VOL. 10 NO. 9,
NOVEMBER, 2025
E-ISSN 3026-958X
P-ISSN 3027-1169

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Science Innovation & Technology Research (JSITR)

Production and Characterization of Solid Fuel Produced from Mahogany Wood Biomass Waste

Mogaji T. S.[1]; Ayeye O. F.[1]; Eiche, J. F.[2]; Akinsade A.[2]; Adebobola T. O.[3]

[1]Department of Mechanical Engineering, School of Infrastructure, Minerals and Manufacturing Engineering, Federal University of Technology, P. M. B. 704, Akure, Ondo State, 340106, Nigeria. [2]Department of Mechanical Engineering, Olusegun Agagu University of Science and Technology, Okitipupa, Nigeria. [3]Department of Mechanical Engineering, Federal Polytechnic Ile-Oluji, P. M. B. 727, Ondo, Ondo State, Nigeria

Corresponding Author: tsmogaji@futa.edu.ng

DOI: https://doi.org/10.70382/ajsitr.v10i9.052

Abstract

The global energy demand, combined with concerns about sustainable alternatives, has driven extensive research into renewable energy sources. This paper focuses on the production of solid fuel from mahogany biomass waste and carries out microstructural analysis of its energy content. The determination of moisture, volatile matter, ash, and fixed carbon was carried out at temperatures of 275 and 285 °C with retention times of 30 minutes and 1 hour using proximate analysis. The elemental analysis provided insights into the chemical composition changes induced by thermal treatment, with carbon content exhibiting significant alterations. The results revealed varying compositions across treatments, indicating the impact of thermal treatment on moisture, volatile matter, ash, and fixed carbon content. Higher temperatures and longer durations led to decreased moisture and volatile matter, increased ash content, and higher fixed carbon, suggesting enhanced carbonization. Bulk density results showcased the influence of treatment conditions on wood density. Thermal treatment decreased bulk density, highlighting the potential for altering wood density by varying treatment conditions. The findings suggest that thermal treatment can influence the suitability of mahogany wood for specific applications in biomass processing and energy generation. Calorific value results demonstrated that thermal treatment significantly increased both the higher heating value (HHV) and lower calorific value (LCV) of the mahogany wood chips torrefied in this study. The results of tests and energy analysis, conducted using Scanning Electron

Microscopy with Energy Dispersive X-ray Analysis (SEM-EDX), provided valuable insights into the microstructural changes induced by thermal treatment in this study. This finding suggested that the torrefaction process influences the material's morphology. The longer the torrefaction duration, the higher the calorific values, indicating improved energy potential of the considered biomass sample for combustion or other energy conversion processes.

Keywords: Biomass, torrefaction, mahogany wood, Torrefaction Temperature, energy content, microstructural analysis.

Introduction

The increasing global demand for energy, coupled with environmental concerns and the need for sustainable alternatives, has prompted extensive research into renewable energy sources. Renewable energy refers to energy sources that can be naturally replenished within a relatively short timeframe. Notable examples of renewable energy sources, as reported in the studies of (Ibitoye *et al.,*2021; Tilahun *et al.,*2021) encompass geothermal, solar, hydro, wind, and biomass. According to Joselin and Krishnan (2016), these energy sources are reported as eco-friendly alternatives to regular fossil fuels because they emit very few greenhouse gases (GHG) and other pollutants that contribute to air pollution and climate change. Findings from the studies of (Heredia *et al*., 2020; San-Miguel *et al.,*2022) revealed that biomass has a smaller carbon footprint than fossil fuels, which means it helps us use fewer non-renewable energy products. As pointed out in the previous studies of (Uddin *et al.*, 2019; Gaurav *et al.,* 2020), over the years, renewable energy technologies have become more cost-effective and efficient. Biomass solid fuels production, like briquettes and pellets, are created by squishing together things like leftover crops, sawdust, and bits from the forest. According to García *et al.* (2020) solid fuel-like product that has more energy and seems denser than the original biomass is produced by pressing these materials hard, either with or without a special binder material. As pointed out in the study of Yoo *et al*. (2019), these solid fuels look and act a lot like coal briquettes and old-fashioned charcoal, so we can use them for cooking, heating, and other energy needs. It is interesting to highlight that Biomass solid fuels have many benefits over regular fossil fuels, such as oil and coal. One of the agricultural residue wastes that are abundantly available as biomass samples and can achieve this objective effectively is woody biomass waste. At biorefinery facilities, Woody biomass can be converted into useful forms of energy (solid, liquid, or gaseous fuels) as well as useful products (polymers, bio-plastics, char, pellets, and acids). To achieve effective biomass thermochemical conversion processes, Ibitoye *et al*. (2021) investigated in their study the influence of biomass sources and processing methods on the morphological and microstructural properties of solid fuels. Their study encompasses various biomass

treatment processes, including gasification, torrefaction, carbonization, hydrothermal carbonization (HTC), and pyrolysis. The authors observed Gasification as efficient but requires high investment, while Pyrolysis produces bio-oil, char, and gases based on feedstock availability.

Carbonization is also observed to generate low-cost biochar for solid fuels and carbon sequestration applications. A recent study by Romero et al. (2023) revealed that 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. Lin et al. (2022) investigated the pyrolysis gas production with physical and chemical properties of the char products carried out experimentally. The results indicated that the pyrolysis temperature had a significant effect on char properties. A high pyrolysis temperature accelerates the gas release rate and improves the final gas production. As the pyrolysis temperature increased, the quality of the char decreased, and the O/C and H/C molar ratios of the biomass char decreased gradually. The calorific value was also affected by the temperature. Chin, et al. (2017) used Bamboo as an energy source by converting it into solid, liquid, and gaseous fuels. However, to utilize bamboo as a high-promise energy crop resource for biofuels, a secure and stable supply is required. Woody biomass waste is one of the biomass resources that is sourced from various forestry, agricultural, and industrial processes, and represents an abundant and often underutilized resource. The challenge of the age is how to determine the best processing technology that can collect and convert currently under-utilized woody biomass into products with higher value. The present study focuses on the production of solid fuel from mahogany biomass waste and evaluates the effects of torrefaction temperature, residence time, including the microstructural changes induced by thermal treatment, on the produced solid fuel properties.

Materials and Methods

Materials Preparation and Experimental Procedure

Mahogany wood chips (MWC) shown in Figure 1 were sourced locally and sun-dried in an ambient atmosphere for four days to reduce the moisture content to 6– 8 wt%. A 79.8-liter torrefaction reactor capacity was utilized to carbonize 5 kg of biomass per batch. The dried biomass was weighed and torrefied in a fixed-bed batch-type 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. There was no heat loss or gain into the reactor chamber, and oxygen was prevented from entering in the course of the carbonation process. The torrefaction reactor test rig is shown in Figure 2**.** A 3.0 kg biomass sample (MWC) was prepared, weighed mechanically, and labeled as MWC_{275} and MWC_{285} for temperatures ranging from 275 °C to 285 °C, respectively. Each of the samples was fed manually into the reactor chamber for thermal degradation between temperatures of 275 °C and 285 °C. The experimental setup was assembled with no ingress of air and no leakage of the vapor. A K-type thermocouple was inserted to monitor the inner temperature of the reactor chamber. At first run, the temperature controller was pre-set at 275 °C, and the reactor was set to use 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 (RT30 minutes), and the obtained torrefied biomass, as shown in Figure 3, was collected from the chamber and labeled as MWCS-275 ºC at RT 30 minutes. A similar experimental procedure was repeated for MWC-275 ºC at RT 1 hour, MWC-285 ºC at RT30 minutes, and MWC-285 ºC at RT1 hour. The solid fuel obtained was assayed for characterization using proximate, ultimate, and elemental analysis to determine its fuel properties. To achieve this in this study, the Weigh samples D1-D5 of the MWC biomass in crucibles in a drying oven at 105°C heated for 1 hour, were cooled to ambient temperature in a desiccator. Thereafter, the moisture-free samples of D1-D5 wood biomass were fed into a covered crucible placed in a muffle furnace and heated to 950 ºC for 7 minutes and then allowed to cool to ambient temperature in a desiccator.





Figure 1**:** Mahogany Wood Figure. 2**:** Fixed-bed batch reactor Figure. 3: Torrefied Mahogany

Torrefied Biomass Characterization

The percentage of moisture content (Mc), volatile matter (Vm), and ash content of the tested sample is calculated using equations 1 to 3, while equations 4 and 5 were employed mathematically to calculate the fixed carbon and bulk density of the sample, respectively. The sample percentage elemental composition, which consists of the following elements: Hydrogen (H), Carbon (C), Nitrogen (N), Sulphur (S), and Oxygen, was also calculated using equations 6 to 10.

$$Mc = \frac{m_1 - m_2}{m_1} X100 \quad (1)$$

$$Vm = \frac{m_2 - m_3}{m_1} X100 \quad (2)$$

$$Ac = \frac{Wc - We}{Ws} 100\% \quad (3)$$

$$FC = 100 - (Mc + Ac + \%Vm) \quad (4)$$

$$Bd = \frac{W_{de}}{V_C} \quad (5)$$

$$\mathrm{C} = \frac{12Z}{44X} \times 100 \quad (6)$$

$$\mathrm{H} = \frac{2Y}{18X} \times 100 \quad (7)$$

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

$$\mathrm{S} = \frac{R * V * D_f}{Weight\ of\ sample\ used} x\ 100 \quad (9)$$

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

Where; m_1 is the weight of the specimen, m_2 is the weight of the specimen after drying in 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 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 the determination (cm^3), W_g is the weight of the sample (g).

Calorific Value and Gas Chromatography-Mass Spectrometry (G C-MS) Analysis

The initial oven-programmed temperature was set at 40°C and continued for 4 min, rising by 5°C/min to 250°C for 10 minutes. All the peaks were identified based on mass spectral matching with 90% or greater spectral matching accuracy. A known amount of the samples D1-D5 for Mahogany wood biomass was burned at constant pressure and under standard conditions (0°C and 1 bar), and the heat released was captured in a known mass of water in a calorimeter after 30 minutes, as found by equation 11. The net calorific value (NCV) is the difference between the Gross calorific value (GCV) and the Latent heat of water vapor. GC-MS was adopted for drug detection, fire investigation, environmental analysis, explosives investigation, and identification of the samples. The strengths of GC/MS analysis helped with quantitative analysis and the determination of traces of organic contamination.

$$H/M = (m_w C_w + Q_c)\,\Delta T \qquad (11)$$

where H is heating energy absorbed (J), ΔT is temperature change (°C), M is mass of biomass, m is mass of water (g), Q_c is heating energy (J/kg°C), and C_w is specific heat capacity (J/kg°C) for water. The resulting energy value divided by the grams of samples D1-D5 for Mahogany wood biomass burned gives the energy content (in J/kg).

Scanning Electron Microscopy (SEM) Analysis

After cleaning the surface, stabilizing, rinsing, dehydrating, drying, mounting, and coating the sample with a thin layer of 20 nm of gold, Energy Dispersive X-ray Spectroscopy (SEM-EDX Hitachi SU 3500 scanning microscope shown in Figure 4) analysis was utilized to observe the physical morphology of sample surfaces and to analyze the element compositions, including the visible light elements such as carbon, nitrogen and oxygen, as well as the analysis on the contamination (quality of the content).

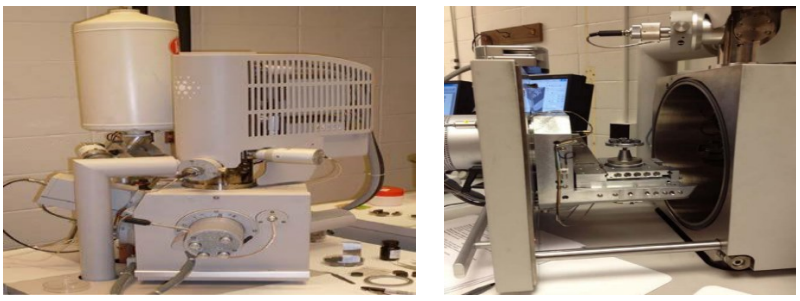


Figure 4: SEM and Hitachi SU 3500 scanning microscope

Results and Discussion

Proximate Analysis of the Biomass Sample

The results of the proximate analysis of moisture, volatile matter, ash, and the calculation of fixed carbon in Mahogany wood biomass samples for controlled samples D1 to D5 are shown in Table 1. The Fixed Carbon content increases with an increase in torrefaction temperature in comparison to the untreated biomass sample. implying enhancement of the torrefied sample Fuel Value Index (FVI). This behavior is more pronounced as observed in sample D4 at 285°C and the resident temperature. These specific treatments impact the composition of mahogany wood, altering its elemental contents and providing valuable insights into the thermal behavior of mahogany wood. This observation is consistent with the report from the previous study by Razi *et al.* (2018). Table 2 shows the bulk density of the wood changes under various treatment conditions for D1 to D5 before and after torrefaction processes. Compared to the untreated biomass sample considered in this research, the torrefaction processes with the increase in torrefied temperature have led to a significant decrease in bulk density across all torrefied biomass samples, increasing the biomass porosity and improving their grindability and energy content. It should be highlighted that denser solid fuels burn longer and are more energy-efficient for storage/transport activities. This behavior is similar to that observed in the studies of (Chen *et al.,* (2015); and Oliveira-Rodrigues and Rousset 2009). The outcomes highlight the influence of thermal treatment conditions on the bulk density of mahogany wood, providing valuable information for understanding the physical changes induced by different treatment processes. The results of the elemental analysis of carbon, hydrogen, oxygen, nitrogen, and sulfur composition of samples D1-D5 are presented in Table 3. The variations revealed the potential alterations in the chemical structure of mahogany wood under different thermal treatment conditions. The results from the table revealed that the C content of the sample increases with the increase in the torrefaction temperature and residence time. It was also noticed that the H and O content of the sample decreased with the increase in the torrefaction temperature and the residence time. The change in nitrogen content is also observed to fluctuate with a slight difference and is thus considered constant. The increased carbon content enhanced energy potential, while changes in nitrogen, sulfur, and oxygen content influenced the combustion and gasification characteristics of the biomass sample tested. The achieved results reveal increases in C content and decreases in H and O contents, including the observed negligible N content of the tested mahogany wood sample, as the torrefaction temperature and the residence time increase in this research are consistent with those observed in the previous studies of (Amin and Murni (2011); Gevers *et al*., 2002).

Table 1: Proximate Analysis Result for Mahogany Wood (Mw)

S/N	Sample label	Moisture Content (%)	Volatile matter (%)	Ash content (%)	Fixed Carbon (%)
D1	Mahogany wood (Control)	14.76	73.79	4.14	7.31
D2	Mahogany wood (RT,275^{o}C,1hr)	6.09	42.19	5.58	46.15
D3	Mahogany wood (RT,275^{o}C,30mins)	4.32	31.24	7.34	57.10
D4	Mahogany wood (RT ,285^{o}C,1hr)	6.33	24.60	6.12	62.94
D5	Mahogany wood (RT ,285^{o}C,30mins)	5.48	42.24	3.80	48.48

Table 2: Result on Bulk Density for Mahogany Wood Biomass

S/N	Samples	Bulk density(kg/m^3)
D1	Mahogany (control)	53.17
D2	Mahogany (T(275C), RT (1hr))	19.95
D3	Mahogany (T(275C), RT (30mins))	25.50
D4	Mahogany (T (285C, RT (1hr))	13.34
D5	Mahogany (T (285C, RT (30 mins))	10.36

Table 3: Elemental Analysis result for Mahogany wood

S/n	Sample	C (%)	H (%)	N (%)	S (%)	O (%)
D1	Mahogany(control)	28.95	16.91	8.90	0.45	44.78
D2	Mahogany(T(275ºC),RT(1hr))	31.99	14.15	15.29	0.27	34.30
D3	Mahogany (T(275ºC),RT(30mins))	41.32	13.99	15.62	0.15	38.92
D4	Mahogany (T(285ºC,RT (1hr))	48.67	11.52	10.00	0.32	27.50
D5	Mahogany (T(285ºC,RT (30 mins))	44.19	10.29	15.06	0.12	30.34

Calorific Value and Sem Results

The heating value of different mahogany wood samples is expressed as higher calorific value (HCV) and lower calorific value (LCV). As shown in Tables 4 to 6, at higher temperatures and longer durations, the thermal treatment significantly increases both HCV and LCV of the torrefied samples in this study. This indicates an improved energy potential for combustion or other energy conversion processes, as observed for the increased FC and C aforementioned in Tables (2 and 3) thus increasing its energy potential, making it a more energy-efficient biomass feedstock for energy production. Tables 4, 5, and 6 show the elemental composition of samples 1 (control D1), 02 (285ºC 1Hr, D4), and 03 (275 ºC 30min, D3).

From the tables, the SEM-EDX analysis reveals a structurally diverse sample with fine particles contributing to its rough surface. The dominance of silicon, along with the presence of oxygen, potassium, and other elements, gives a complex composition. The torrefaction process has induced structural change and is affected by notable changes in carbon content and other elements. Table 7 presents the varying percentages of carbon, oxygen, aluminum, silicon, iron, potassium, sulfur, and calcium contributing to the altered composition after torrefaction. Samples 04 and 05 indicate signs of torrefaction-induced changes, including a porous surface and elemental composition. Figures 7 to 13 show the EDX and SEM Chromatograph images of Samples D1 to D5 used for experimentation. Sample D1 has a rough surface due to the high percentage of Sulphur, low density, and poor grindability. This is because, the observed rough surface and particle clusters suggest a complex microstructure, which could impact the material's properties and behavior. Samples D2-D5 were treated biomass samples, which show a porous, loosely packed structure with fine particles and improved grindability and high energy content, as presented in Figures 9-12 (SEM images).

Table 4: Elemental Composition of Sample 01 (control D1),

Element	Composition (%)
Carbon (C)	4.30
Oxygen (O)	33.67
Aluminum (Al)	0.85
Silicon (Si)	50.29
Iron (Fe)	0.65
Potassium (K)	6.32
Sulphur (S)	2.87
Calcium (ca)	0.79

Table 5: Elemental Composition of Sample 02 (275ºC 1Hr, D2)

Element	Composition (%)
Carbon (C)	31.90
Oxygen (O)	12.46
Aluminum (Al)	0.54
Silicon (Si)	45.23
Iron (Fe)	0.92
Potassium (K)	4.15
Sulphur (S)	3.25
Calcium (ca)	1.54

Table 6: Elemental Composition of Sample 03 (275 ºC 30min, D3

Element	Composition (%)
Carbon (C)	28.61
Oxygen (O)	19.03
Aluminum (Al)	0.63
Silicon (Si)	40.52
Iron (Fe)	0.75
Potassium (K)	6.18
Sulphur (S)	2.84
Calcium (ca)	1.31

Table 7: Elemental Composition of Sample 04 (285ºC 1Hr, D4)

Element	Composition (%)
Carbon (C)	35.63
Oxygen (O)	10.73
Aluminum (Al)	0.71
Silicon (Si)	41.84
Iron (Fe)	0.74
Potassium (K)	7.13
Sulphur (S)	1.87
Calcium (ca)	1.32

Microstructural Analysis of the Biomass Sample

As depicted in Figures (9-13), Heat treatment induced a series of complicated chemical reactions, such as decatillation, depolymerization, cross-linking, and recondensation, which resulted in cracks in the cell walls. The mass loss rate increases with increasing temperature, and the degradation of wood components results in cracks in the cell walls. The hardness of the cell walls increased after heat treatments (See Figure 13), which reduced creep behavior compared to the untreated one (See Figure 7). The observed enhanced hardness of the torrefied biomass samples' cell walls and the microstructure shows that the energy content of the torrefied mahogany wood sample improved the efficiency and effectiveness of the biomass for more sustainable and cost-effective fuel sources.

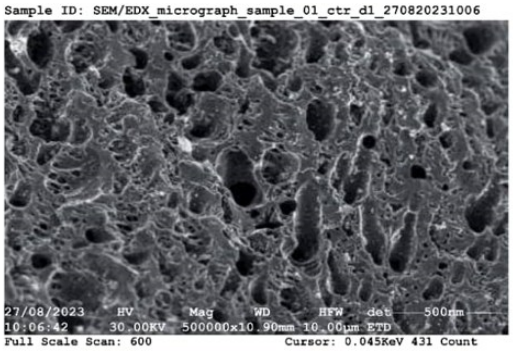


Figure 7: SEM Analysis of Sample D1

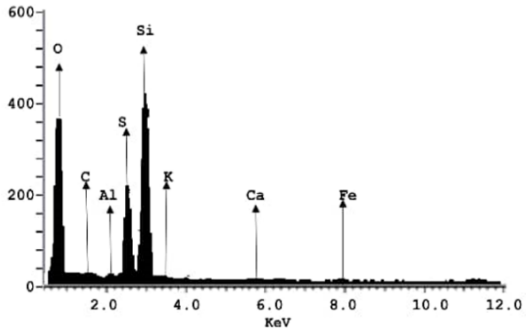


Figure 8: EDX Analysis of Sample D1

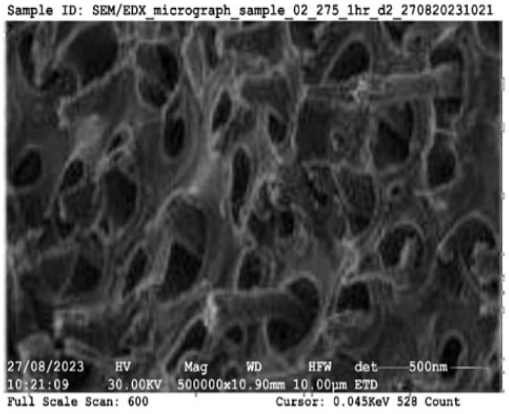


Figure 9: SEM Analysis of Sample of D2

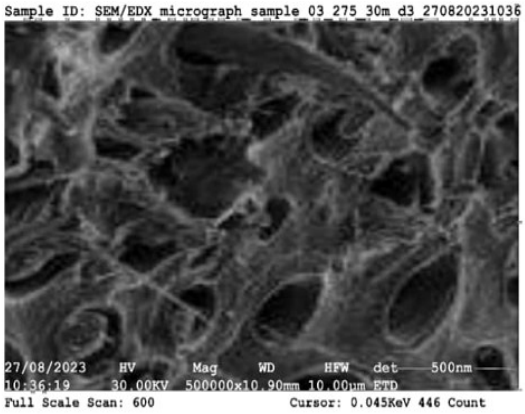


Figure 10: SEM Analysis of Sample D3

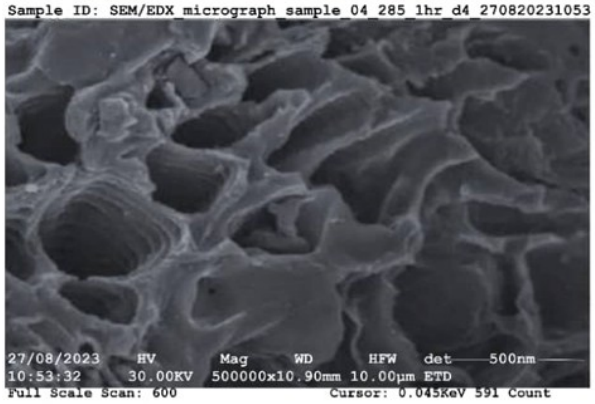


Figure 11: SEM Analysis of Sample of D4 SEM

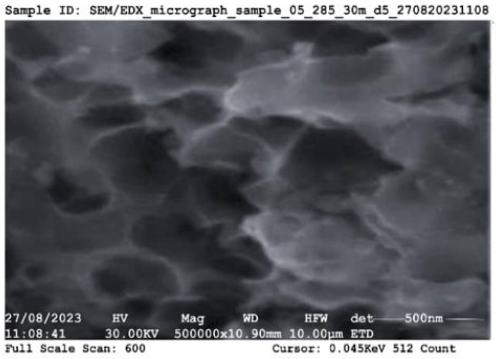


Figure 12: SEM Analysis of Sample D5

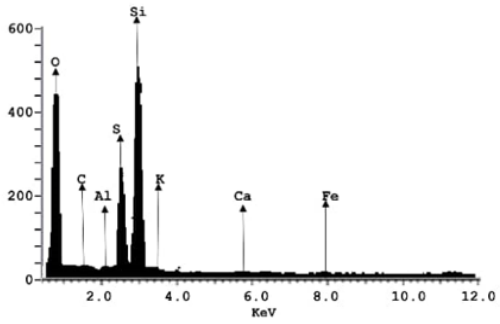


Figure 13: EDX Analysis of Sample D5

Conclusions

The study converted woody mahogany biomass into a valuable energy resource by utilizing waste materials from forestry, agriculture. The production of solid fuel from mahogany wood and the analysis of the microstructural characteristics' influence on its energy content were conducted. The proximate analysis, bulk density measurements, elemental analysis, calorific value determination, and SEM-EDX analysis, and the effects of thermal treatment on the produced solid fuel were investigated. The results showed the impact of temperature and duration on the composition of mahogany wood by reducing moisture and volatile matter, increasing ash content, and higher fixed carbon, suggesting successful carbonization. This shift in composition has significant implications for the suitability of mahogany wood as a biomass feedstock for increasing energy output and practicality. At higher temperatures and longer durations, there was a decrease in bulk density, indicating structural changes. These findings underline the potential to tailor wood density based on treatment conditions for applications in biomass processing. Alterations in carbon content, along with changes in other elements, suggest a transformation in the chemical structure of mahogany wood and an impact in the material's reactivity, energy yield, and suitability for various applications. Calorific value results indicated that thermal treatment significantly enhanced the energy potential of

mahogany wood, making it a more efficient and viable feedstock for energy conversion processes. SEM-EDX analysis provided a visual structure, particle sizes, and elemental compositions after torrefaction. These insights offer valuable information for optimizing torrefaction conditions for specific energy applications.

Recommendations

The study recommends that;

i. Torrefied product can be upgraded into briquette form using a briquette pelletizer machine. This will also reduce the bulk density for easy storage and transportation.
ii. Thermal treatment, especially higher temperature and longer duration, significantly increases the HHV and LCV of mahogany wood. Thus, temperatures higher than 285 degrees should be worked on too for greater energy production.

Acknowledgements

The Authors (MTS), (AOF), (EJF), (AA), and (ATO) acknowledge the management of Federal University of Technology, Akure, Nigeria, for the administrative and technical support towards the success of the research work.

References

Amin A. J, and Murni M. A. (2011) Torrefaction of Malaysian Palm Kernel Shell into Value-Added Solid Fuels, World Academy of Science, Engineering and Technology International Journal of Chemical and Molecular Engineering Vol:5, No:12, 1106-1109

Chen, W.H., Peng, P., 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

Chin, K., Ibrahim, S., Hakeem, K., H'ng, P., Lee, S., and Mohd L.M. (2017). "Bioenergy production from bamboo: Potential source from Malaysia's perspective," *BioRes.* 12(3), 6844-6867.

García, R., González-Vázquez, M.P., Martín, A.J. and Pevida, C. and Rubiera, F. (2020). "Pelletization of torrefied biomass with solid and liquid bio-additives Renew", Energy, 151, pp. 175-183

Gaurav, G.K., Mehmood, T., Cheng, L., Klemeš, J.J. and Shrivastava, D.K. (2020). "Water hyacinth as a biomass: a review", J. Clean. Prod., 277, Article 122214

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

Heredia S.M., Tarelho, L.A.C., Rivadeneira, D., Ramírez, V. and Sinche, D. (2020) "Energetic valorization of the residual biomass produced during *Jatropha curcas* oil extraction Renew", Energy, 146, pp. 1640-1648

Ibitoye, S.E., Jen, T.C. Mahamood, R.M. and Akinlabi, E.T. (2021). "Generation of Sustainable Energy from Agro-residues through Thermal Pretreatment for Developing Nations: A Review", Adv. Energy Sustain. Res., 2, Article 2100107.

Joselin Herbert GM, Unni Krishnan A. (2016). Quantifying the environmental performance of biomass energy. Renew Sustain Energy Rev 2016; 59: 292–308

Lin, M., Ranyu, W., Pengwei, X., Yonglin, L., Xiankun, H., Hongchao, Y. and Ming, D. (2022). "Comparative investigation on the pyrolysis of crop, woody, and herbaceous biomass: Pyrolytic products, structural characteristics, and CO_2 gasification", Vol. 335(1) 2126940 https://doi.org/10.1016/j.fuel.2022.126940

Oliveria Rodrigues T and PLA Rousset (2009) "Effects of Torrefaction on Energy Properties of Eucalyptus Grandis Wood," Cerne, 15:4, pp. 446–452

Razi, A. Mohd-Azlan M. I., Khudzir, I., Nur-Nasulhah, K. (2018) Influence of Torrefaction on Gasification of Torrefied Palm Kernel Shell, Advances in Science, Technology and Engineering Systems Journal Vol. 3, No. 5, 166-170

Romero, J.A., Daniele, D., Vittorio, M., Sara D.S., Carmine D. F. and Giuseppe, T. (2023) "Preliminary Study on the Thermal Behavior and Chemical-Physical Characteristics of Woody Biomass as Solid Biofuels. Department of Agricultural, Food and Environmental Sciences, Università Politecnica Delle Marche, Via Brecce Bianche, 60131 Ancona, Italy", *Processes* 2023, *11*(1), 154; https://doi.org/10.3390/pr11010154

San M.G, Sánchez, F., Pérez, A. and Velasco, V. (2022). "One-step torrefaction and densificationof woody and herbaceous biomass feedstocks Renew", Energy, 195, pp. 825-840

Tilahun, F.B., Bhandari, R. and Mamo, M. (2021). "Design optimization of a hybrid solar-biomass plant to sustainably supply energy to industry: methodology and case study" Energy, 220, Article 119736.

Uddin, M.N., Taweekun, J., Techato, K., Rahman, M.A. Mofijur, M. and Rasul, M.G. (2019). "Sustainable biomass as an alternative energy source: Bangladesh perspective", Energy Procedia, 160, pp. 648-654

Yoo, H.M., Park, S.W., Seo, Y.C. and Kim, K.H. (2019). "Applicability assessment of empty fruit bunches from palm oil mills for use as bio-solid refuse fuels", J. Environ. Manag., 234, pp. 1-7.