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Energy Potential of Malaysian Forestry Waste Residues

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Abstract

The National Biomass Strategy (NBS-2020) was established in 2011 by the Malaysian government to identify and explore sustainable approaches to valorise the nation's abundant agricultural and forestry wastes. Therefore, this paper seeks to examine the solid biofuel and bioenergy potentials of *Acacia mangium* (ACM), *Macaranga* sp. (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves. The low cost, abundant, and lignocellulosic nature of the forestry wastes makes these resources potential feedstocks for biofuels and bioenergy applications. Hence, the residues were characterised by physicochemical and thermal analyses to determine their elemental composition, higher heating values, thermal degradation, and temperature profile characteristics. The results showed that the samples contain high carbon, hydrogen, and oxygen, along with low nitrogen and sulphur contents. Thermal analysis revealed significant mass loss ranging from 70% to 96% and residual masses between 3.8% and 29.9% based on the TG plots. In addition, the DTG plots showed that thermal degradation process occurred in three (3) stages; drying (25-110)°C, devolatilization (110-600)°C, and char degradation (600-800)°C during TGA. Based on the findings, the FGL is most suited for biochar production due to its high residual mass, whereas ACM could yield higher pyrolysis bio-oils and bio-gases.

Keywords *Biomass; Bioenergy; Forestry; Waste Residues; Malaysia.*

1. Introduction

The agroforestry industry in Malaysia is a significant contributor to socio-economic growth and sustainable development. According to the Agency for Innovation in Malaysia (AIM), the agroforestry industry contributes 8-10% of the gross domestic product of Malaysia [1]. However, the sector also generates large quantities of waste residues comprising woody or herbaceous materials, twigs, leaves, and roots [2-3]. Over the years, the accumulation of these residues in forests, farmlands, and plantations have aggravated the emission of greenhouse gases (GHG), loss of biodiversity, and ecosystem disruptions [4-7]. Furthermore, the lack of proper disposal, management or valorisation practices has caused significant environmental challenges such as forest fires, haze, and particulate matter pollution, which pose severe risks to human health and safety [7-9].

Considering these developments, the government of Malaysia (GoM) established the National Biomass Strategy (NBS-2020) to explore sustainable approaches to valorise the nation's vast agroforestry wastes [10]. The low cost, abundant, and lignocellulosic nature of forestry wastes suggests these resources could be potentially viable biomass feedstock for future clean energy recovery [11-13]. Consequently, the valorisation of forestry wastes has been examined by various biomass conversion technologies (BCT), including combustion, gasification, and pyrolysis [14-18].

Among these technologies, pyrolysis is considered the most practical approach for the valorisation of biomass-based resources into biofuels and biomaterials [19-20]. During pyrolysis, the high volatile matter and lignocellulosic content of biomass undergo devolatilization and thermochemical degradation into solid, liquid, and gaseous products. Therefore, pyrolysis is considered a crucial intermediate step for predicting the products yield, selectivity, and distribution during thermochemical conversion of biomass feedstocks [14, 20].

However, there are limited studies on the valorisation and bioenergy potential of forestry waste residues in Malaysia, particularly above-ground biomass (AGB) such as leaves. The high leaf litter accumulation rate and lignocellulosic nature of *Acacia mangium* (ACM), *Macaranga sp*. (MCG), Breadfruit tree (BFT), and Fig Tree (FGL) present promising potentials for bioenergy, biofuels, and biomaterials production. Therefore, this paper seeks to present preliminary findings on the solid biofuel properties and bioenergy potential of the forestry waste residues through non-oxidative (pyrolysis) thermochemical conversion.

2. Experimental

The *Acacia mangium* (ACM), *Macaranga sp* (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves examined in this study were acquired from the Skudai campus of Universiti Teknologi Malaysia. Next, the leaves were ground in a dry miller (Model: Panasonic MX-AC400TSK Mixer Grinder, Malaysia) and sieved using an analytical sieve (Mesh size 60, Retsch, Germany) to obtain particles below 250 µm for solid biofuel characterization and analyses. Next, the physicochemical analysis was performed to determine the elemental composition of the samples. Hence, the composition of carbon, hydrogen, nitrogen, sulphur and oxygen was determined using the elemental combustion analyser (Model: vario MACRO Cube Elementar, Germany). Lastly, the higher heating values (HHV) of the forest waste residues were calculated using the formula of Parikh *et al.* [21] as presented in Eq.1.

$$\text{HHV} = 3.6165 + 0.3181\text{C} + 0.6107\text{H} - 0.4380\text{N} - 0.0613\text{O} \qquad (1)$$

Thermal analysis was performed by thermogravimetric analysis (TGA). For each test, 11 mg of pulverised sample was placed in an alumina crucible and heated from 30 °C to 800 °C based on the non-isothermal heating program of the thermal analyser (Model: Shimadzu TG-50, Japan). On completion, the mass loss was computed as a function of temperature and time to determine the thermogravimetric (TG) and derivative (DTG) plots, as presented in Figures 1 & 2. Lastly, the thermal degradation behaviour was examined by temperature profile analysis. The temperature profile characteristics (TPC) of each sample was deduced using the Shimadzu thermal analysis software (TA Workstation). The software was used to determine the onset (ignition) (T_{ons}), midpoint (T_{mid}), endpoint (T_{end}), and devolatilization peak (T_{max}) temperatures along with the mass loss (M_L) and residual masses (R_M) of each sample under non-oxidative (pyrolysis) conditions during TGA.

3. Results and discussion

The elemental (CHNS), thermal (TGA/DTG), and temperature profile characteristics of the *Acacia mangium* (ACM), *Macaranga* sp. (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves are presented in this section of the paper. The elemental analysis typically presents crucial information on the physicochemical fuel properties of potential biomass feedstocks for energy applications, whereas the thermal and TPCs present insights into the thermal behaviour and degradation mechanisms or pathways during thermochemical conversion processes such as pyrolysis.

3.1. Physicochemical analysis

Table 1 presents the elemental composition and heating values of the forestry waste residues. As observed, the *Acacia mangium* (ACM), *Macaranga* sp. (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves contain carbon, hydrogen, nitrogen, sulphur and oxygen in various proportions. The compositions range from C = 32.27 - 51.86%; H = 4.33 - 6.61%; N = 0.84 - 1.63%; S = 0.07 - 1.06% and O = 38.84 - 62.38%.

Table 1. Physicochemical fuel properties of forestry waste residues

Element	ACM	BFT	FGL	MCG
C (wt.%)	51.86	36.54	32.27	46.10
H (wt.%)	6.61	4.84	4.33	5.54
N (wt.%)	1.63	0.84	0.96	0.97
S (wt.%)	1.06	0.11	0.07	0.14
O (wt.%)	38.84	57.68	62.38	47.24
HHV (MJ/kg)	21.06	14.29	12.28	18.35

The highest compositions of C, H, N, and S were observed in ACM, although it exhibited the lowest oxygen, which accounts for its high heating value of 21.06 MJ/kg. In comparison, FGL has the lowest C, H, S but the highest oxygen, which accounts for its rather low heating value of 12.28 MJ/kg. Overall, the HHV values are in good agreement with the findings of other biomass 14-20 MJ/kg and lignite coal reported in the literature [2, 22-24]. In addition, the lowest N content was observed in BFT.

Based on the higher heating values and physicochemical properties, ACM and MCG are the most suitable feedstocks for bioenergy recovery potential through thermal conversion. To further examine this, the thermal degradation behaviour of the samples was carried out under inert and non-isothermal thermogravimetric (TGA) conditions to determine its bioenergy recovery potential during pyrolysis.

3.2. Thermogravimetric analysis

Figures 1 and 2 present the mass loss or thermogravimetric (TG) and derivative mass loss or thermogravimetric (DTG) curves for the forestry waste residues of *Acacia mangium* (ACM), *Macaranga* spp. (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves.

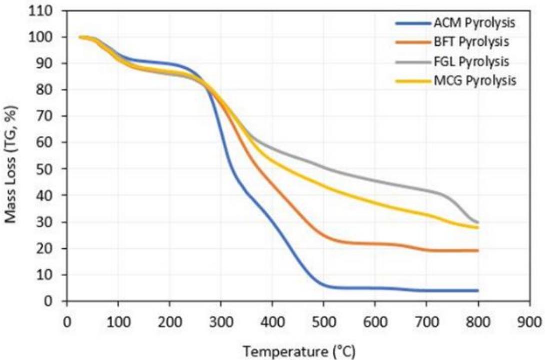

Fig. 1. TG plots of forestry waste residues

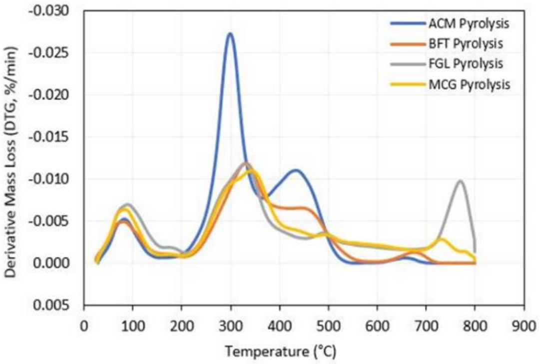

Fig. 2. DTG of forestry waste residues

The TG plots indicate the samples experienced significant mass loss, as evident in the downward sloping curves observed between 30°C and 800°C during TGA. The increase in temperatures caused significant loss of mass in the samples, which could be ascribed to the thermal degradation and devolatilization of the volatile matter and the lignocellulosic components such as hemicellulose, cellulose and lignin in the forestry waste residues examined during TGA. As observed in Figure 1, ACM experienced the highest mass loss during TGA, followed by BFT, MCG and FGL. The extent of the mass loss and thermal degradation behaviour of the samples based on the TG plots is presented in Table 2.

Likewise, the DTG plots showed that temperature exerted a significant effect on the thermal behaviour of the samples. As observed, the thermal degradation resulted in several endothermic peaks within the temperature range from 30°C to 800°C. Based on the number, shape, and size of the peaks, it can be reasonably inferred that thermal degradation occurred in the following ranges; (i) 25°C - 110°C (ii) 110°C - 600 °C, and (iii) 600°C - 800°C. The mass loss from 25°C - 110°C is typically ascribed to drying or loss of moisture during TGA, whereas it is ascribed to devolatilization or loss of volatile matter in the range from 110°C to 600 °C. Lastly, the mass loss in the range from 600°C to 800°C is ascribed to char degradation into gaseous products during TGA. The extent of the mass loss and thermal degradation of the samples based on the DTG plots is presented in Table 3.

3.3. Temperature profile analysis

The temperature profile characteristics (TPC) of the forestry waste residues of *Acacia mangium* (ACM), *Macaranga* sp. (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves were determined from the TG/DTG plots. Table 2 presents the TPCs deduced from the TG plots. The results indicate that the T_{ons} for the samples ranged from 215.22°C to 251.07°C; whereas the T_{mid} was from 318.17°C to 341.80°C; and lastly the T_{end} was from 384.47°C to 466.17°C. The lowest T_{ons} = 215.22°C was observed for FGL, which indicates it exhibits a low ignition temperature compared ACM, which begins thermal decomposition or devolatilization at 251.07°C. However, the lowest T_{end} = 384.47°C was observed for ACM, which indicates the sample completed devolatilization at lower temperatures compared to BFT, FGL and lastly MCG which exhibited the highest T_{end} = 466.17°C. Overall, the results showed that all the samples required temperatures above 200°C to begin devolatilization, although the process was completed below 470 °C during TGA.

Table 2. TGA-TPCs of forest biomass residues

Sample	Temperatures Onset (T_{ons}, °C)	Midpoint (T_{mid}, °C)	Endset (T_{end}, °C)	Mass loss (M_L, %)	Residual mass (R_M, %)
ACM	251.07	318.17	384.47	96.24	03.76
BFT	248.23	341.80	447.78	81.03	18.97
FGL	215.22	322.74	438.15	70.02	29.98
MCG	217.11	341.56	466.17	72.31	27.69

Lastly, the ML observed during TGA for the samples ranged from 70.02% to 96.24% resulting in the mass residuals (RM) ranging from 3.76% to 29.98%. The highest mass loss (M_L = 96.24%) and lowest residual mass (R_M = 3.76%) was observed for ACM, whereas FGL exhibited the lowest mass loss (M_L = 70.02%) but the highest residual mass (R_M = 29.98%). Based on the findings, it can be reasonably inferred that FGL could be most suited for biochar production due its high mass of residuals, whereas ACM could yield higher bio-oil and biogas due to its high mass loss and devolatilization. However, extensive reactor experiments and parametric studies are required to validate the product selectivity and distributions predicted.

Likewise, the DTG temperature profile characteristics of forest biomass residues are presented in Table 3. The data presents the peak decomposition temperatures during drying and devolatilization of the forest waste residues along with the mass loss during the three stages (SI, SII, and SIII) of the process during TGA.

Table 3. DTG-TPCs of forest biomass residues

Sample	Drying peak(°C)	Devolatilization peak (°C)	TGA Stages SI (%) 25 - 110°C	SII (%) 110 - 600°C	SIII (%) 600 - 800°C
ACM	83.63	299.86	7.50	87.78	0.96
BFT	80.55	330.94	9.69	68.76	2.58
FGL	89.60	329.42	8.58	45.77	15.67
MCG	85.00	343.24	9.36	53.61	9.34

The results show that the drying stage occurred between 80.55°C and 89.60°C, whereas the devolatilization was between 299.86°C and 343.24°C for all the samples. The samples FGL and BFT required the highest and lowest temperatures for the drying process respectively, whereas ACM and MCG exhibited the lowest and highest and temperatures for devolatilization. The findings indicate that ACM is the most thermally reactive with mass loss of 7.50% and 87.78% in stages SI and SII, respectively. In contrast, the highest mass loss in SI was observed for BFT, whereas the lowest mass loss in SII was observed at FGL, although this is compensated by the high mass loss in SIII.

4. Conclusion

The study presented preliminary findings on solid biofuel properties, and bioenergy potential of *Acacia mangium* (ACM), *Macaranga sp*. (MCG), Breadfruit tree (BFT) and Fig Tree (FGL) leaves. The forestry waste residues were characterised by CHNS analysis to determine their elemental composition and higher heating values. In addition, the thermal properties were examined by non-oxidative (pyrolysis) and non-isothermal thermogravimetric analysis. Results showed that the samples contain high proportions of carbon, hydrogen, and oxygen but low content of nitrogen and sulphur. Thermal analysis showed that the samples experienced significant mass loss ranging from 70.02% to 96.24% resulting in a mass of residuals between 3.76% and 29.98%. The thermal degradation process occurred in three (3) stages; drying, devolatilization and char degradation during TGA. Based on the findings, it can be rationally inferred that FGL could be most suited for biochar production due to its high mass of residuals, whereas ACM could yield higher pyrolysis bio-oils and bio-gases.

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