Assessing Bamboo culm of Different Ages as Potential Solid Fuel for Power Generation

Aliyu Buba Ngulde
Department of Chemical Engineering, University of Maiduguri

Wan Azlina Wan Binti Abdulkarim Ghani
Sustainable Process Engineering Research Centre (SPERC), Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia

Nazmi Mat Nawi
Institute of Plantation Studies, Universiti Putra Malaysia

Umer Rashid
Institute of Nanoscience and Nanotechnology, Universiti Putra Malaysia

他

https://doi.org/10.5109/7342476

出版情報：Evergreen. 12 (1), pp.574-582, 2025-03. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
バージョン：

Assessing Bamboo culm of Different Ages as Potential Solid Fuel for Power Generation

Aliyu Buba Ngulde[1,2,*], Wan Azlina Wan Binti Abdulkarim Ghani[3], Nazmi Mat Nawi[2,4], Umer Rashid[5,6,7], Silas Kiman[1]

[1]Department of Chemical Engineering, University of Maiduguri, PMB 1069, Maiduguri, Borno State, Nigeria

[2]Institute of Plantation Studies, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia

[3]Sustainable Process Engineering Research Centre (SPERC), Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia

[4]Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia

[5]Institute of Nanoscience and Nanotechnology, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia

[6]Center of Excellence in Catalysis for Bioenergy and Renewable Chemicals (CBRC), Faculty of Science, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand

[7]Department of Chemical Technology, Faculty of Science, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand

*Author to whom correspondence should be addressed:
E-mail: abngulde@unimaid.edu.ng

(Received March 15, 2024; Revised February 5, 2025; Accepted March 4, 2025).

Abstract: Bamboo as a lignocellulosic biomass is one of the most abundant non-timber plants of tropical and sub-tropical regions in the world. In-effectiveness in the utilization of conventional biomass in their raw form to generate electricity in the biomass thermal power plant is largely associated with low heating value, high moisture content, and high impurity. This study investigates the potential of torrefied bamboo as an enhanced biofuel for electricity generation. The objective was to improve the fuel properties of bamboo culms of varying ages (1, 1.5, and 2 years) to overcome the limitations of raw biomass in biomass thermal power plants. In this paper, three different bamboo culms samples were torrefied and analyzed using ultimate analysis, proximate analysis and calorific value (CV) of each feedstock. It was found that BBC C after torrefaction has CV of 22.59MJ/Kg against an initial of 16.17MJ/kg, elemental carbon of 54.8wt.% with H/C and O/C ratios of 0.10 and 0.72 respectively The findings highlight the novelty of torrefied bamboo samples to generally have better fuel properties such as lower moisture content, higher elemental carbon and significantly improved calorific value making it suitable for use either independently or in a blend with other fuel types such as coal in the furnaces of power plants for the purpose of generating electricity. Additionally, for torrefied char applications in combustion engines, older bamboo culms are recommended for optimal performance.

Keywords: Bamboo; Ultimate Analysis; proximate analysis; Calorific Value, Torrefaction

1. Introduction

The global warming caused by the increased CO_2 concentrations has emerged as one of the most critical issues to be globally addressed[1] and the top two sectors contributing to many countries emissions are forestry and energy, largely emissions from deforestation, and power generation[2]. With the rising energy demand arising from rapid industrialization and urbanisation[3] the other renewable energy sources showcase great potentials of replacing fossil in their utilization for power generation[4]. In line with policy target to achieve net zero emission by the year 2030, biochar has shown potential of green bio-coal candidate for power generation[5]. As a renewable energy source, biomass is the fourth largest energy source worldwide in terms of capacity after coal, oil and natural gas[6] with the decline in fossil fuel[7]. Bamboo is an economically important plant group of enormous utilities and offers extensive genetic diversity, the plant group harbors approximately 1670 species representing 125 genera and are spread across 22.0 × 106 ha of the forest areas across the world[8]. Bamboo is considered a promising solution to mitigate climate change because of its carbon sequestration capability and versatile applications[9]. Bamboo is one of the fast-growing perennial herbaceous plant in south eastern Asia and it also possesses important fuel characteristics such as low-ash content and alkali index[10]. The treated bamboo that used chemical treatment were improved the bonding strength and reduced water absorption more than 50% compared to the untreated bamboo[11]. Bamboo strips can be disintegrated into bamboo fiber bundles using alkali treatment and crushing by flat press[12]. The composite from these fiber bundles thus obtained have better mechanical properties[13]. Bamboo is highly renewable with better strength to weight ratio than conventional building materials and wood[14].

The conversion of waste biomass into bioenergy appears to be a workable solution to the energy crisis[15]. Solid biofuel sometimes referred to as biochar[16] is one of the most effective strategies to attain the carbon peak by 2030 and carbon neutrality by 2060 due to its similar utilization path of coal[17]. Production methods and activation conditions have high impact on biochar characteristics[18]. Renewable and bio-based materials conversion into commodity chemicals is a promising strategy to reduce society's dependence on petrochemical-based production[19], which is expected to contribute significantly to the push for sustainable development[20].Using torrefied char, or bio coal, as solid fuel provides an opportunity to introduce a sustainable feedstock into the energy market[21]. It seems to be a suitable method of introducing renewable energy to existing power plants[22]. Coal power plants provide 30 % of global primary energy needs[23] and generate more than 41 % of the world's electricity[24]. While traditional uses of coal (i.e., combustion) are associated with the release of CO_2 emissions into the atmosphere[25], Co-Combustion of sub-bituminous coal with biomass[26] /bio-coal improves combustion efficiency and emission of CO_2 and SO_2[27], hence the need to process biomass before further use as solid fuel need not to be overemphasized[28]. The aim of this work however is to assess the potentials of bamboo as a suitable solid fuel candidate for power generation by taking advantage of the baboo plant culm of different ages[29] extensively reviewed the potential of different bamboo species of diverse height and thickness in energy generation, while[30] highlighted the need for their continuous cultivation in Malaysia for biofuel production. Bamboo as described by[31], differ in terms of density and tissue arrangement compared to other biomass, in addition to exhibiting structural changes while aging. Unlike other studies where the feedstock is used regardless of its age, this study investigates the properties of different age bamboo stems as their properties may vary, thereby affecting its feasibility for power generation. Thus, the specific objectives of this work are to determine the proximate, ultimate, calorific values, TGA and DTG data of bamboo culm of varying ages and pinpoint the bamboo age (whether young or older) with the best fuel property for power generation. The motivation of this work is the urgent need to mitigate global warming and achieve net zero emissions necessitate exploring renewable energy sources like bamboo, which offers significant carbon sequestration potential and fuel properties. Furthermore, improving biomass utilization through torrefaction addresses inefficiencies in raw biomass combustion for power generation. This study is novel since it uniquely evaluates bamboo culms of varying ages to determine the optimal harvest period for superior fuel properties, enabling its effective use as bio-coal for sustainable energy production.

2. Experimental

2.1 Samples

The feedstock used in this study, which is the Raw bamboo culm *Dendrocalamus asper* (Buluh Betung) was collected from a bamboo plantation in Kuala Kubu Baru, a domain in Malaysia. Three different sample culms of ages 1, 1.5, and 2 years of stem length of 9.4m, 9.45m, 12.7m and stem mass of 7.4kg, 8.7kg and 16kg respectively was collected and the raw sample was later chopped into smaller particle size with the aid of a mechanical chopping machine and then stored in sample bags labelled A, B and C respectively and then subsequently used at the Materials characterization laboratory where the proximate and ultimate analysis as well as calorific value analysis were carried out. Feedstocks A, B and C were dried in an oven for 24hrs at 105ºC. After this has been completed the preparatory step to the torrefaction experiment is concluded thereby making the samples easier to handle and further process.

2.2 Method

Torrefaction of Raw feedstock A, B and C was carried out using top lit updraft, auto thermally heated reactor, where about 50g of feedstock is fed in each run for period of 2 hours under an inert atmosphere at a temperature of 300ºC. The choice of 300°C for torrefaction was based on literature[32] evidence that this temperature range enhances the thermal decomposition of hemicellulose, improves fuel properties such as calorific value, and minimizes energy losses during the process, this temperature is also optimal for producing bio-coal with desirable properties for power generation while maintaining the structural integrity of the biomass.

The samples are then left to cool off for at least 60 minutes before another run will be initiated. The process otherwise termed non oxidative torrefaction with the feedstock having no contact with air and a modification in the residence time of the feedstock in the reactor as well as the operating temperature. Proximate analysis was performed using Thermogravimetric Analyzer (Brand: Mettler Toledo and Model: TGA-DSC HT 3) for simultaneous thermal analysis (TGA/DSC). Each feedstock was ran starting from 25°C (room temperature) to 105°C at a heating rate of 20K/min under nitrogen gas flow at 50ml/min. Further heating was discontinued, and the temperature was kept at 105°C under nitrogen gas at 50ml/min for 3 minutes. The sample is now heated further from 105°C to 950°C at a heating rate of 50k/min under a nitrogen flow of 50ml/min after which the feedstock was left to cool off at a rate of -10k/min under nitrogen flow of 50ml/min until a temperature of 450°C was achieved where further heating will be continued at a rate of 50k/min until a temperature of 800°C is attained under an Air flow of 50ml/min. The feedstock will be held at this temperature of 800°C under air flowing at 50ml/min for five minutes after which no subsequent heating will be continued and profile for each sample is obtained.

Ultimate Analysis was carried out using the CHNS Analyzer (Thermo flash EA1112), here the combustion of weighed feedstock under a controlled /inert condition followed by the analysis of its gaseous products. During the combustion carbon is converted to CO_2, Sulphur to SO_2, hydrogen to H_2O and Nitrogen to NO_X. The products of combustion are then passed out of the combustion chamber through heated copper of high purity which can remove any oxygen reduce NO_x to N_2. Finally, the contents of Carbon, hydrogen, Nitrogen and Sulphur are detected through the release of CO_2, H_2O, N_2 and SO_2. The resulting data obtained gives the quantitative values of C, H, N and S values of each feedstock

Calorific value of feedstocks was detected using the oxygen bomb calorimeter (IKA C 2000) where feedstock in each sample run was fed in crucible with a thread to aid ignition of the sample which later filled with oxygen and then subsequently heated under Nitrogen gas for about 15-25 minutes depending on sample after which the calorific value will be displayed, and sample ejected from the chamber. This process is replicated for each feedstock age and the resulting Heating value is obtained and recorded as a key parameter to evaluate solid fuel quality and potential performance.

Table 1. Proximate and ultimate analysis of raw bamboo and torrefied bamboo at 300°C.

	Ultimate Analysis					**Atomic Ratio**		**Proximate Analysis**				**Calorific Value (MJ/Kg)**
	C	H	N	S	O	H/C	O/C	VM	FC	AC	MC	CV
RBS A	8.64	9.98	0.33	0.34	81.37	1.16	9.42	12.69	6.36	9.78	71.17	16.50
RBS B	9.16	9.83	0.36	0.40	80.98	1.07	8.84	16.76	9.89	27.67	45.68	16.10
RBS C	11.53	9.71	0.37	0.70	78.44	0.84	6.80	20.41	7.17	15.96	56.46	16.17
BBC A	54.87	5.50	0.18	0.10	39.35	0.10	0.72	89.17	1.96	1.82	7.05	18.59
BBC B	51.42	5.30	0.41	0.11	42.76	0.10	0.83	52.73	13.93	28.51	4.83	19.36
BBC C	54.81	5.26	0.62	0.12	39.19	0.10	0.72	52.80	1.69	40.12	5.39	22.59
Lignite[33]	66.10	4.70	0.73	0.31	30.10	0.85	0.07	0.46	47.00	3.83	13.40	14.0
Bituminous[33]	83.5	4.95	1.90	0.90	8.01	0.71	0.06	0.10	60.30	5.10	1.70	30.20

Oxygen calculated by difference in ultimate analysis, (dry ash free basis). Proximate analysis on dry basis: Volatile matter, Fixed carbon, this study.

Atomic Mass Used:

H=1
C=12
O=16
Note:

O (wt.%) = 100wt%− C (wt.%) – H (wt.%) – N (wt.%) – S (wt.%) (1)

FC (wt.%) = 100wt%− AC (wt.%) – VM (wt.%) – MC (wt.%) (2)

In Table 1 above Ultimate analysis data are presented which entails the Carbon, hydrogen, Nitrogen, and Sulphur contents of each feed stock on dry ash free basis. However, the oxygen content in the respective bamboo samples and resulting torrefied feedstock are obtained by subtracting the values of the respective constituents from 100wt.% as illustrated by equation 1 above. This is also reported by[34]. Notable increase is seen in Carbon values from the least aged feed stock 8.64% carbon to 11.53% carbon in the oldest unprocessed feedstock. A similar pattern is observed in the decreasing oxygen content from 81.37% in RBS A to 80.98% oxygen content in RBS B with the least oxygen content in the raw samples seen in RBS C. Decrease in hydrogen content for non-torrefied samples is also observed from 9.98% in the least aged feedstock to 9.71% in RBS C, further affirming decrease in moisture content with increase in age consistent with decreased oxygen and hydrogen contents with increased age in non-torrefied feedstocks above. An increase in Nitrogen and Sulphur Contents from 0.33% to 0.37% as well as 0.34% to 0.70% respectively in RBS A and RBS C are also noted with increase in age of the feedstock similar to the findings of[35]. After torrefaction has taken place the carbon content in the oldest feedstock improved significantly to 54.81% with least hydrogen contents of 5.26% as well as oxygen contents of 39.19% and the highest Nitrogen and sulfur contents of 0.62% and 0.12% respectively, thus indicating that devolatilization as well as dehydration that accompanies the torrefaction process is evident consistent with the findings in[36].

On the other hand, proximate analysis data reveals information such as moisture content, volatile matter, fixed carbon, and ash content which can be evaluated mathematically by equation 2. For the non-torrefied set of data RBS C has a meager fixed carbon content of 7.17% compared to RBS A that has a fixed carbon content of 6.36%. the highest moisture content value was seen the youngest feedstock consistent with the decreasing hydrogen and oxygen content observed with increasing age earlier revealed by the ultimate analysis values. After torrefaction has taken place, fixed carbon content is increased to 13.93% in BBC B with a moisture content that has been significantly reduced to 4.83% and volatile matter at 52.73%. This is also reported in[37].

Considering[38] the H/C and O/C ratios it can be seen that when the feedstock was not torrefied, it exhibited high ratios in relation to carbon which is greater than 1, with the highest ratios of 1.

16 and 9.42 seen in RBS A further affirming hydrophilicity, however RBC C has a relatively lower hydrophilicity due to its age with ratios of 0.84 and 6.80 as H/C and O/C ratios respectively. After torrefaction the materials has been transformed to relatively hydrophobic materials with ratios less than 1, as seen in BBC C with H/C and O/C ratio of 0.10 and 0.72 respectively with 0.10 and 0.83 for BBC B.

There is an evident increase in the calorific value of non-torrefied feedstock with increase in age from RBS A to RBS C. There is an increasing calorific value of torrefied feedstock with increased in age as it is seen from approximately 18.6MJ/Kg in the torrefied youngest feedstock to 19.40MJ/Kg in BBC B and lastly to the oldest torrefied which is BBC C at approximately 22.60 MJ/Kg. the heating value obtained for the feedstock suggests that it supersedes lignite in terms of its energy content and can compete favorably with sub bituminous coal in terms of its overall energy content thus suggesting its use for complete replacement of coal or blending with

3. Results and Discussion

Figure 1 shows the TGA and DTG of Raw samples A, B and C. TGA Shows the percent weight loss with increase in temperature while the DTG is indicative of the rate of weight loss with increase in temperature. For the raw samples A, it can be observed that the weight loss is in three regimes like its rate, the first loss observer from room temperature to 105ºC is linked directly to the moisture content of the sample. The loss is a physical change where moisture is stripped from the feedstock consistent with the values obtained in Table 1 above and reported by[38]. The second weight loss was observed after heating from 105ºC to 950ºC which is attributed to the volatile matter presence in the feedstock. The third weight loss regime is indicative of the fixed carbon content of the material while the residue that was gotten is perceived to be the Ash content found therein, similar to reports in[39].

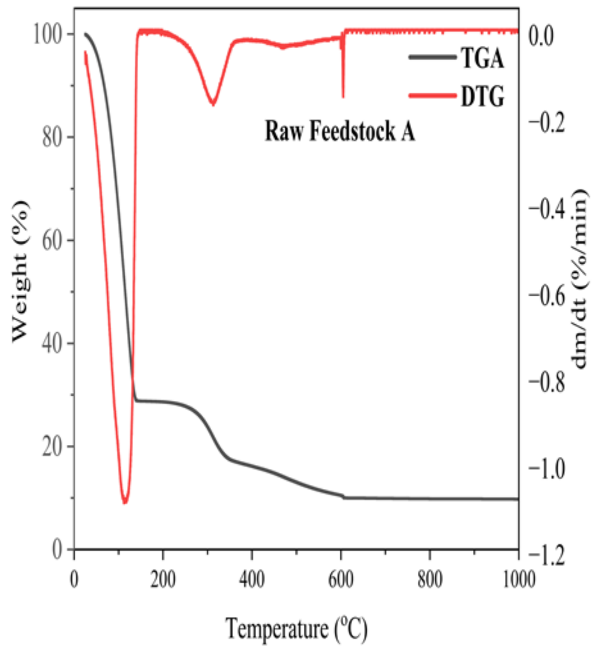

Fig. 1: TGA and DTG of raw feedstock A.

Similar weight loss regimes exist for Fig. 2 below, where its moisture content, volatile matter, fixed carbon, and ash content were evaluated like that of A as shown in Table 1 above, the rapid rate of loss is usually seen during the moisture content loss between 25ºC to 105ºC and the least is observed during the fixed carbon evaluation regime for raw sample that has not been treated. The feedstock is wet/hydrophilic, however the devolatilization stage shows less weight loss on the TGA plots as well as slow rates of loss on the DTG. This finding is consistent with that reported by[40].

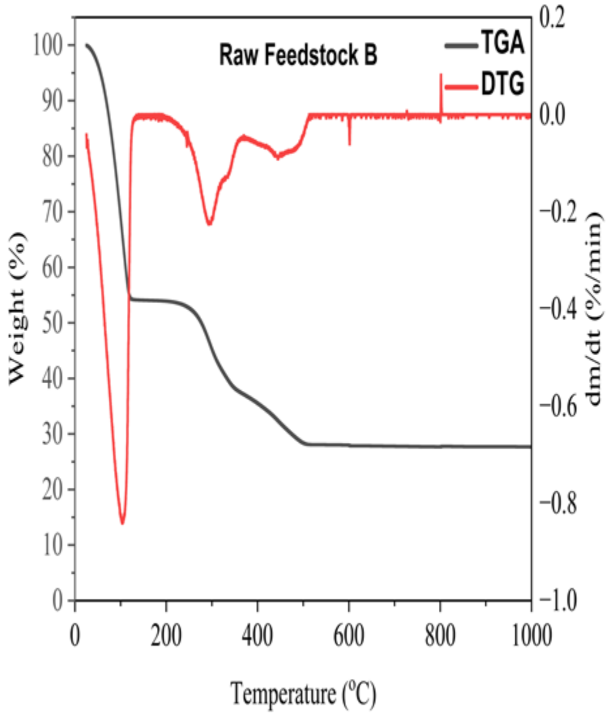

Fig. 2: TGA and DTG of raw feedstock B

Observation of similarity was also seen in Fig. 3 below; where the weight loss profile in the first instance lasted less longer compared to that seen in RBS A and RBS B which can be attributed to the feedstock less amount of moisture in relation to the two other feedstock as supported by values in Table 1 above, however, the sample C tends to have a relatively high fixed carbon content and the highest elemental carbon level among the three feedstocks used in this study similar to[39]. This is indicative that it exhibits a relatively fair solid fuel property prior to its processing[41].

Atomic Ratio (O/C, H/C) of the feed stock A, B and C is indicative that bamboo is highly hydrophilic in its raw form because of the visible greater than one ratio seen in the raw feedstock suggesting the dominance of hydrogen and oxygen over carbon in several folds. However, after treatment, it was found that the hydrophobicity of bamboo was greatly improved with H/C ratios of as low as 0.10 and O/C ratio 0.72 found in BBC C compared to the highest H/C and O/C found in RBS A of 1.16 and 9.42 respectively which indicative of lower solid fuel stability in this form. However, the solid fuel is more stable after torrefaction as show by atomic ratio parameter in Table 1. This is in conformity with the work[36]. Further processing by torrefaction for its candidature as a solid fuel is however justifiable, considering its poor parameters in its raw form suggesting the treatment will improve its solid fuel essentials such as increased calorific value, elemental and fixed carbon and reduced moisture and volatile matter content.

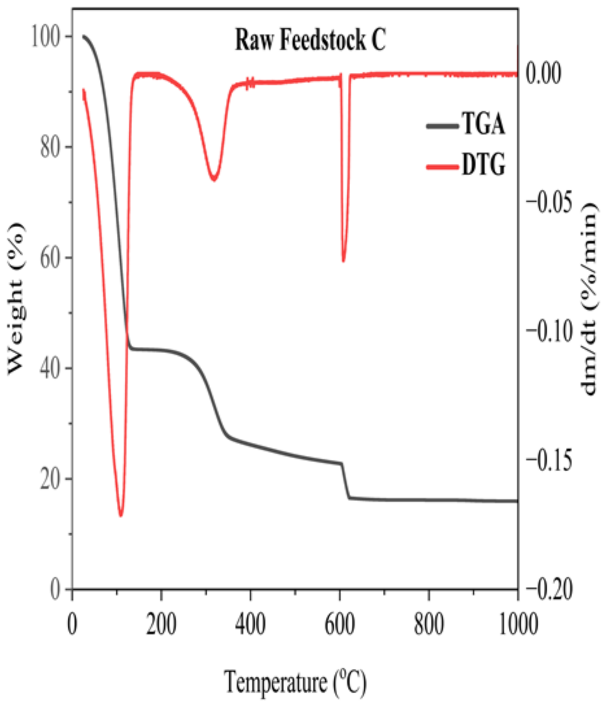

Fig. 3: TGA and DTG of raw feedstock C.

After torrefaction was carried out at 300°C, the weight loss against temperature as well as the rate of weight loss in relation to temperature which are the TGA and DTG plot is represented by Fig 4, 5 and 6 below respectively. For the three feedstocks, however a distinctive variation was observed in TGA, DTG, Calorific value and CHNS parameters which are powerful tools for the measurement of thermal stability of materials. Firstly, in BBC A as shown by Fig. 4, transformation in the carbon hydrogen, Nitrogen, sulfur, and oxygen contents was observed with elemental carbon standing at 54.87wt.% against an initial 8.64 wt.% in RBS A. Calorific value increased significantly from 16.50MJ/kg to 18.59MJ/kg indicating positive improvement in solid fuel parameter consistent with TGA and DTG plots as observed by[34], which shows a lower moisture content and overall decrease in the rate of weight loss in the DTG plot as seen in Fig. 4 Below.

In Figure 5 there is also an improved calorific from 16.10 MJ/Kg in RBS B to 19.36MJ/Kg due to torrefaction effect as well as increased elemental carbon composition from 9.16wt.% in RBS B to 51.42wt.% in BBC B. TGA shows minimal drop in the first weight loss regime as a pointer to moisture content which implies a drop in moisture content with increased fixed carbon contents and the DTG plots also affirms by reduced rate of weight loss seen simultaneously with the loss of weight in TGA AS Show in Fig. 2 for BBC B. This was similarly reported in the work of[42]

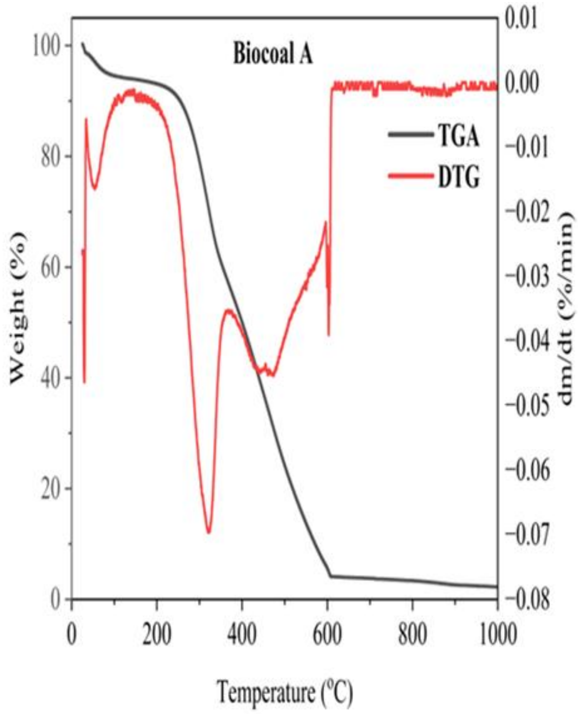

Fig. 4: TGA and DTG of torrefied feedstock A.

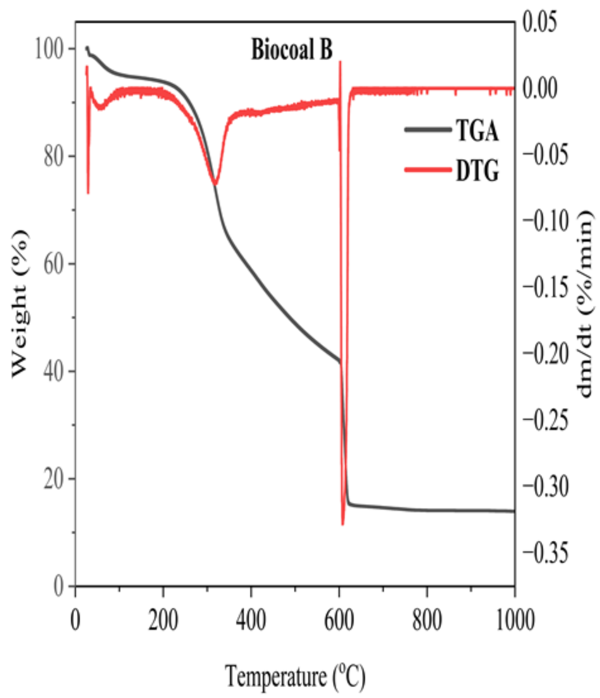

Fig. 5: TGA and DTG of torrefied feedstock B.

TGA and DTG Plots shown in Fig. 6 for BBC C shows a reduced drop in weight as well as the rate of loss of weight in comparison with RBS C TGA and DTG plots in Fig. 1 with moisture content lower than that of lignite coal as shown in Table 1. CHNS Values also appreciated significantly with torrefaction with an elemental carbon content of 54.81wt.% against an initial 11.53wt.% in RBS C consistent with the findings of[43]. Consequential increase in calorific value as a precursor for higher energy content was observed as BBC C has a CV of 22.59MJ/Kg against an initial 16.17MJ/kg before the torrefaction of the feedstock at 300 °C.

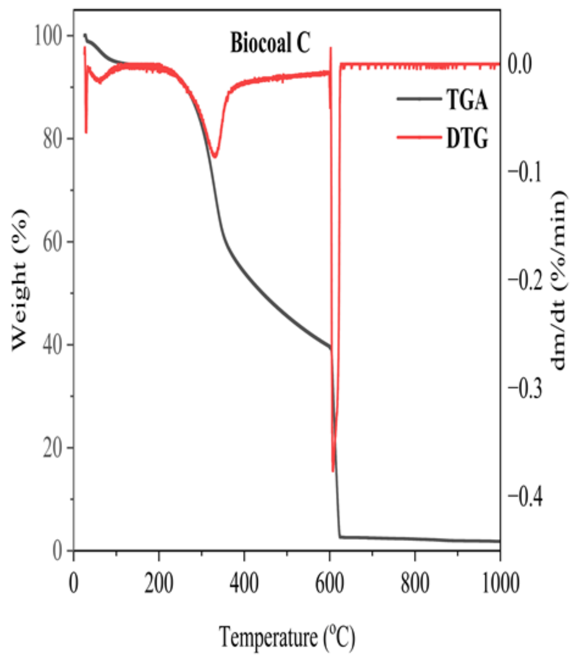

Fig. 6: TGA and DTG of torrefied feedstock C.

4. Conclusion

Bamboo is highly hydrophilic in its raw form with high H/C and O/C ratios, it also has low calorific value, high moisture content, low elemental, and fixed carbon respectively. Torrefaction of the RBS A, B and C to produce BBC A, B, C at 300°C has greatly improved the feedstock into a solid fuel which is relatively hydrophobic with calorific value as high as 22.59MJ/Kg greater than that of lignite coal, better elemental and fixed carbon contents was similarly observed. In a note shell the older bamboo sample RBS C which was torrefied to BBC C tend to exhibit better fuel property prior to and after treatment among the three samples hence implying that torrefaction is a suitable technique to produce solid fuel from biomass. In view of that, the older the bamboo culm, the better the fuel property and ability to serve as biofuel in power combustion engines. While this study focused on evaluating the fuel properties of bamboo culms of varying ages for power generation, future studies should explore the technoeconomic feasibility of utilizing torrefied bamboo for large-scale applications. Investigating production costs, scalability, and market integration would provide valuable insights into its practical implementation and economic viability.

Acknowledgements

I wish to acknowledge the profound support and contributions of the staff of the Universiti Putra Malaysia especially Encik Ismail of Combustion Engineering Laboratory, Ali Rani of the Institute for Nanoscience and Nanotechnology and the the OSS staff of PTDF. This research is funded by the Geran Inisiatif Putra Siswazah (GP-IPS), GP_IPS/2023/9768900 and the Petroleum Technology Development Fund (PTDF) under PTDF/ED/OSS/PHD/EAB/1829/20 by 22PHD035.

Nomenclature

TGA	-Thermogravimetric Analysis
DTG	-Differential Thermogravimetric Analysis
CV	-Calorific Value
MC	-Moisture Content
VM	-Volatile Matter
FC	-Fixed Carbon
AC	-Ash Content
Wt.%	-Weight Percent
MJ/Kg	-Mega Joule/ Kilogram
RBS	-Raw Bamboo Sample
BBC	-Bamboo Bio Coal

References

1) A. Kismanto, R. Fajar, N.K. Supriatna, Aminuddin, F.J. Ermada, S. Yarsono, R.P. Dewa, L.M.T.

Nainggolan, R. Alamsyah, and A. Surjosatyo, "Techno-economic assessment of a 1,200 liter rotary kilnbatch reactor for the production of oil from plastic waste," *Evergreen*, 10 (*3*) 1877–1888 (2023). doi:10.5109/7151738.
2) W. Eko, B. Joy, W. Setyawati, and R. Mahdi, "Materials today : proceedings projection of co 2 emissions in indonesia," *Mater. Today Proc.*, 63 S438–S444 (2022). doi:10.1016/j.matpr.2022.04.091.
3) M.S. Reza, S. Afroze, K. Kuterbekov, A. Kabyshev, K. Zh. Bekmyrza, M.N. Haque, S.N. Islam, M.A. Hossain, M. Hassan, H. Roy, M.S. Islam, M.N. Pervez, and A.K. Azad, "Advanced applications of carbonaceous materials in sustainable water treatment, energy storage, and co2 capture: a comprehensive review," *Sustain.*, 15 (*11*) 8815 (2023). doi:10.3390/SU15118815/S1.
4) J. Santosa, A.H. Kuncoro, A. Dwijatmiko, N.W. Hesty, and A. Darmawan, "The role of nuclear power plants in indonesia towards net zero emissions (nze) in 2060 with a multi regions approach," *Evergreen*, 10 (*03*) 1660-1673 (2023). doi:10.5109/7151715
5) M.S. Md Said, A.A. Azni, W.A. Wan Ab Karim Ghani, A. Idris, M.F.Z. Ja'afar, and M.A. Mohd Salleh, "Production of biochar from microwave pyrolysis of empty fruit bunch in an alumina susceptor," *Energy*, 240 122710 (2022). doi:10.1016/j.energy.2021.122710.
6) J. Li, X. Yao, J. Ge, Y. Yu, D. Yang, S. Chen, K. Xu, and L. Geng, "Investigation on the pyrolysis process, products characteristics and bp neural network modelling of pine sawdust, cattle dung, kidney bean stalk and bamboo," *Process Saf. Environ. Prot.*, 162 752–764 (2022). doi:10.1016/j.psep.2022.04.055.
7) M.S. Reza, S. Afroze, K. Kuterbekov, A. Kabyshev, K. Zh. Bekmyrza, J. Taweekun, F. Ja'afar, M. Saifullah Abu Bakar, A.K. Azad, H. Roy, and M.S. Islam, "Ex situ catalytic pyrolysis of invasive pennisetum purpureum grass with activated carbon for upgrading bio-oil," *Sustain.*, 15 (*9*) 7628 (2023). doi:10.3390/SU15097628/S1.
8) S. Biswas, T. Rahaman, P. Gupta, R. Mitra, and S. Dutta, "Biomass and bioenergy cellulose and lignin profiling in seven , economically important bamboo species of india by anatomical , biochemical , ftir spectroscopy and thermogravimetric analysis," *Biomass and Bioenergy*, 158 (*September 2021*) 106362 (2022). doi:10.1016/j.biombioe.2022.106362.
9) J. Gan, M. Chen, K. Semple, X. Liu, C. Dai, and Q. Tu, "Life cycle assessment of bamboo products: review and harmonization," *Sci. Total Environ.*, 849 (*June*) 157937 (2022). doi:10.1016/j.scitotenv.2022.157937.
10) B. Zheng, Y. Zhu, S. Zheng, Y. Mo, S. Sun, J. Ren, Y. Li, A. Wu, and H. Li, "Upgrade the torrefaction process of bamboo based on autohydrolysis pretreatment," *Ind. Crops Prod.*, 166 (*January*) 113470 (2021). doi:10.1016/j.indcrop.2021.113470.
11) N. Syazwani Saadun, M.A. Majid, M. Hanif Ismail, and S. Hani Adnan, "An overview on physical and mechanical properties of bamboo as a natural reinforcement in concrete," *IOP Conf. Ser. Earth Environ. Sci.*, 1022 (*1*) 1–9 (2022). doi:10.1088/1755-1315/1022/1/012049.
12) Z. Moldagazyyeva, M. Suleimenova, S. Abdreshov, and S. Kokanova, "Development of a comprehensive technology for processing consumer waste," *Evergreen*, 10 (*3*) 1199–1208 (2023). doi:10.5109/7148440.
13) C. Ramprasad, P.K. Kushwaha, S. Vidyashankar, M.R. Praveen Kumar, and B.K. Venkatesha, "Study on the physical and mechanical properties of strands obtained by disintegration of bamboo strip for manufacturing of moulded product," *Mater. Today Proc.*, 54 307–309 (2022). doi:10.1016/j.matpr.2021.09.176.
14) D. Kumar, and A. Mandal, "Review on manufacturing and fundamental aspects of laminated bamboo products for structural applications," *Constr. Build. Mater.*, 348 (*April*) 128691 (2022). doi:10.1016/j.conbuildmat.2022.128691.
15) M.S. Reza, J. Taweekun, S. Afroze, S.A. Siddique, M.S. Islam, C. Wang, and A.K. Azad, "Investigation of thermochemical properties and pyrolysis of barley waste as a source for renewable energy," *Sustain. 2023, Vol. 15, Page 1643*, 15 (*2*) 1643 (2023). doi:10.3390/SU15021643.
16) M.S. Reza, I. Zhanar Baktybaevna, S. Afroze, K. Kuterbekov, A. Kabyshev, K.Z. Bekmyrza, M.M. Kubenova, M.S.A. Bakar, A.K. Azad, H. Roy, and M.S. Islam, "Influence of catalyst on the yield and quality of bio-oil for the catalytic pyrolysis of biomass: a comprehensive review," *Energies 2023, Vol. 16, Page 5547*, 16 (*14*) 5547 (2023). doi:10.3390/EN16145547.
17) L. Ni, Z. Feng, T. Zhang, Q. Gao, Y. Hou, Y. He, M. Su, H. Ren, W. Hu, and Z. Liu, "Effect of pyrolysis heating rates on fuel properties of molded charcoal: imitating industrial pyrolysis process," *Renew. Energy*, 197 (*July*) 257–267 (2022). doi:10.1016/j.renene.2022.07.132.
18) M.H. Khan, N.M. Akash, S. Akter, M. Rukh, C. Nzediegwu, and M.S. Islam, "A comprehensive review of coconut-based porous materials for wastewater treatment and co2 capture," *J. Environ. Manage.*, 338 117825 (2023). doi:10.1016/J.JENVMAN.2023.117825.
19) K. Silas, A.B. Ngulde, and H.D. Mohammed, "Utilization of date tree leaves biomass for the removal of heavy metals from water," *J. Eng. Res. Sci.*, 1 (*4*) 137–147 (2022). doi:10.55708/js0104016.
20) X. Fang, Y. Li, J. Zhao, J. Xu, C. Li, J. Liu, Y. Liu, and H. Guo, "Improved interfacial performance of bamboo fibers/polylactic acid composites enabled by

a self-supplied bio-coupling agent strategy," *J. Clean. Prod.*, 380 (*P1*) 134719 (2022). doi:10.1016/j.jclepro.2022.134719.
21) N. Saha, E. Fillerup, B. Thomas, C. Pilgrim, T. Causer, D. Herren, and J. Klinger, "Improving bamboo's fuel and storage properties with a net energy export through torrefaction paired with catalytic oxidation," *Chem. Eng. J.*, 440 (*February*) 135750 (2022). doi:10.1016/j.cej.2022.135750.
22) A. Kumar, and A.K. Tiwari, "Solar-assisted post-combustion carbon-capturing system retrofitted with coal-fired power plant towards net-zero future: a review," *J. CO2 Util.*, 65 (*September*) 102241 (2022). doi:10.1016/j.jcou.2022.102241.
23) B. Pranoto, I. Adilla, H. Soekarno, N.K. Supriatna, Adrian, L. Efiyanti, D.A. Indrawan, N.W. Hesty, and S.R. Fithri, "Using satellite data of palm oil area for potential utilization in calculating palm oil trunk waste as cofiring fuel biomass," *Evergreen*, 10 (*3*) 1784–1791 (2023). doi:10.5109/7151728.
24) D.Y. Wiranata, S.H. Yang, C.M. Akgul, H.Y. Hsien, and M.Z.P. Nugraha, "Use of coal ash cement stabilized material as pavement base material: laboratory characterization and field evaluation," *Constr. Build. Mater.*, 344 (*June*) 128055 (2022). doi:10.1016/j.conbuildmat.2022.128055.
25) T.N. Gemeda, Y.T. Melaku, T.A. Chamada, and A.T. Adugna, "Optimization mixing ratio of the brewery waste water sludge and coal as energy source for cement industry and fuel ash effect on the raw material composition," *Environ. Challenges*, 7 (*July 2021*) 100476 (2022). doi:10.1016/j.envc.2022.100476.
26) I. Haryono, M.T. Suryantoro, B. Rochmanto, A. Kurniawan, A.T. Rohman, M. Ma'ruf, H. Setiapraja, T. Yuwono, N.M. Fuad, and E. Riswandi, "An effective three level filtration system for improved contaminant removal in high ratio biodiesel blends," *Evergreen*, 10 (*3*) 1633–1641 (2023). doi:10.5109/7151711.
27) C. Ellison, V. Abdelsayed, M. Smith, and D. Shekhawat, "Comparative evaluation of microwave and conventional gasification of different coal types: experimental reaction studies," *Fuel*, 321 (*April*) 124055 (2022). doi:10.1016/j.fuel.2022.124055.
28) N.A. Nudri, W.A. Wan Abdul Karim Ghani, R. Thomas Bachmann, B.T.H.T. Baharudin, D.K.S. Ng, and M.S. Md Said, "Co-combustion of oil palm trunk biocoal/sub-bituminous coal fuel blends," *Energy Convers. Manag. X*, 10 100072 (2021). doi:10.1016/j.ecmx.2020.100072.
29) Z. Liang, A. Neményi, G.P. Kovács, and C. Gyuricza, "Potential use of bamboo resources in energy value-added conversion technology and energy systems," *GCB-Bioenergy*, 15 (*8*) 936–953 (2023). doi:10.1111/gcbb.13072.
30) K.N.A.K. Aizuddin, K.-S. Lai, N.A. Baharum, W.T.L. Yong, L.N. Hoon, and M.Z. Abdul Hamid, "Bamboo for biomass energy production," *BioResources*, 18 (*1*) 2386–2407 (2023). doi:10.15376/biores.18.1.Aizuddin.
31) C.D. Montaño, and J.E.G. Van Dam, "Potential of bamboo for renewable energy: Main issues and technology options," 2021.
32) K.A. Abdulyekeen, W.M.A.W. Daud, and M.F.A. Patah, "Torrefaction of wood and garden wastes from municipal solid waste to enhanced solid fuel using helical screw rotation-induced fluidised bed reactor: effect of particle size, helical screw speed and temperature," *Energy*, 293 (*February*) 130759 (2024). doi:10.1016/j.energy.2024.130759.
33) T. Abbas, P. Costen, N.H. Kandamby, F.C. Lockwood, and J.J. Ou, "The influence of burner injection mode on pulverized coal and biomass co-fired flames," *Combust. Flame*, 99 (*3–4*) 617–625 (1994). doi:10.1016/0010-2180(94)90055-8.
34) J. Cai, Y. He, X. Yu, S.W. Banks, Y. Yang, X. Zhang, Y. Yu, R. Liu, and A. V. Bridgwater, "Review of physicochemical properties and analytical characterization of lignocellulosic biomass," *Renew. Sustain. Energy Rev.*, 76 (*March*) 309–322 (2017). doi:10.1016/j.rser.2017.03.072.
35) S. Sattasathuchana, J. Parnthong, S. Youngian, K. Faungnawakij, P. Rangsunvigit, B. Kitiyanan, R. Khunphonoi, A. Wanichsombat, N. Grisdanurak, and P. Khemthong, "Energy efficiency of bio-coal derived from hydrothermal carbonized biomass: assessment as sustainable solid fuel for municipal biopower plant," *Appl. Therm. Eng.*, 221 (*September 2022*) 119789 (2023). doi:10.1016/j.applthermaleng.2022.119789.
36) S.H. Park, J.H. Jang, N.J. Wistara, F. Febrianto, and M. Lee, "Fuel properties of indonesian bamboo carbonized at different temperatures," *BioResources*, 14 (*2*) 4224–4235 (2019). doi:10.15376/biores.14.2.4224-4235.
37) R. Kumar, J. Gunjal, and S. Chauhan, "Effect of carbonization temperature on properties of natural fiber and charcoal filled hybrid polymer composite," *Compos. Part B Eng.*, 217 (*December 2020*) 108846 (2021). doi:10.1016/j.compositesb.2021.108846.
38) K.A. Abdulyekeen, W.M.A.W. Daud, M.F.A. Patah, and F. Abnisa, "Torrefaction of organic municipal solid waste to high calorific value solid fuel using batch reactor with helical screw induced rotation," *Bioresour. Technol.*, 363 (*September*) 127974 (2022). doi:10.1016/j.biortech.2022.127974.
39) L. Ni, Z. Feng, Q. Gao, Y. Hou, Y. He, H. Ren, M. Su, Z. Liu, and W. Hu, "A novel mechanical kiln for bamboo molded charcoals manufacturing," *Appl. Energy*, 326 (*September*) 119937 (2022). doi:10.1016/j.apenergy.2022.119937.
40) C.F. Yu, B. Jiang, L. Yuan, Y. Zhang, B. Ji, Y. Zheng, and B. Ren, "Inhibiting effect investigation of

ammonium dihydrogen phosphate on oxidative pyrolysis characteristics of bituminous coal," *Fuel*, 333 (*P2*) 126352 (2023). doi:10.1016/j.fuel.2022.126352.

41) Q. Gao, T. Zhang, Z. Feng, J. Yang, L. Ni, W. Hu, and Z. Liu, "Energy performances of molded charcoals from bamboo and chinese fir blends: influence of pyrolysis temperatures and residence times," *Ind. Crops Prod.*, 177 (*January*) 114500 (2022). doi:10.1016/j.indcrop.2021.114500.
42) E. Garcia, I.F. Ejim, and H. Liu, "Thermogravimetric analysis of co-combustion of a bituminous coal and coffee industry by-products," *Thermochim. Acta*, 715 (*July*) 179296 (2022). doi:10.1016/j.tca.2022.179296.
43) Z. Ma, Y. Zhang, Y. Shen, J. Wang, Y. Yang, W. Zhang, and S. Wang, "Oxygen migration characteristics during bamboo torrefaction process based on the properties of torrefied solid, gaseous, and liquid products," *Biomass and Bioenergy*, 128 (*March*) 105300 (2019). doi:10.1016/j.biombioe.2019.105300.