Ekiti, Ekiti State, 36110, Nigeria

[3]Department of Mechanical Engineering, Air Force Institute of Technology, (AFIT), Nigerian Air Force Base, Kawo, Kaduna State, Nigeria

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ABSTRACT

Thermal pretreatment of biomass is a process that promotes an increase in its energy quality, making it a more efficient energy generation for combustion and co-firing applications. This research presents outcomes on the torrefaction of selected herbaceous biomass solid waste, coconut shells (CS). The torrefaction was carried out using a 79.8-liter capacity fixed bed reactor designed to carbonize 5kg of biomass per batch. Solid fuel was produced at varying torrefied temperatures (TT) of 275°C and 285°C and residence time (RT) effect at 30 minutes and 1 hour respectively. The torrefied biomass was collected and assays for their energy content characterization. The result from this study showed an increase in total carbon content, whereas the hydrogen, oxygen, and moisture content decreased, this behavior is found to be more pronounced with the increase in torrefaction temperature (TT). Compared to raw biomass, the carbon content of torrefied biomass increases 26-33 wt.% with an increase in (TT) and (RT). Analysis of the energy yield of the torrefied CS biomass sample was found to be higher than that of its mass yield as expected, Similarly, the obtained bulk density content of the torrefied biomass sample (CS) is observed to increase with increment in (TT). Findings from this study showed that torrefied products exhibited up to a 32% higher heating value compared to raw biomass and the highest calorific value of about 16 MJ/kg was also achieved. Overall, this research yields a solid fuel that could contribute to reducing the emission of contaminants into the atmosphere compared with the use of fossil fuels.

Keywords: Biomass, Torrefaction, Coconut Shell, Torrefaction Temperature, Energy Content, Higher Heating Value.

1 Introduction

The concerns effect of climate change problems including the need to reduce the greenhouse gas (GHG) emissions due to the use of fossil fuels with an alarming increase in energy consumption as the world's population and industrialization upsurge has led to global interest in clean and sustainable fuel programs. According to Berrueco *et al.* [1], one of the major problems with fossil fuels is the emission of contaminants into the atmosphere, such as carbon dioxide, sulfur, and nitrogen oxide. Zieminski and Frac [2] also opined those traditional methods of producing energy through the use of fossil fuels (mostly oil and gas) have led to harmful practices that degrade the atmosphere, deplete the Ozone layer, and lead to the excess emission of harmful gases. Due to this, societies all over the world are undergoing a substantial and urgent need for change in the production and use of energy. It should be highlighted that among the available means of curbing the observed environmental effects that occurred due to the use of fossil fuels as reported in the open literature, biomass is regarded as one viable option in the quest for renewable energy sources that can reduce the emission of harmful gases to the atmosphere. As reported in the study by Herbert and Krishnan [3], energy production from biomass can reduce greenhouse gas (GHG) emissions, mitigate climate change, promote environmental sustainability, and improve human health and wealth. According to the International Energy Agency [4], Bioenergy is a source of energy from the organic material that makes up plants, known as biomass. Obi *et al.* [5] reported biomass to be in the form of solid biofuels or gasified biofuels that allow for direct combustion and energy generation. Generally, reports from the open literature also revealed that because of carbon-neutral and generated sustainably, biomass is quickly becoming a key part of the energy mix. Biomass solid fuels have many benefits over regular fossil fuels, such as oil and coal. They come from natural materials or leftovers that would otherwise be burned or thrown away, causing pollution. However, according to Yue *et al.*, [6], the performance of biomass for direct combustion is poor because of the typically low energy density, high moisture content, poor grind ability, poor handling properties, and high heterogeneity in the physical properties and chemical composition. The authors concluded that these issues reduce the efficiency and commercial viability of biomass recycling. Similarly, Bhar *et al.* [7] in their study reported that using raw biomass fuels, on the other hand, has major effects during biomass thermal conversion. These effects such as high moisture content, low calorific value, and high oxygen content, which lead to low conversion efficiency as well as a high cost of biomass collection, storage, and transportation were also reported as a significant drawback in using biomass as solid fuel [8]-[11]. As

*Corresponding Author Email Address: tsmogaji@futa.edu.ng

a result of this observed limitation in using biomass as solid fuel, pretreatment of biomass through thermochemical processes is an alternative means to overcome the drawbacks and improve the production of high-quality solid biofuels as reported in the previous studies [12]-[13]. One of the means of achieving this biomass thermal conversion objective is through the application of the torrefaction process. Torrefaction stands as a preparatory procedure aimed at enhancing the properties of biomass for more efficient energy generation through thermochemical conversion technologies. The process as reported by Niu *et al.* [14], and Ahmed *et al.* [15] is defined by gradual particle heating and relatively extended residence times. The process is usually conducted in a limited oxygen environment at a heating temperature within the range of 200-300ºC, resulting in the production of a solid, energy-dense product with improved fuel properties. According to Pestano *et al*. [16], by removing moisture, volatile organic compounds, and other impurities, torrefaction is a technological advancement aimed at increasing the energy density and stability of biomass, making it more appropriate for use as a fuel in power production and other uses. Abnisa *et al.* [17] in their study also pointed out that the objective of torrefaction is to create the fuel that would be used for the production of heat and electrical energy. Similarly, Wild and Calderon [18], in their study regarded torrefaction as a game-changing technology for lowering handling and storage expenses as well as lowering investment for co-firing applications. Romero *et al.* [19] carried out a study on the Thermal Behavior and Chemical-Physical Characteristics of Woody Biomass as Solid Biofuels. The chemical composition of woody biomass directly influences its thermal degradation and, subsequently, the selection of processes and technologies used for its conversion into energy or value-added products. Chin *et al.* [20] carried out a study on bioenergy production from bamboo: Potential source from Malaysia's perspective and concluded that Several studies have been conducted on a wide range of bamboo species and the results have shown that bamboo could potentially be used as a suitable fuel because it shares desirable fuel characteristics present in other woody biomass. Tumulru *et al.* [21] in their study found that at the end of the torrefaction process, a solid homogenous product with reduced moisture and higher energy content is created and also makes the torrefied biomass more hydrophobic resulting in boosting its storage stability. One of the most important aspects of torrefied biomass's utility as a fuel source is its calorific content. Several studies have shown that increasing the torrefaction temperature leads to an increase in the calorific value of the biomass. A high Calorific value of about 5454 cal/g at a torrefaction temperature of 270°C and 15 minutes of residence time was attained in the study of Sukiran *et al.* [22]. Similarly, Dethan *et al.* [23] in their study found that the increased heating/torrefied temperature causes more thermal breakdown, which raises the carbon and decreases the oxygen content of the torrefied biomass. With a view to enhance the energy content and convert selected harbaceous biomass solid waste into value-added products in this study, more research is carried out to investigate the impact of the torrefaction process in improving the fuel properties of coconut biomass solid waste. Coconut named Cocos nucifera L according to Yerima [24] is an agricultural product grown throughout the year in contrast with other fruits. According to Ahmed *et al.* [25] coconut contributes to the growth of coconut water, oil, and milk processing industries, which discard coconut shells globally as biomass waste in all tropical countries. The torrefied coconut shells will be investigated to evaluate their potential as an alternative fuel to coal in this study.

2 Materials and Methods

2.1 Materials

The selected feedstock (herbaceous biomass solid waste) type used in this study is Coconut Shell (CS). The considered feedstock was obtained from Akure Metropolis in Ondo State, Nigeria. The appearance of the feedstock is shown in Fig. 1.

Fig. 1 The feedstock used in the experiments

2.2 Torrefaction Experiments

Torrefaction experiments were carried out in a bioreactor using a batch system. The flowchart showing experimental procedures is presented in Fig. 2. The schematic view of the experimental apparatus is shown in Fig. 3. The reactor as detailed in Mogaji *et al.* [26] has a capacity of 79.8 litres and it was designed to carbonize 5 kg of biomass per batch. The biomass waste was sundried in an ambient atmosphere for 10 days to reduce the moisture content to about 6 – 8 wt.%. The dried biomass sample, CS was weighed using mechanical weighing balance. In these experiments, 3 kg of the feedstock was fed into the torrefaction reactor at varying temperatures of 275˚C and 285 ˚C taking into consideration the residence temperature (RT) effect on the torrefied biomass waste for 30 minutes and 1 hour respectively. The reactor lid was screwed with bolts to ensure that there is no ingression of air and leakages of the vapor. The k-type thermocouple was inserted using the probe to monitor the inner temperature of the reactor and controlled by the temperature controller fitted with the reactor chamber. At the first run, the temperature controller was pre-set at 275 ˚C, and the reactor was set on using liquified petroleum gas (LPG) as a source of power, heating the feedstock internally. At 275 ˚C, the controller triggered and the reactor was unplugged from the source of power. The obtained torrefied biomass feedstock was allowed to cool down for a residence temperature of 30 minutes, ($RT@_{30\ minutes}$), the obtained torrefied biomass was collected from the chamber and labeled as $CS_{275\ °C}$ @ $RT@_{30\ minutes}$. At the end of each run, all the parts of the system were cleaned before reassembling for the next run. Similar experimental procedures were repeated for $CS_{275°C}$ @ $RT@_{1hour}$, $CS_{285°C}$ @ $RT@_{30\ minutes}$ and $CS_{285°C}$ @ $RT@_{1hour}$. Presented in Fig. 4 is the sample of the obtained torrefied Coconut shell in this study.

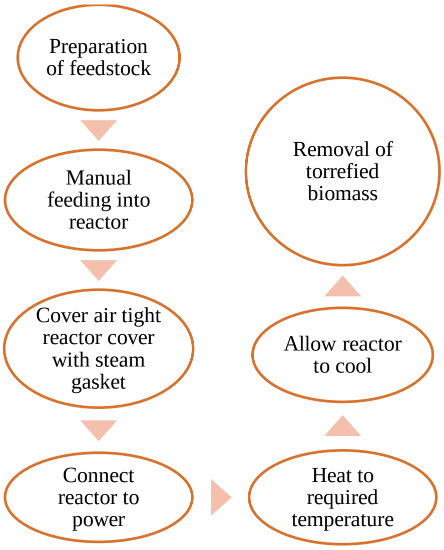
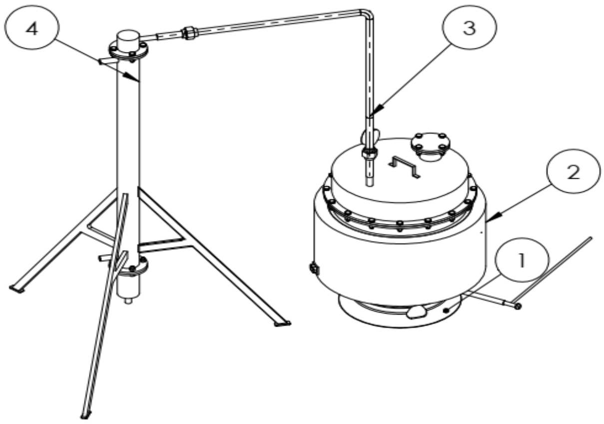


Fig. 2 Flowchart of Experimental Procedure



S/N	Name	Description	Qty
1	Gas burner	1500btu/hr. LPG Burner	1
2	Reactor	Reactor	1
3	Pipe	24×500mm mild steel pipe	2`
4	Condenser	Single-pass shell-tube condenser`	1

Fig. 3 Schematic view developed pyrolysis plant

Fig. 4 Torrefied Coconut shell produced in this study

2.3 Test Methods

In order to evaluate the impact of the torrefaction process in elevating the fuel properties of selected harbaceous biomass solid waste in this study, the considered respective biomass feedstock samples displayed in Fig. 1 and Fig. 4 were assayed for physiochemical characterization in the laboratory to obtain their respective fuel properties. The percentage of moisture content (Mc), volatile matter (Vm), and ash content in the analysis sample is calculated using Eqs. (1) to (3), while Eqs. (4) and (5) were employed mathematically to calculate the fixed carbon and bulk density of the sample, respectively. The sample percentage elemental composition of Hydrogen (H), Carbon (C), Nitrogen (N), Sulphur (S), and Oxygen were calculated using Eqs. (6) - (10). Presented in Fig. 5 is the obtained bulk density test result of the CS biomass sample before and after torrefaction processes. The physiochemical characterization carried out on each biomass sample are Proximate analysis using a furnace for Volatile Matter (VM) and Ash Content (AC), while an oven drier was used for the considered sample Moisture Content (MC) analysis. Presented in Fig. 6 are the obtained proximate analysis results of the analyzed biomass samples in this study. The result of the Ultimate Analysis also performed in the Laboratory using an elemental analyzer (Thermo FlashEA 1112), according to the ASTM-D 5291 method to analyze the weight percentage of Carbon, Hydrogen, Oxygen, Sulphur and Nitrogen, are presented in Fig. 7, while the obtained energy content for the Torrefied and raw CS biomass sample in this study is presented in Fig. 8. The Energy content analyses (HHV) of the considered biomass samples in this work were obtained using (bomb calorimeter). It should be highlighted that all the characterization carried out in this work were determined experimentally in the Research Laboratory of the Department of Chemical Engineering, Afe Babalola University Ado-Ekiti, (ABUAD) Ekitit State, Nigeria using the standard procedure as detailed in Mogaji *et al.* [27]. In this study, as reported in the study of Pahla *et al.* [28] the mass yield and energy yield of the torrefied biomass sample were obtained using Eqs. (11) and (12) correspondingly.

$$Mc = \frac{m_1 - m_2}{m_1} X100 \tag{1}$$

$$Vm = \frac{m_2 - m_3}{m_1} X100 \tag{2}$$

$$Ac = \frac{Wc - We}{Ws} 100\% \tag{3}$$

$$FC = 100 - (Mc + Ac + Vm) \tag{4}$$

$$Bd = \frac{W_{de}}{V_c} \tag{5}$$

$$C = \frac{12Z}{44X} \times 100 \tag{6}$$

$$H = \frac{2Y}{18X} \times 100 \tag{7}$$

$$N_{sw} = \frac{0.0014 * 5 * Vt}{Wg} \times 100 \tag{8}$$

$$S = \frac{R * V * D_f}{Weight\ of\ sample\ used} \times 100 \tag{9}$$

$$(H + O) = 100 - (\%C + N + S) \tag{10}$$

Where; m_1 is the weight of the specimen, m_2 is the weight of the specimen after drying in the moisture test, m_3 is the weight of the specimen after drying in a muffle furnace for 7 minutes, W_c is the weight of the crucible plus sample, W_e is the weight of empty crucible, W_s is the weight of the sample, W_{ds} is the weight of the dried sample and V_c is the volume of the shape (cylinder). X is the weight of the sample taken, Y is the increase in the weight of the $CaCl_2$ tube, Z is the increase in the weight of the KOH tube, V_1 is the volume of H_2SO_4 neutralized (cm^3), V_2 is the volume of H_2SO_4 neutralized in determination (cm^3), W_g is the weight of the sample (g).

$$Mass\ yield\ (\%) = \frac{mass\ of\ torrefied, CS}{mass\ of\ raw\ CS} \times 100 \tag{11}$$

$$Energy\ yield\ (\%) = mass\ yield \times \frac{Higher\ heating\ value\ of\ torrefied\ CS}{Higher\ heating\ valueof\ raw\ CS} \tag{12}$$

3 Results and Discussions

3.1 Mass and Energy Yield Determination for the Biomass Sample

Mass and energy yield is referred to as the quantity of energy preserved after the pretreatment of the CS biomass sample and is measured using the mass yield of the final product. Presented in Table 1 are the profiles of mass and energy yield of the torrefied CS at different torrefaction temperatures and residence times.

Table 1 Estimation of mass and energy yield of the torrefied CS sample

Sample		Moisture Content (%)	HCV (MJ/Kg)	Mass yield (kg)	Energy yield (kW)
Coconut shell control	C1	14.72	10.815	-	-
Coconut shell TT, 275ºC, RT 30mins	C2	5.73	13.330	0.3892	0.5541
Coconut shell TT, 275 ºC, RT 1hr	C3	4.33	12.912	0.2927	0.3607
Coconut shell TT, 285 ºC, RT 30mins	C4	5.60	15.866	0.3777	0.4646
Coconut shell TT, 285 ºC, RT 1hr	C5	4.43	13.416	0.3009	0.3732

From Table 1, as expected, the percentage of mass yield decreases with the increase in the torrefaction temperature and residence time. This behavior is similar to the results reported by Jaafar and Ahmad [29] and Ahmed *et al.* [30]. It is also found that the estimated energy yield presented in Table 1 ranges from 55 to 36 % of the torrefied CS at temperature ranges of 275 to 285 °C. This behavior is observed to be more pronounced with biomass sample C2 in this study indicating that enhancement of fuel qualities and combustion properties of the torrefied CS in comparison to the raw biomass sample was increased from 45 to 64 %. This behavior agrees with what is asserted by Randell *et al.* [31]that reducing or eliminating water and ash content components of biomass as also observed in Fig. 6 in this study, increases the energy content of the biomass as expected. It is also noticed from the results that the temperature has a more significant effect on torrefaction than the residence time. It is also interesting to point out that the estimated energy yield of the torrefied CS biomass sample in this study is found to be higher than the mass yield, thus, the energy densification of the torrefied sample is achieved. This result matches the results reported by Prins *et al.* [32].

3.2 Effect of Torrefaction Conditions on Bulk Density of the Biomass CS Waste Sample

Fig. 5 provides the bulk density test results of the CS biomass sample before and after torrefaction processes. These results were obtained based on Laboratory tests conducted on the torrefied CS biomass samples achieved in this study. Bulk density represents the mass of a material per unit volume and is an important parameter considered for biomass samples in various applications, including combustion, gasification, transportation, and storage. From Fig. 5, it can be noticed that the Bulk density content of the biomass sample decreases with an increase in torrefaction temperature and residence time, this behavior is observed to be more pronounced for sample C5 at 285°C and Resident Temperature (1 hr) in this study. In comparison to the raw biomass sample considered in this research, the torrefaction processes with an increase in torrefaction temperature have led to a significant decrease in bulk density across all torrefied biomass samples resulting in an increase in the biomass porosity improving their grindability and energy content as also observed in previous studies [33]-[34].

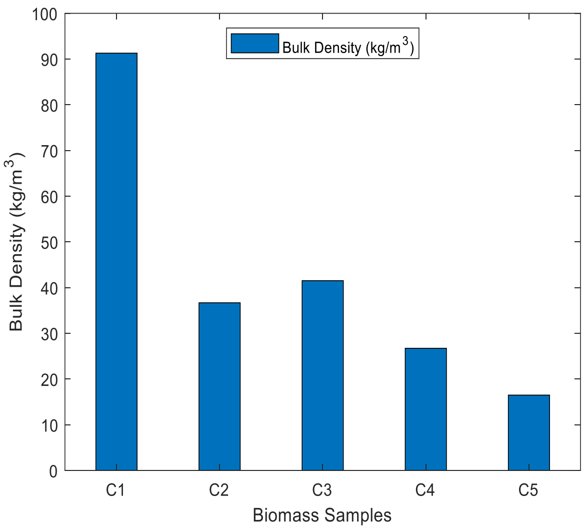


Fig. 5 Profiles of bulk density from coconut shell torrefaction

3.3 Proximate Analysis of the Biomass Sample

The following component content such as moisture content (MC), volatile matter (VM), fixed carbon (FC), and ash content (AC) were obtained based on a proximate analysis laboratory test conducted in this study. The MC, VM, AC, and FC contents of the raw and torrefied CS are presented in Fig. 6. As expected, in comparison to the raw biomass CS sample, the MC, VM, AC of the torrefied CS decrease as the torrefaction temperature increases, while the FC content increases. This behavior is due to the decomposition of hemicellulose via the devolatilization and carbonization process that results in the liberation of a higher proportion of oxygen and hydrogen content than carbon content during the torrefaction process as shown in Fig. 7. The attained decrease in the MC, VM, AC of the torrefied CS biomass sample as (68-21 %, 7.6-4.7 % and 79-14 %) respectively with the increase in the torrefaction temperature and residence time corroborated the observed decrease in the torrefied CS biomass sample bulk density presented in Fig. 5 thus resulting in increment of the sample heating value and improve their grind-ability property. The result from Fig. 6 also revealed that the FC increases by 26-42 % with the increase in the torrefaction temperature, however decreases with the increase in the residence time. It is noticed, that heating temperature has a more significant influence on the torrefied product than the residence time. This observation is consistent with the report from the previous study [30].

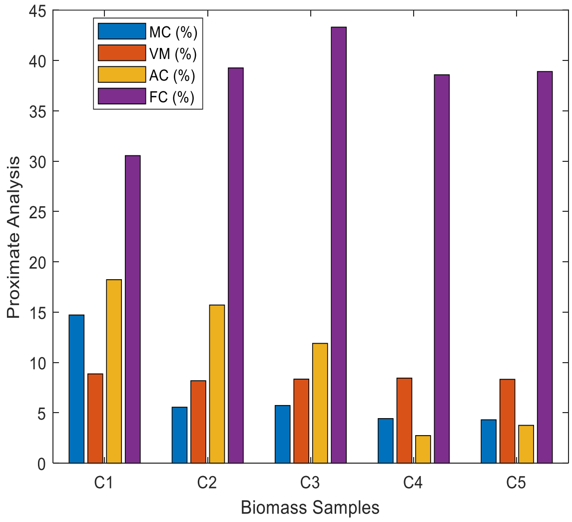


Fig. 6 Profiles of proximate analysis from coconut shell torrefaction

3.4 Elemental Composition of the Biomass Sample

In this research, Ultimate analysis tests were performed on the considered biomass sample (CS) to get their elemental composition status before and after the torrefaction process. The obtained elemental composition components such as Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S), and Oxygen (O) contents of the raw and torrefied CS are presented in Fig. 7. The results from Fig. 7 revealed that the C content of the sample increases by 26-33% with the increase in the torrefaction temperature and residence time. The percentage of H decreases by 4-15% with the increase of the torrefaction temperature and residence time. Meanwhile, the percentage of O decreases by 20-25% with the increase of the torrefaction temperature and residence time. The change in Nitrogen content is also observed to fluctuate with a slight difference of 0.13% and is considered constant. The achieved results reveal an increase in C content, and decreases in H and O contents, while the N content is constant, as the torrefaction temperature and residence time increases in this research are consistent with those observed in the previous studies of Jaafer and Ahmad [29] and Gevers *et al.* [35]. It is also found that the trend of the elemental composition of the torrefied CS at every respective residence time is similar to the results reported by Bridgeman *et al.* [36]. The percentage of Sulphur content is also noticed to be maintained low, i.e., below 1%, with the increase of the torrefaction temperature and residence time. The achieved Low Sulphur content of the torrefied CS in the study justifies the enhanced biomass sample through the torrefaction process to be an environmentally friendly solid fuel type.

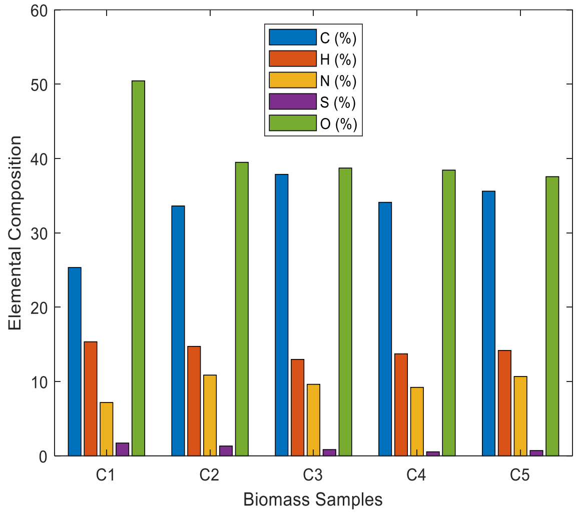


Fig. 7 Profiles of Elemental composition results from coconut shell torrefaction

3.5 Effect of Torrefaction Condition on Calorific Value of the Biomass Sample

The obtained energy content for the torrefied and raw CS biomass sample in this study is presented in Fig. 8. in terms of Higher Calorific Value (HCV) and Lower Calorific Value (LCV). The estimation of LCV and HCV of the considered biomass sample is required to know the actual available energy to be converted to heat or electricity using the obtained torrefied biomass in this research. The HCV represents the total energy released per unit mass of the sample, including the energy released by condensing the water vapor formed during the combustion process while the LCV represents the energy released excluding the energy in the water vapor.

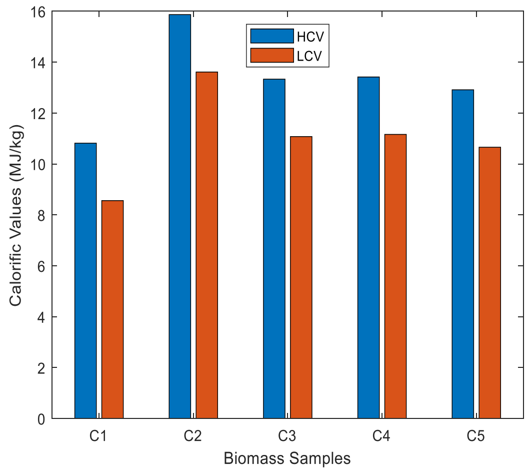


Fig. 8 Profiles of Calorific values from coconut shell torrefaction

As can be seen in Fig. 8 as expected, the HCV and LCV values of the torrefied biomass sample CS increase with the increase of the torrefaction temperature. Similarly, the torrefaction temperature condition imposes a more significant effect than the residence time. These behaviors could be explained by the observed pronounce increment of Carbon and Fixed Carbon contents attained from their respective proximate and ultimate analysis test results depicted in Fig. 6 and Fig. 7

where an increase in the C: C concentration leads to an increase in the energy content presented in Fig. 8. This behavior is consistent with those observed in the previous studies [29], [37]-[38]. Also, in comparison to the raw biomass sample C1 and torrefied CS biomass samples (C2-C5), the torrefied biomass sample C4 (Coconut Shell TT 285°C, RT, 30 mins) attained a heating value of 15.866 MJ/kg in this study. Overall, the increase of the energy content of the torrefied CS biomass sample in this study is found to be in the range of about 19.4-37.1 %.

4 Conclusions

The study involved torrefaction of selected harbaceous biomass solid waste (coconut shells) where Coconut Shell (CS), was torrefied at varying temperatures of 275 °C and 285 °C. The products of the torrefaction process were collected and assayed for their compositions, contents, and characteristics. The following conclusions can be drawn from this study.

- The estimated energy yield of the torrefied CS biomass sample in this study is found to be higher than the mass yield, thus, the energy densification of the torrefied sample is achieved
- Bulk density of the considered biomass sample (CS) is observed to decrease with increment in torrefaction temperature resulting in an increase in the obtained torrefied products porosity improving their grindability and energy content.
- The elemental composition of the torrefied biomass sample in this study revealed that the Carbon content of the obtained solid fuel increases by 26-33 % with the increase in the torrefaction temperature and residence time.
- A constant and less than 10 % Nitrogen content and negligible low Sulphur content is observed for the torrefied products as the torrefaction temperature and residence time increases in this research justify the attained solid fuel to be an environmentally friendly type
- Comparison results of the torrefied biomass CS sample to the raw biomass CS sample revealed a 26-42 % increment in FC of the torrefied CS as the torrefaction temperature increases
- It is also found that compared to all other biomass samples torrefied in this research biomass sample C4 (Coconut Shell TT 285 °C, RT, 30 mins) attained a heating value of 15.866 MJ/kg

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: **Study design:** Imuekemhe Hassan, Mogaji, T. S.; **Data collection:** Imuekemhe Hassan; **Analysis:** Imuekemhe Hassan, Mogaji, T. S., Adache L.A.; **Draft manuscript preparation:** Oginni, O.T. Fadiji A. E. All authors reviewed the results and approved the final version of the manuscript.

References

[1] Berrueco, C., Recari, J., Güell, B.M. and Del Alamo, G., 2014. Pressurized gasification of torrefied woody biomass in a lab scale fluidized bed. *Energy*, *70*, pp.68-78.

[2] Ziemiński, K. and Frąc, M., 2012. Methane fermentation process as anaerobic digestion of biomass: Transformations, stages and microorganisms. *African Journal of Biotechnology*, *11*(18), pp.4127-4139.

[3] Herbert, G.J. and Krishnan, A.U., 2016. Quantifying environmental performance of biomass energy. *Renewable and Sustainable Energy Reviews*, *59*, pp.292-308.

[4] International Energy Agency- IEA (2023), Tracking Clean Energy Progress 2023, IEA, Paris https://www.iea.org/reports/tracking-clean-energy-progress-2023, License: CC BY 4.0.

[5] Obi, O.F., Olugbade, T.O., Orisaleye, J.I. and Pecenka, R., 2023. Solid Biofuel Production from Biomass: Technologies, Challenges, and Opportunities for Its Commercial Production in Nigeria. *Energies*, *16*(24), p.7966.

[6] Yue, Y., Singh, H., Singh, B. and Mani, S., 2017. Torrefaction of sorghum biomass to improve fuel properties. *Bioresource technology*, *232*, pp.372-379.

[7] Bhar, R., Tiwari, B.R., Sarmah, A.K., Brar, S.K. and Dubey, B.K., 2022. A comparative life cycle assessment of different pyrolysis-pretreatment pathways of wood biomass for levoglucosan production. *Bioresource Technology*, *356*, p.127305.

[8] Chai, M., Xie, L., Yu, X., Zhang, X., Yang, Y., Rahman, M.M., Blanco, P.H., Liu, R., Bridgwater, A.V. and Cai, J., 2021. Poplar wood torrefaction: Kinetics, thermochemistry and implications. *Renewable and sustainable energy reviews*, *143*, p.110962.

[9] Wang, C., Yuan, X., Li, S. and Zhu, X., 2021. Enrichment of phenolic products in walnut shell pyrolysis bio-oil by combining torrefaction pretreatment with fractional condensation. *Renewable Energy*, *169*, pp.1317-1329.

[10] Namkung, H., Park, J.H., Lee, Y.J., Song, G.S., Choi, J.W., Park, S.J., Kim, S., Liu, J. and Choi, Y.C., 2021. Performance evaluation of biomass pretreated by demineralization and torrefaction for ash deposition and PM emissions in the combustion experiments. *Fuel*, *292*, p.120379.

[11] Yan, B., Jiao, L., Li, J., Zhu, X., Ahmed, S. and Chen, G., 2021. Investigation on microwave torrefaction: parametric influence, TG-MS-FTIR analysis, and gasification performance. *Energy*, *220*, p.119794.

[12] Basu, P. and Kaushal, P., 2023. *Biomass Gasification, Pyrolysis, and Torrefaction: Practical Design, Theory, and Climate Change Mitigation*. Elsevier.

[13] de Oliveira Brotto, J., da Silveira Salla, J., da Silva, J.C.G., Rodriguez-Castellon, E., Jose, H.J., de Amorim, S.M. and Moreira, R.D.F.P.M., 2022. Investigation of the thermal behavior of Pinus wood pellets during torrefaction for application in metallurgical processes. *Journal of Materials Research and Technology*, *19*, pp.3749-3759.

[14] Niu, Y., Lv, Y., Lei, Y., Liu, S., Liang, Y. and Wang, D., 2019. Biomass torrefaction: properties, applications, challenges, and economy. *Renewable and Sustainable Energy Reviews*, *115*, p.109395.

[15] Ahmad, R., Ishak, M.A.M., Ismail, K. and Kasim, N., 2018. Influence of torrefaction on gasification of torrefied palm kernel shell. *Advances in Science, Technology and Engineering Systems Journal*, *3*(5), pp.166-170.

[16] Pestaño, L.D.B. and José, W.I., 2018. Development of Torrefaction Technology for Solid Fuel Using Renewable Biomass. *Gasification for Low-grade Feedstock*, IntechOpen.

[17] Abnisa, F., Daud, W.W. and Sahu, J.N., 2011. Optimization and characterization studies on bio-oil production from palm shell by pyrolysis using response surface methodology. *Biomass and bioenergy*, *35*(8), pp.3604-3616.

[18] Wild, M. and Calderón, C., 2021. Torrefied biomass and where is the sector currently standing in terms of research, technology development, and implementation. *Frontiers in Energy Research*, *9*, p.678492.

[19] Romero, M.J., Duca, D., Maceratesi, V., Di Stefano, S., De Francesco, C. and Toscano, G., 2023. Preliminary Study on the Thermal Behavior and Chemical-Physical Characteristics of Woody Biomass as Solid Biofuels. *Processes*, *11*(1), p.154.

[20] Chin, K.L., Ibrahim, S., Hakeem, K.R., San H'ng, P., Lee, S.H. and Lila, M.A.M., 2017. Bioenergy Production from Bamboo: Potential Source from Malaysia's Perspective. *BioResources*, *12*(3).

[21] Tumuluru, J.S., Ghiasi, B., Soelberg, N.R. and Sokhansanj, S., 2021. Biomass torrefaction process, product properties, reactor types, and moving bed reactor design concepts. *Frontiers in Energy Research*, *9*, p.728140.

[22] Sukiran, M.A., Abnisa, F., Daud, W.M.A.W., Bakar, N.A. and Loh, S.K., 2017. A review of torrefaction of oil palm solid wastes for biofuel production. *Energy Conversion and Management*, *149*, pp.101-120.

[23] Dethan, J. J. S., Bale-Therik, J. F., Telupere, F. M. S., Lalel, H. J. D., and Sanggono, A., 2023. The Effect of Smoking Duration Use of Kesambi Leaf Biobriquette-Processed Torrefaction on Cooking Shrinkage and Characteristics Organoleptic Sei's Meat. *East African Scholars Journal of Agriculture and Life Sciences*. 6(8), pp.150-156.

[24] Yerima, I. and Grema, M.Z., 2018. The potential of coconut shell as biofuel. *The Journal of Middle East and North Africa Sciences*, *4*(8), pp.11-15.

[25] Ahmed, A., Bakar, M.S.A., Hamdani, R., Park, Y.K., Lam, S.S., Sukri, R.S., Hussain, M., Majeed, K., Phusunti, N., Jamil, F. and Aslam, M., 2020. Valorization of underutilized waste biomass from invasive species to produce biochar for energy and other value-added applications. *Environmental Research*, *186*, p.109596.

[26] Mogaji, T.S., Omoaka, A. and Ayodeji, O.Z., 2023. Development and Performance Evaluation of a Fixed Batch-type Pyrolysis Reactor for Bio-oil Production from Plastic Wastes. *Journal of Engineering Advancements*, *4*(01), pp.19-24.

[27] Mogaji, T.S., Moses, E.O., Idowu, E.T. and Jen, T.C., 2020. Thermal Degradation Conditions Effects on Selected Biomass Wastes and Characterization of Their Produced Biochar. *J. Energy Res. Rev.*, *4*, pp.46-59.

[28] Pahla, G., Mamvura, T.A. and Muzenda, E., 2018. Torrefaction of waste biomass for application in energy production in South Africa. *South African Journal of Chemical Engineering*, *25*(1), pp.1-12.

[29] Jaafar, A.A. and Ahmad, M.M., 2011. Torrefaction of Malaysian palm kernel shell into value-added solid fuels. *International Journal of Chemical and Molecular Engineering*, *5*(12), pp.1120-1123.

[30] Ahmad, R., Ishak, M.A.M., Ismail, K. and Kasim, N., 2018. Influence of torrefaction on gasification of torrefied palm kernel shell. *Advances in Science, Technology and Engineering Systems Journal*, *3*(5), pp.166-170.

[31] Espina, R., Barroca, R. and Abundo, M.L.S., 2022. The optimal high heating value of the torrefied coconut shells. *Engineering, Technology & Applied Science Research*, *12*(3), pp.8605-8610.

[32] Prins, M.J., Ptasinski, K.J. and Janssen, F.J., 2006. Torrefaction of wood: Part 2. Analysis of products. *Journal of analytical and applied pyrolysis*, *77*(1), pp.35-40.

[33] Chen, W.H., Peng, J. and Bi, X.T., 2015. A state-of-the-art review of biomass torrefaction, densification and applications. *Renewable and Sustainable Energy Reviews*, *44*, pp.847-866.

[34] Oliveira Rodrigues, T. and Rousset, P., 2009. Effects of torrefaction on energy properties of Eucalyptus grandis wood, CERNE, 15(4), pp.446–452.

[35] Gevers, P. Ramaekers, G., Frehen, A., Sijbinga, M., Van Steen, E., Sturms, J. and Taks, I. B., 2002. Green energy, from wood or torrefied wood?," University of Technology Eindhoven.

[36] Bridgeman, T.G., Jones, J.M., Shield, I. and Williams, P.T., 2008. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. *Fuel*, *87*(6), pp.844-856.

[37] Orisaleye, J.I., Jekayinfa, S.O., Pecenka, R., Ogundare, A.A., Akinseloyin, M.O. and Fadipe, O.L., 2022. Investigation of the effects of torrefaction temperature and residence time on the fuel quality of corncobs in a fixed-bed reactor. *Energies*, *15*(14), p.5284.

[38] Uemura, Y., Omar, W., Tsutsui, T., Subbarao, D. and Yusup, S., 2010. Relationship between calorific value and elementary composition of torrefied lignocellulosic biomass.