Thermochemical Characterization of Oil Palm Fronds, Coconut Shells, and Wood as A Fuel For Heat and Power Generation

Muddasser Inayat[1,*], *Shaharin* A. Sulaiman[1], and *Muhammad* Yasin Naz[2]

[1]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia
[2]Department of Physics, University of Agriculture, 38040 Faisalabad, Pakistan

Abstract. This study investigated the thermochemical characterization of oil palm fronds (OPF), coconut shells (CS) and wood for their use as a solid fuel for thermal conversion processes. The ultimate analysis, proximate analysis, calorific values, and elemental contents through energy dispersive X-ray spectroscopy of OPF, CS, and wood samples were measured. The results of OPF and CS were compared with wood considered as benchmark solid fuel. Proximate analysis was performed as per ASTM standard procedure in a muffle furnace and used thermos-gravimetric analysis technique. The ultimate analysis was used to determine the weight percentage of carbon, hydrogen, and nitrogen in CHNS analyzer. Elements analysis was done using energy dispersive X-ray spectroscopy. The ultimate analysis results show carbon content was higher in CS as compared to OPF and wood. The hydrogen content was higher in OPF. Proximate analysis results revealed that volatile matter was higher in wood, whereas fixed carbon and higher heating value were found higher in CS while ash content was lower in CS. From EDX results found that the OPF has Al, Si, Cl, and K, while, in wood and CS these elements are absent. The thermochemical characterization results of OPF and CS were comparable with the wood. Therefore, it concluded that OPF and CS have the potential to be used as renewable energy source by using appropriate energy conversion technologies, such as gasification, pyrolysis, and torrefaction.

1 Introduction

World's industrial and commercial activities result in a rapid increase in energy demand day by day, limited fossil fuels resources, and their high rate of pollutant emissions are serious problems of the 21st century [1, 2]. The bioenergy is a renewable, sustainable and environmentally friendly alternative to fossil fuels. Currently, biomass conversion processes have emerged as a rapidly growing field of science and technology endeavored to fulfill ever-growing energy demand [3, 4]. Biomass is normally obtained from green plants that convert sunlight, carbon dioxide, and water into energy via photosynthesis. The nature of biomass considered as organic because the sunlight energy stored in the plants in the form of chemical

---

* Corresponding author: muddasser_engr@yahoo.com

bonding energy. This chemical bonding of biomass can be broken down using different thermochemical techniques such as combustion, pyrolysis, and gasification [5].

Malaysian agricultural sector contributes the huge amount of biomass resources. However, palm oil wastes contribute the largest source of biomass in Malaysia with approximate 4.5 million hectares plantation area at 5% annual growth [6]. There are two sources of palm oil waste one at generates at plantation site during harvesting (oil palm fronds (OPF)) and other produces during oil extraction process at the factory (empty fruit brunch (EFB), palm kernel shell (PKS), palm oil mill effluent (POME), and mesocarp fiber). On an average one hectare of palm oil plantation can generate 50-70 tonnes of biomass residues [6, 7]. Nearly all type of biomasses produced during the oil extraction process are commercially utilized, mainly in energy and manufacturing sectors. Nevertheless, oil palm fronds (OPF) have very limited usage. Oil palm trees are pruned during the harvesting of fresh fruit bunches to produce oil. The fronds are pruned regularly but have little use and are mainly left on the ground in a huge quantity for the slow process of natural decomposition. It mainly consists of the hard and fibrous petiole and the leaflets. The average bulk density of OPF was reported to be about 700 kg/m^3 and the weight of each frond is between 15 and 20 kg depending on the age of the palm tree [8]. Similarly, to oil palm, coconut is also belong to palm family and it is another industrial crop in Malaysia, which is the third biggest in plantation area size. Basically, coconut is a source of edible oil and coconut milk, which is the main ingredient of most of Malaysian foods. In 2009, the total domestic coconut production was about 459,000 tons. From coconut processing, coconut husk (0.166 Mton), coconut shell (0.735 Mton), coconut frond (0.103 Mton) and coconut empty bunches (0.022 Mton) are obtained as a by-products [9]. These potential biomasses can be utilized for heat and power generation via different thermochemical process.

Another big source of biomass supply in Malaysia is forest and timber processing factories. These timber factories and woodland are considered as one of the major unexploited biomass sources in Malaysia. The wood waste generated during the logging operation is 5.1 million m^3 in form of stumps, branches, bark, tops, broken logs, defective logs and injured standing trees, all these are 43% of total volume of the tree [9]. About 70-75% of the global wood harvest is either used or potentially available as a renewable energy source [10]. Therefore, the wood base lignocellulosic biomass materials are considered as a potential source of energy in the Malaysian context, which could be exploited by thermochemical conversion process [9].

In this paper, thermochemical properties of oil palm fronds, coconut shells, and wood examined, and results of oil palm fronds and coconut shells are compared with wood considered it as a benchmark biomass, for various thermal conversion process such as pyrolysis, torrefaction, gasification and as well as for general incineration purposes.

2 Methodology

2.1 Collection and preparation of feedstock

Freshly pruned oil palm fronds (*Elaeis guineensis*) were collected from the FELCRA palm oil plantation site in Bota Kanan, approximately 220 km to the Northwest of Kuala Lumpur. At the plantation site, the leaflets were removed from OPF with a machete, divided it into three to four petioles with approximate sizes of 0.75 to 1.0 m long intended for ease in handling and transportation of OPF from the plantation site to the laboratory. Wood (*acacia mangium*) was collected from the landscape area within the campus of Universiti Teknologi PETRONAS, which was made available during the annual tree trimming activities. Wood logs diameter varied from 4 cm to 20 cm with an approximate length of 0.75 to 1.0 m. The

third feedstock is coconut shells, scientifically known as *Cocos nucifera L*. Coconut shell is a by-product of coconut milk processing industries. Sufficient amounts of coconut shells are available at grocery stores that make coconut milk from fresh copra. Coconut shells for the present study were collected from grocery stores nearby Universiti Teknologi PETRONAS. The leaflets of the fronds and outer fiber of the coconut shells were removed and were then ground and sieved to 250 μm particles for feedstock characterization. The ultimate analysis was determined by using CHNS analyzer, Leco CHNS-932 model. According to ASTM D3176-09 standard procedure [11]. Moisture content, volatile matter, ash content were determined by ASTM E871-82 [12], ASTM E872-82 [13], and ASTM E1755-01 [14] respectively. The fixed carbon content was found from outstanding mass after the release of volatiles excluding the ash and moisture contents [15]. The calorific values were determined in the Leco AC-350 automatic bomb calorimeter by ASTM D4809-00 standard procedure [16]. A SUPRA 55VP model FESEM analyzer in combination with EDX was used examine the surface morphology and desired elements present in samples at nanometer scale.

3 Characterization results of biomass feedstock

Characterization of biomass materials includes ultimate and proximate analysis, heating value and element analysis. The ultimate analysis is an important factor to assess the properties of fuels like percentages of N and S, which concern with the environmental impact of biomass. Additionally, it helps to calculate the percentage of C, H, and O of biomass materials. On the other hand, proximate analysis is an essential way to understand the gasification phenomenon of biomass materials, while a heating value portrays the amount of energy released by the unit mass of solid biomass, which shows its potential as bio-fuels. Moreover, element analysis presents the inorganic elements like potassium, sodium, chlorine, and silicon in biomass materials.

3.1 Ultimate analysis

Ultimate analysis is important in determining the basic composition of a feedstock to know the suitability of the feedstock for energy production [17]. Table 1 shows the results of ultimate and proximate analysis of processed (dried, ground and sieved) feedstock of wood, coconut shells and OPF feedstock on weight percentage. The carbon content of coconut shell was high at 46.93% (by weight) as compared to other biomass materials (wood and OPF). The high carbon content implies a good potential of coconut shell to utilize as feedstock. OPF has high hydrogen content at 5.71%, which is associated with the strong domination of water gas reaction. Lower nitrogen (0.42%) and sulphur (0.16%) contents in the OPF and wood, respectively, lower contents of these elements in fuel portray that fuel is eco-friendly. Lower concentrations of sulphur and nitrogen yield lower oxides of these elements and its derivatives emit in the open atmosphere. This will increase the potential of aforementioned fuels as an environmental friendly renewable energy source. Based on ultimate analysis of OPF and coconut shells are found that these feedstocks comparable with the woody biomass.

Table 1. Characteristics of processed wood, coconut shell and OPF

Biomass	Ultimate Analysis (wt. %)					Proximate Analysis (wt. %)				HHV MJ/kg
	C	H	O*	N	S	MC	VM	FC*	Ash	
W	43.54	3.59	51.70	1.00	0.16	4.25	88.07	10.61	1.32	17.53
CS	46.93	3.96	48.21	0.71	0.19	2.29	81.67	17.50	0.83	19.43
OPF	42.60	5.71	51.00	0.42	0.29	6.15	80.55	16.43	3.02	17.00

W; Wood (*acacia mangium*), CS; Coconut Shells, OPF; Oil Palm Fronds. * On difference basis

3.2 Proximate analysis

The proximate analysis included moisture content, volatile matter, fixed carbon and ash content on the weight basis. Processed OPF has high moisture content 6.15%, followed by wood 4.25% and coconut shell 2.29% on a wet basis. As shown in Fig. 2c, OPF has porous structure and it has an intensity to absorb moisture from the surrounding atmosphere. Therefore, it is very hard to keep moisture level at the lower side, due to the hygroscopic nature of OPF. Similarly, wood also has same, as OPF to some extent, but wood is harder, denser and less porous as compared to the OPF as shown in Fig. 2a, thus it has a lower intensity of moisture absorption. On the other hand, coconut shell has a denser, harder, brittle and packed structure as compared to other biomass materials (wood and OPF) as shown in Fig. 2b. Therefore, it has less potential to absorb the moisture from surrounding due to its morphological aspects. Plant-based biomass contains high volatile matter and low fixed carbon [18]. Similarly, a current proximate analysis result of wood has high volatile matters 88.07%, followed by coconut shell 81.67% and OPF 80.55%. These biomass materials have more than 80% volatile matters, which produce high gas yield and lower char. A lower ash content of biomass is a mark of good quality fuel. Coconut shells have a low ash content of 0.83%, followed by wood and OPF. OPF contained maximum 3.02% ash content by weight percentage.

The function of thermogravimetric analysis (TGA) is to categorize the devolatilization characteristics or weight loss of the feedstock sample with temperature is shown in Fig. 1. TGA technique is also used for characterizing proximate analysis in which weight loss is measured against the increasing temperature. First weight loss phase represents the moisture loss at temperature around 100°C. The second large continuous decreasing section represents the removal of volatile matter. While at the end of second last phase, a sharp decreasing slope shows the depletion of fixed carbon, at the end of weight loss curve, become almost the horizontal line represents the amount of unburned residual called ash content.
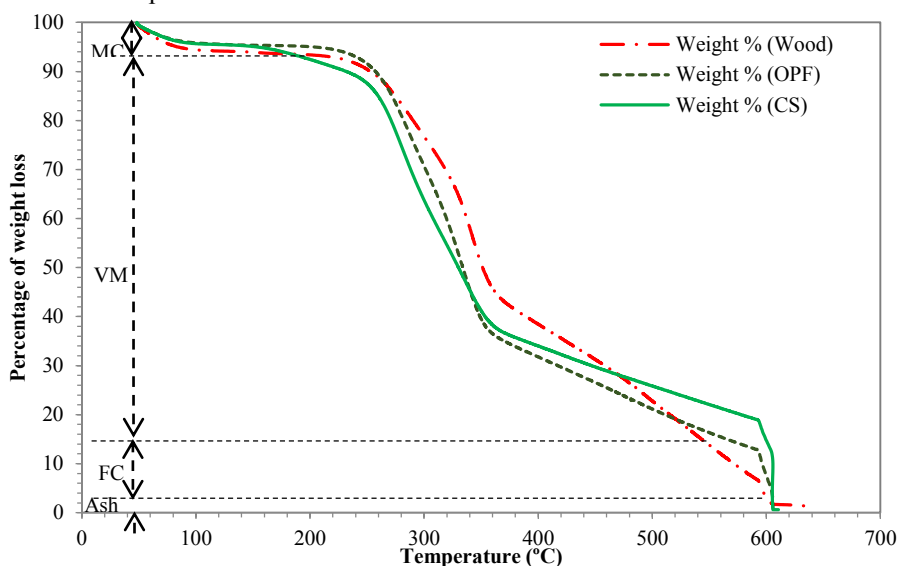

Fig. 1. Percentage weight loss of OPF, CS, and wood with temperature

The proximate analysis of wood, coconut shells and OPF, which is determined by ASTM methods, is shown in Table 1. In the proximate analysis, which is determined by ASTM standard procedure and thermogravimetric analysis (TGA), both results have a good agreement in terms of volatile matters and ash contents. The differences in results of volatile

matters determined by ASTM, from TGA results are 2.24%, 5.67% and 1.12% for wood, coconut shells and OPF, respectively. Whereas, the difference in fixed carbon from ASTM and TGA results are 4.21%, 1.17% and 6.1% for wood, coconut shells and OPF, respectively. The volatile matter content of the feedstock determined by TGA is slightly lower than the ASTM value. This might be caused by high temperature of ASTM procedure, which enhances the conversion from the solid phase to the gaseous phase. Fixed carbon of coconut shell has a high value of 17.50% among other feedstock followed by OPF 16.42% and wood 10.61%. In the ASTM standard procedure, fixed carbon is determined on a difference basis while, in TGA, fixed carbon is determined by the weight loss against temperature increase. Higher heating values (HHV) of coconut shell was 19.43 MJ/kg of HHV followed by wood 17.53 MJ/kg and OPF 17.00 MJ/kg. Wood and OPF HHV values are close to each other while, the coconut shell has a higher value.

3.4 Elemental analysis

The images obtained from FESEM shown in Fig. 2. The major elements of feedstock on weight percentage and atomic percentage, which are analyzed on the spectrum surface by using EDX, shown in Table 2. The values of carbon and oxygen contents from ultimate analysis results are lower than EDX analysis. The reason of this difference is that EDX is unable to detect hydrogen and nitrogen contents, which could be resultant higher carbon and oxygen contents during EDX analysis. Inorganic elements as shown in Table .2, only OPF has Al, Si, Cl, and K, while, in the wood and coconut shell these elements are absent. In fibrous part of OPF have 1.89% Cl and 2.36% K on a weight basis, whereas outer skin of OPF contained Si, Al, Cl, and K as 4.13%, 1.18%, 1.41% and 0.90% on a weight basis, respectively, while K in feedstock mainly contributed as catalytic effect. The presence of Cl and K elements in the OPF feedstock is probably due to the application of a chemical (KCl and K_2O) fertilizer at the fertilization stage of the oil palm tree.

Table 2. Elemental compositions of wood, coconut, OPF fiber and OPF skin obtained from EDX analysis

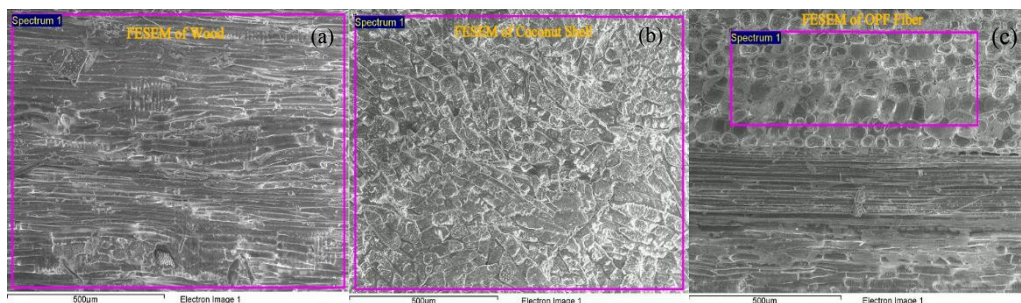| Elements	Wood		Coconut Shells		OPF (Fibre)		OPF (Skin)	
	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
C	55.72	62.63	54.91	61.86	39.58	47.62	53.08	61.99
O	44.28	37.37	45.09	38.14	56.17	50.74	39.31	34.46
Al	-	-	-	-	-	-	1.18	0.61
Si	-	-	-	-	-	-	4.13	2.06
Cl	-	-	-	-	1.89	0.77	1.41	0.56
K	-	-	-	-	2.36	0.87	0.90	0.32

Fig. 2. Field Emission Scanning Electron Microscopy (FESEM) image of (a) wood, (b) coconut shell, and (c) OPF fiber at 50X magnification

4. Conclusions

This study investigated the thermochemical characterization of OPF, CS, and wood. The results of OPF and CS were compared with wood. Carbon content was found higher in CS as compared to other biomass whereas hydrogen content was higher in OPF. The volatile matter was higher in wood, whereas fixed carbon and higher heating value were found higher in CS while ash content was lower in CS. EDX results found that only OPF has Al, Si, Cl, and K, while, in wood and CS these elements are absent. Characterization results of OPF and CS are comparable with the wood. Therefore, it concludes that OPF and CS have the potential to be used as renewable energy source by using appropriate energy conversion technologies, such as gasification, pyrolysis, and torrefaction.

References

1. M. Inayat, S. A. Sulaiman, A. Kumar, and F. M. Guangul, JMES. **10**, 2187-2199 (2016)
2. M. Inayat, S. A. Sulaiman, and K. Sanaullah, 4th IET CEAT. 1-7 (2016)
3. S. A. Sulaiman, R. Roslan, M. Inayat, and M. Y. Naz, J. Energ. Inst. **91**, 779-785 (2018)
4. S. A. Sulaiman, M. Inayat, H. Basri, F. M. Guangul, and S. M. Atnaw, JMES. **10**, 2176-2186 (2016)
5. P. McKendry, Bioresour. Technol. **83**, 37-46 (2002)
6. S. M. Shafie, T. M. I. Mahlia, H. H. Masjuki, and A. Andriyana, Renew. Sust. Energ. Rev. **15**, 4370-4377 (2011)
7. M. S. Umar, P. Jennings, and T. Urmee, Renew. Energ. **60**, 107-115 (2013)
8. S.A. Sulaiman, S. Balamohan, M.N.Z. Moni, S.M. Atnaw, and A. O. Mohamed, JEMS. **9**, 1744-1757 (2015)
9. M. Inayat, S. A. Sulaiman, and J. C. Kurnia, MATEC Web Conf., **131**, 03015 (2017)
10. M. Parikka, Biomass Bioenergy, **27**, 613-620 (2004)
11. D3176-09 *Standard Practice for Ultimate Analysis of Coal and Coke*, ed. West Conshohocken, ASTM International, (2009)
12. E871-82, Standard Test Method for Moisture Analysis of Particulate Wood Fuels, ed. Pennsylvania, USA, ASTM International, (2006)
13. R. Habibi, J. Kopyscinski, M. S. Masnadi, J. Lam, J. R. Grace, C. A. Mims, and J. M. Hill, Energy Fuels, **27**, 494-500 (2013)
14. E1755-01, Standard Method for the Determination of Ash in Biomass, ed. Philadelphia, USA, ASTM International, (2007)
15. P. Basu, Biomass Gasification, Pyrolysis, and Torrefaction Practical Design and Theory, Second ed. USA, Elsevier's Sci. Technol. (2013)
16. D4809-00, Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter, ed. Pennsylvania, USA, ASTM International, (2013)
17. S. A. Sulaiman, H. S. Bamufleh, S. N. A. Tamili, M. Inayat, and M. Y. Naz, Bull. Chem. Soc. Ethpa. **30**, 465-472 (2016)
18. R. Saidur, E. A. Abdelaziz, A. Demirbas, M. S. Hossain, and S. Mekhilef, Renew. Sust. Energ. Rev. **15**, 2262-2289 (2011)