International Journal of Biological, Life and Agricultural Sciences
ISSN: 2415-6612
Vol:8, No:8, 2014

Characterization of Banana (*Musa* spp.) Pseudo-Stem and Fruit-Bunch-Stem as a Potential Renewable Energy Resource

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Abstract**—**Banana pseudo-stem and fruit-bunch-stem are agricultural residues that can be used for conversion to bio-char, bio-oil, and gases by using thermochemical process. The aim of this work is to characterize banana pseudo-stem and banana fruit-bunch-stem through proximate analysis, elemental analysis, chemical analysis, thermo-gravimetric analysis, and heating calorific value. The ash contents of the banana pseudo-stem and banana fruit-bunch-stem are 11.0 mf wt.% and 20.6 mf wt.%; while the carbon content of banana pseudo-stem and fruit-bunch-stem are 37.9 mf wt.% and 35.58 mf wt.% respectively. The molecular formulas for banana stem and banana fruit-bunch-stem are $C_{24}H_{33}NO_{26}$ and $C_{19}H_{29}NO_{33}$ respectively. The measured higher heating values of banana pseudo-stem and banana fruit-bunch-stem are 15.5MJ/kg and 12.7 MJ/kg respectively. By chemical analysis, the lignin, cellulose, and hemicellulose contents in the samples will also be presented. The feasibility of the banana wastes to be a feedstock for thermochemical process in comparison with other biomass will be discussed in this paper.

Keywords**—**Banana Waste, Biomass, Renewable Energy, Thermo-chemical Characteristics.

I. Introduction

As the second most widely cultivated fruit in Malaysia, banana plantation covers about 26,000 hectare with a total production of 530,000 metric tonne per year [1], [2]. Banana requires 10-12 months from planting to harvest. However, it only bears fruit only once in a lifetime. Whenever the fruit is harvested, normally the banana tree will be cut, leaving the bottom part of the stem and rhizome untouched. For every tonne of bananas picked, 100 kg of fruit is rejected and about 4 tonnes of wastes are generated [3]. It means that for every cycle of production, four times of wastes are generated. Banana wastes range from the rotten fruit, peel, fruit-bunch-stem, leaves, pseudo-stem, and rhizome.

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There are many ways to utilize the banana, from fruits till its wastes. The fruits can be eaten raw, cooked, or processed becoming candy or liquor. The rotten fruits and the peels can be processed to feed poultry, pigs, and other animals. The leaves can be used for wrapping food. The pseudo-stems can be processed becoming ropes, crafts, textile, paper and boards. All parts of banana wastes can also be composted as fertilizer, suitable for some vegetables. Banana wastes can also be a potential source of energy. The wastes can be compacted into briquette [4]-[6]. The wastes can also be biochemically converted to methane gas with anaerobic digestion [7], [8] or fermented to ethanol [9]-[11]. Direct combustion of pseudo-stems and leaves can also generate power [8].

In Malaysia however, farmers only pick banana fruits for food, and fresh leaves for food wrapping. Other portions of banana plant are dumped as wastes. Consequently, farmers often face the problem of disposal of pseudo-stems and other wastes. Hence, these huge stocks are getting accumulated in banana growing areas. Transforming these wastes into energy should be a good consideration for banana culture in Malaysia. It is a big potential for banana wastes to be the feedstock for energy generation and it will solve the country's agricultural disposal problem in an eco-friendly manner.

Very limited studies have been done using banana tree or its peel as feedstock in pyrolysis, which is a promising technology in energy conversion of biomass. Most studies focus on biological conversion (anaerobic digestion) instead. Nevertheless, a group of researchers studied pyrolysis behaviour of four biomass materials: banana stem, bagasse, babool and castor oil plant [12]. All materials have been slowly pyrolyzed to 650^{o}C after thermo-gravimetric analysis. The banana stem produced the highest percentage of char compared to other materials. The char produced from the banana stem also showed the highest adsorption capacity for methylene blue compared to other materials studied. In other studies, lingo-cellulosic materials were extracted from the banana stem, and were characterized later. Chemical treatment on the materials efficiently reduced non-cellulosic components and raised the holocellulose percentage and thermal stability [13]. Banana leaves presented 77.8% volatile solids, 44% carbon and a heating value of 19MJ/kg with low emission of pollutant gases[3].

Authors have not found literatures on the characterization of fruit-bunch-stem of banana tree at the time of this study. The fruit-bunch-stem is originated from the most inner part of the pseudo-stem itself [14]. Hence the study on the fruit-bunch-stem and its comparison with the stem might be useful. The aim of this work is to characterize banana pseudo-stem and banana fruit-bunch-stem through proximate, elemental, chemical, and thermo-gravimetric analyses, and heating caloric value, in order to evaluate their uses as combustible biomass in generating energy and obtaining added value products.

II. Experimental Aspects

A. Sample Origin and Preparation

The feedstock was supplied by a farmer from Pendang, Kedah. A single mature banana tree of 11 months was cut onto a clean canvas to prevent contamination of soil to the sample. The pseudo-stem and fruit-bunch-stem were oven-dried at 105^{o}C until the moisture content of the sample was less than 10% on dry basis. The samples should have moisture content less than 10 mf wt.% to avoid growth of fungus or microorganism [15]. The banana stem and fruit-bunch-stem were then manually chopped into smaller pieces so that they could be fed into a shredder. Subsequently, a Retsch cross beater mill with a screen size of 500μm was used to reduce the banana stems' and fruit-bunch-stem's sizes.

B. Sample Characterization

The sample is characterized through five different analyses as follow:

1. Proximate Analysis

The moisture, volatile, and ash contents of the samples were determined through thermogravimetry process. The moisture was determined using standard method ASTM E871-82 [16] in a conventional oven. The volatile matter was determined using standard method ASTM E872 [17], and the ash was determined using standard method ASTM D 1102-84 [18]. The fixed carbon was determined through the difference of the sum of the others in relation to the total sample. All analyses were performed in triplicate.

2. Elemental Analysis

The carbon, hydrogen, nitrogen and sulphur content of the samples were determined in the Perkin-Elmer Series II CHNS/O 2400 Elemental Analyser. The oxygen content was determined through the difference of the sum of the others in relation to the total sample.

3. Heating Value

Higher heating values (HHV) of the samples were determined using an Adiabatic Bomb Calorimeter (Nenken 1013-B, Japan). All analyses were performed in duplicate. Lower heating values (LHV) of the samples were calculated from the higher heating value (HHV) and hydrogen content according to (1) [19].

$$\mathrm{LHV_{dry}} = \mathrm{HHV_{dry}} - 2.442(8.936\mathrm{H}/100)\ \ \mathrm{MJ/kg} \quad (1)$$

The difference between the two heating value is equal to the heat of vaporisation of water formed by combustion of the fuel.

4. Chemical Analysis

The extractives, lignin, holocellulose, alpha-cellulose, and ash content were determined using standard test methods ASTM D1107 [20], D1106 [21], D1104 [22], D1103 [23], and D1102-84 [18] respectively. The hemi-cellulose was determined through the difference of holocellulose and alpha-cellulose. All analyses were performed in triplicate.

5. Thermal Analysis

Thermal behaviour of the samples was evaluated through thermo-gravimetric (TG/DTG) analysis. The temperature range used was from room temperature up to 900^{o}C, with nitrogen gas at 30mL/min volumetric flow. The heating rate used was 10^{o}C/min. These analyses were carried out with a computerized Perkin-Elmer 7 Thermogravimetric Analyser.

III. Results and Discussion

Table I shows the results of proximate, elemental, chemical analyses, and heating value of banana stem and banana fruit-bunch-stem respectively. In Table I, the stem presents a higher volatile solid contents 88.8 mf wt.% compared to the fruit-bunch-stem with 79.1 mf wt.% volatile solid. Volatile matters in the banana wastes are comparable with other biomass such as cassava stalk 79.9 mf wt.% [24], cassava rhizome 77.75 mf wt.% [24], sugarcane 72.9mf wt.% [25], and palm EFB 83.9 mf wt.% [26] as presented in Table II. All banana samples demonstrate relatively high ash contents, between 11.0mf wt.% and 20.6 mf wt.%. Only carbon content in the stem is higher than in the fruit-bunch-stem, while hydrogen, nitrogen, and sulphur contents in banana stem are lower compared to their contents in the fruit-bunch-stem. Comparing with other biomass such as cassava stalk, cassava rhizome; sugar cane; and palm oil empty fruit bunches (EFB) in other literatures as presented in Table II, all banana wastes contain lower carbon and hydrogen but higher nitrogen, sulphur, and oxygen contents. The high oxygen content of biomass implies high volatility and the high hydrogen content of biomass implies high liquid yields [27]. Calculated from elemental analysis, the molecular formulas for banana stem and banana fruit-bunch-stem are $C_{24}H_{33}NO_{26}$and $C_{19}H_{29}NO_{33}$ respectively if the sulphur contents in the samples are negligible. From these molecular formulas, it can be expected that the banana stem will have higher energy value than the banana fruit-bunch-stem as the banana stem has higher carbon ratio, which is 24, compared to banana fruit-bunch-stem, which is 19. Higher carbon ratio also indicates bigger molecular size. In this case, the banana stem has bigger molecular size compared to banana fruit-bunch stem. The higher oxygen ratio, on the other hand, indicates lower heating value. In this case, it is expected that the banana fruit-bunch-stem will have a lower heating value than the banana stem. The measured calorific higher heating value of banana stem is 15.5 MJ/kg, and the measured calorific higher heating value of banana fruit-bunch-stem is 12.7 MJ/kg. Those values are in line with the carbon ratio and oxygen ratio they have in their molecular formulas. Nevertheless, their heating values are lower than the calorific heating value in palm oil wastes (EFB), which is 19.4 MJ/kg

[28], and are also lower than calorific heating value of banana leaves which is 17.1 MJ/kg [6].The lignocellulosic contents of banana stem are 44.0 mf wt.% for cellulose, 17.5 mf wt.% for hemicellulose, and 37.3 mf wt.% for lignin. The lignocellulosic contents of banana fruit-bunch-stem are 39.8 mf wt.% for cellulose, 27.8 mf wt.% for hemicellulose, and 18.0 mf wt.% for lignin. The banana stem has the highercellulose and lignin contents but the lower in hemicellulose compared to the banana fruit bunch. The behaviour of a biomass during pyrolysis can be forecasted from knowledge of relative proportions of ligno-cellulosic components [27], [29]. The relative proportions of cellulose to lignin and hemicellulose to lignin of banana stem are 1.180 and 0.469 respectively. The relative proportions of cellulose to lignin and hemicellulose to lignin of banana fruit bunch stem are 2.211 and 1.544 respectively. It is expected that the banana stem and banana fruit bunch stem, which have high cellulose contents, will give high amount of bio-oil with high rate of pyrolysis, according to previous studies [30]-[36].

TABLE I
PROPERTIES OF BANANA WASTES

Component / Property	Banana Pseudo-Stem			Banana FBS	Standard Method
	Literature values	References	Measured		
Proximate analysis (mf wt.%)					
Moisture	8.46,8.57,9.74	[13],[37],[38]	10.2	11.4	ASTM E871-82
Volatile Matter	-	-	88.8	79.1	ASTM E872
Ash	8.65	[38]	11.0	20.6	ASTM D1102-84
Fixed carbon	-	-	0.2	0.3	By difference
Elemental analysis (mf wt.%)					
C	36.83	[38]	37.93	35.58	Elemental Analyser
H	5.19	[38]	4.46	4.62	
N	0.93	[38]	1.87	2.19	
S	-	-	0.37	0.45	
O	43.62	[38]	55.37	57.16	By difference
Molecular formula	-	-	$C_{24}H_{33}NO_{26}$	$C_{19}H_{29}NO_{33}$	
Heating value (MJ/kg)					
HHV	-	-	15.5	12.7	Bomb Calorimeter
LHV	-	-	14.5	11.7	
Chemical analysis (mf wt.%)					
Holocellulose	43.25, 50.92	[13],[37]	61.5	67.6	ASTM D1104
Alpha-cellulose	31.27, 50.15,	[38],[37]	44.0	39.8	ASTM D1103
Hemi-cellulose	0.77, 14.98	[37],[38]	17.5	27.8	By difference
Lignin	15.07, 17.44	[38],[37]	37.3	18.0	ASTM D1106
Extractives	4.46	[38]	9.7	6.0	ASTM D1107
Relative proportion					
$\frac{Cellulose}{Lignin}$	2.074, 2.876	[38],[37]	1.180	2.211	
$\frac{Hemicellulose}{Lignin}$	0.051,0.859	[38],[37]	0.469	1.544	

TABLE II
MAIN CHARACTERISTICS OF AGRICULTURAL WASTES

Characteristics	Cassava stalk [24]	Cassava rhizome [24]	Sugarcane (whole plant) [25]	Palm EFB [26]	Banana Leaves [6]	Banana Pseudo-stem [This work]	Banana FBS [This work]
Proximate analysis (mf wt.%)							
Moisture	15.5	8.3	6.0	8.0	7.9	10.2	11.4
Volatile Matter	79.9	77.8	72.9	83.9	78.2	88.8	79.1
Ash	6.0	4.1	6.2	5.4	6.2	11.0	20.6
Fixed carbon	14.1	18.2	14.9	10.8	15.6	0.2	0.3
Ultimate analysis (mf wt.%)							
Carbon	51.12	51.59	43.74	49.07	43.28	37.93	35.58
Hydrogen	6.87	6.69	6.30	6.48	6.23	4.46	4.62
Nitrogen	0.67	1.27	0.44	0.7	0.98	1.87	2.19
Sulphur	<0.1	<0.1	0	<0.1	0.49	0.37	0.45
Oxygen	41.34	40.45	42.42	38.29	49.02	55.37	57.16

Fig. 1 shows the TG and DTG profiles of banana pseudo-stem for the temperature range of 30°C to 920°C, with a heating rate of 10°C/min. According to the TG curve, the main pyrolysis reactions including depolymerisation, decarboxylation and cracking take place over a temperature range of 150°C to 730°C. The TG plot presented in Fig. 1 shows that heat propagated into the raw banana pseudo-stem and drove off the inherent moisture, which is about 1.63% of the sample weight, at about 150°C. At a heating rate of 10°C/min, thermal degradation of raw banana pseudo-stem is initiated at approximately 150°C, and the rate is maximum between 300°C and 350°C. At a temperature of about 430°C, the devolatization process the sample is almost complete. The residue as char is left about 39% of the sample weight. The DTG curve shows the thermal decomposition of hemicellulose and cellulose occurs at temperatures of around 325°C at a devolatization rate of 6.386-weight loss per minute.

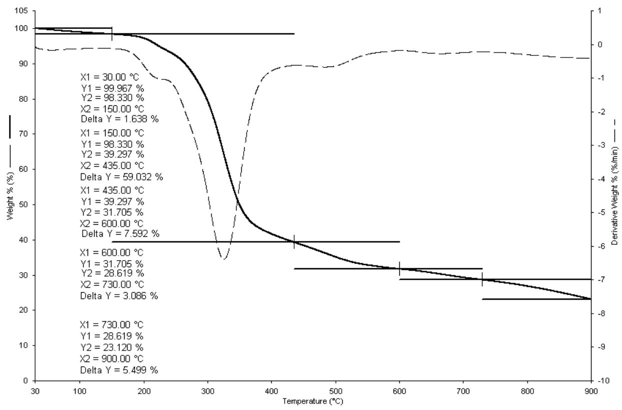

Fig. 1 Thermogravimetric (TG) and derivative Thermogravimetric (DTG) plots for pyrolysis of banana pseudo-stem at heating rate of 10°C/min

Fig. 2 shows the TG and DTG profiles of banana fruit-bunch-stem for the temperature range of 30°C to 920°C, with a heating rate of 10°C/min. According to the TG curve, the main pyrolysis reactions including depolymerisation, decarboxylation and cracking take place over a temperature range of 150°C to 660°C. The TG plot presented in Fig. 2 shows that heat propagated into the raw banana fruit-bunch-stem and drove off the inherent moisture, which is about 3.29% of the sample weight, at about 150°C. At a heating rate of 10°C/min, thermal degradation of raw banana fruit-bunch-stem is initiated at approximately 150°C, and the rate is maximum between 300°C and 350°C. At a temperature of about 660°C, the devolatization process the sample is almost complete. The residue as char is left about 13% of the sample weight. The DTG curve shows the thermal decomposition of hemicellulose and cellulose occurs at temperatures of around 322°C at a devolatization rate of 0.280-weight loss per minute.

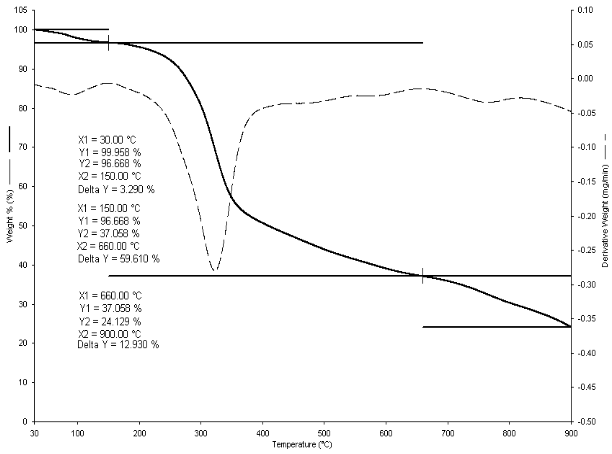

Fig. 2 Thermogravimetric (TG) and derivative Thermogravimetric (DTG) plots for pyrolysis of banana fruit-bunch-stem at heating rate of 10°C/min

IV. Conclusion

Two natural fibres from banana were studied from a physical, chemical and thermal approach. The analysis of the banana pseudo-stem and fruit-bunch-stem showed a chemical composition and thermal behaviour similar to other types of lignocellulosic biomass. Banana fibres exhibited high moisture content, volatile matter, and ash content. Banana fibres had high nitrogen and oxygen, but low carbon and hydrogen. The sulphur content in banana wastes was similar to other types of lignocellulosic biomass. The characterization of banana pseudo-stem and fruit-bunch-stem showed a marked difference in their chemical constituents. Both banana pseudo-stem and fruit-bunch-stem had a high amount of lignocellulose of more than 85 mf wt.% of their dry weight with higher holocellulose, hemicellulose, lignin, and extractive contents, but lower cellulose contents than the reported values elsewhere. Thermal stability of both banana pseudo-stem and fruit-bunch-stem was around 150°C. Decomposition of both banana pseudo-stem and fruit-bunch-stem occurred between 300°C and 350°C, while the degradation of the materials took place above 430°C for banana pseudo-stem and, 430°C for banana fruit-bunch-stem. The results obtained in the physical, chemical and thermal behaviour of the samples was similar to the other biomass already used for generation of renewable energy. It also implies their potential for obtaining value added products through combustion and pyrolysis processes. These thermochemical conversion processes can significantly reduce the volume of wastes. Consequently, it helps reducing environmental impact generally caused by its disposal. It is therefore, the used of banana plantation wastes as a feedstock in thermochemical process should be further studied.

ACKNOWLEDGMENT

The authors wish to thank Universiti Sains Malaysia for providing financial supports under research grant (1001/PFIZIK/814087), short term grant (304/PFIZIK/6310073), short term grant (304/PFIZIK/6310087), and short term grant (304/PFIZIK/6313016). The authors also would like to thank UNISEL for providing educational scholarship and Muhammad Sabki Bin Yusoff for supplying the banana wastes, which is the primary material in this study.

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