UTILIZATION OF DRIFTWOOD AS AN ENERGY SOURCE AND ITS ENVIRONMENTAL AND ECONOMIC BENEFIT ANALYSIS IN TAIWAN

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Using standard methods for the determination of approximate analysis, ultimate analysis, and calorific value, the thermochemical properties of driftwood have been analyzed in the present study. The preliminary results showed that woody waste obviously comprised a large percentage of volatile matter at 72.56 ± 4.58 wt%. The molar ratio of hydrogen to carbon (H/C) was about 1.1, which was lower than those of cellulose (H/C = 1.67) and hemicellulose (H/C = 1.6), and seemed to be in accordance with its higher heating value (18.7 MJ/kg). However, the content of nitrogen was slightly higher, suggesting that the emissions of nitrogen oxide gases from biomass-to-heat facilities will arouse concern. Under the carbonization temperature of around 500 ^{o}C, the calorific value (25.5 MJ/kg) of the resulting biochar from driftwood was relatively enhanced. Based on the 1,000,000 tons driftwood in Taiwan and the Tier 1 method recommended by the Intergovernmental Panel on Climate Change (IPCC), the environmental benefit of mitigating greenhouse gas emissions and the economic benefit of selling electricity were preliminarily calculated to be around 1.5×10^{6} tons and US$ 7.0×10^{7}, respectively.

Keywords: Driftwood; Biomass energy; Thermochemical property; Benefit analysis

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INTRODUCTION

Lignocellulosic biomass is the most abundant solid biomaterial in the world, thus suggesting that it can provide some of the available and sustainable bioresources for the production of energy, fuel, food, and chemicals. In this regard, lignocellulose comprises more than 60% of plant biomass produced by photosynthesis in the ecosystem. In response to the global warming issue, the rapidly increasing global demand and decreasing reserves of petroleum, the energy supply from domestic biomass resources has received much attention in recent years because it not only enhances fuel diversification but also mitigates the emissions of greenhouse gases (especially in carbon dioxide) and air toxics (especially in sulfur oxides and mercury) as compared to fossil fuels (Klass 1998). Although agricultural residues, forest and mill residues, cellulosic portions of municipal solid waste (MSW), industrial waste, and energy crops have been utilized as alternative energy sources in the combined heat and power (CHP) systems for power generation (Tsai 2010a) and biofuels production (Kumarappan et al. 2009), a diversity of woody biomass could be utilized to develop a bioenergy industry if efficient and economical biomass harvest and transportation and bioenergy conversion systems are employed (Sims 2002).

Regarding forest residues, they generally are comprised of logging residues that are generated during the harvesting operations; thus logging residues are currently left at harvesting sites. As a consequence, these woody residues need to be collected and transported from the forests for the purpose of utilizing them as energy sources and other material resources. Occasionally, forest residues could be derived from natural disasters such as typhoons and heavy rain. Driftwood is a special woody biomass that has been generated from flooding or other natural forces as the remains of trees, whole or in part. This biomass is often found along rivers, reservoirs, and marine shores by the action of wind, tide, wave, or man. There are many sources for driftwood. Large branches may be brought down during stormy weather. However, it was found that tree fall due to landslides is the major cause of driftwood (Alix 2005). In some cases, the driftwood may hinder and block fishing ports, farms, and irrigation channels, accumulating in reservoirs, harbors, and beaches. Among these driftwood materials, high-value tree species including cypress and incense cedar are first screened and collected for furniture making and decorative woodwork, or other art sculpture forms. The remaining collected driftwood has been generally disposed of into landfills without any utilization, or mostly crushed and then sold to gardening business to be used as organic fertilizer (Chen 2009). In Taiwan, some of the driftwood was also reused as an incubating medium by mushroom farms (COA 2010).

Taiwan is an island region with high industrialization, dense population (over 650 people/km^2), and limited natural resources. The domestic energy consumption reached a total of 120.3 million kiloliters of oil equivalent (KLOE) in 2010, in contrast to 51.0 and 91.7 million KLOE in 1990 and 2000, respectively (MOEA 2011). On average, the growth rate of energy consumption is about 4.4% per year. During the period, Taiwan's dependence on imported energy increased from 96.0% in 1990 to 99.3% in 2010. On the other hand, the environmental issues such as waste management, global warming, and sustainable development have been arousing the concerns of the public in recent years. With respect to the greenhouse gases (GHG) emissions, the carbon dioxide (CO_2) emissions per capita were directly proportional to the energy consumption from 5.5 metric tons in 1990 to over 12.0 metric tons in 2010. As a result, the energy strategies and regulations for promoting energy utilization and waste-to-energy have actively provided some environmental, energy, and economic incentives to pursue environmental sustainability. On the other hand, Taiwan is located in a significant typhoon region of the southeastern rim of Asia, making it one of the vulnerable regions frequently suffering from natural disasters. On 7 August 2009, Typhoon Morakot dumped more than 3000 mm of precipitation in the Southern Taiwan within three days, resulting in massive landslides, and large amounts of driftwood (Shieh et al. 2010). It was estimated that more than 3.0 million tons of driftwood or fallen trees were thus produced to be washed up along the water bodies and also washed into farms (Doong et al. 2011). According to the official reports (COA 2010), the total clean-up amount of driftwood after Typhoon Morakot was over 1.0 million tons, which were obtained from upstream regions (i.e., forests and reservoirs), river banks, farms, and coasts (i.e., harbors, foreshores and backshores).

From the viewpoints of bioresource recycling and energy conservation, wood-to-energy processing can be considered as one of the best available biomass management methods for utilizing driftwood in a combined heat & power (CHP) system such as incinerator, boiler, and kiln. The biomass-to-energy conversion in the CHP system will create the lowest impacts in terms of GHG and heavy metals emissions due to the high-temperature process for allowing the complete combustion of organic components in the driftwood. Furthermore, studies on the energy utilization of driftwood for manufacturing power and biofuels by thermochemical processes have been very limited. However, burning driftwood can produce polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans (PCDD/Fs, or called dioxins), because this biomass may be salt-laden wood waste (Luthe et al. 1997; Leclerc et al. 2006). The formation of dioxins is well documented when organic components are combusted under uncontrolled and incomplete conditions in the presence of chlorine (Yasuhara et al. 2003; Lavric et al. 2004), which may be present as a result of soaking in seawater.

Therefore, the aim of this preliminary study is to investigate the properties affecting the energy utilization of dry matter from driftwood. The characteristics of driftwood studied in this work include ultimate analysis, proximate analysis, and heating (calorific) value. Furthermore, the environmental and economical benefits of utilizing driftwood as biomass fuel and its potential pollutant emissions are discussed in the manuscript.

EXPERIMENTAL

Materials

A typical sample, China tree (*Melia azedarach*), was obtained from a local driftwood dump in Southern Taiwan. The bulk driftwood samples were sliced into strips, further dried by indoor air, crushed by a rotary cutting mill, and then sieved to the mesh number ranges of 40 to 60 (0.250-0.425 mm, average size ≒ 0.34 mm). Prior to the thermochemical analyses, the as-received driftwood sample was stored in the desiccator.

Carbonization of Driftwood

Although several operating parameters during the carbonization process contribute to the characterization of resulting biochar, the treatment temperature is expected to be the most important factor because the thermochemical changes (e.g., the release of volatiles and condensable compounds from the unorganized phase of the biomass) are all temperature dependent (Downie et al. 2009). Thus, only the temperature parameter was considered in the preliminary study. The biochar product was prepared from the carbonization of the driftwood sample in a brick-made kiln at about 500 ^{o}C. In order to evaluate the availability of biochar products as solid fuels, the thermochemical properties were further measured as described below.

Measurement Methods

Proximate analysis

The proximate analysis provides the weight percentages of moisture, volatile matter, ash and fixed carbon in the sample. Fixed carbon was obtained by difference. The analysis was carried out in the driftwood sample according to the American Society for Testing and Materials (ASTM) Standard Test Methods (D-3172).

Ultimate analysis

The ultimate analyses of biomass provide the weight fractions of major elements (i.e., carbon, hydrogen, nitrogen, oxygen, and sulfur), which can be used to determine combustion air requirements, to examine the extent of heating value, and to evaluate the emissions of hazardous air pollutants (i.e., nitrogen oxides and sulfur oxides). The samples (2 to 3 mg) were evaluated by using an elemental analyzer (Model: vario EL III; Elementar Co., Germany).

Calorific value analysis

The air-dried driftwood was placed in the calorimeter (Model: CALORIMETER ASSY 6200; Parr Instrument Co., USA) to measure the constant volume heat released by the combustion of the biomass with oxygen.

RESULTS AND DISCUSSION

Thermochemical Characteristics of Driftwood

Table 1 shows results of proximate, ultimate, and heating value for the driftwood.

Table 1. Thermochemical Analyses of Driftwood and Driftwood-based Biochar

Property	Driftwood [e]	Driftwood-based Biochar [e]
Proximate analysis [a]		
Moisture (wt%)	2.35 ± 0.18	1.86 ± 0.33
Volatile (wt%)	72.56 ± 4.58	12.16 ± 2.77
Ash (wt%)	6.73 ± 1.44	3.62 ± 1.84
Fixed carbon [b] (wt%)	18.36 ± 5.84	82.36 ± 4.24
Ultimate analysis [c]		
Carbon (wt%)	59.42 ± 0.06	79.96 ± 0.04
Hydrogen (wt%)	5.49 ± 0.00	1.86 ± 0.06
Oxygen (wt%)	34.62 ± 0.10	15.94 ± 0.02
Nitrogen (wt%)	0.26 ± 0.06	0.47 ± 0.03
Sulfur (wt%)	0.00 ± 0.00	0.00 ± 0.00
HHV [c, d] (MJ/kg)	18.71 ± 0.94	25.47 ± 0.90

[a] Dry basis (as received sample).
[b] By difference.
[c] Dry basis.
[d] Higher heating value, measured for dry-basis sample under laboratory conditions.
[e] Average ± standard deviation (for two measurements at the same sample).

Obviously, the biomass comprised a large percentage of volatile matter at 72.6 ± 4.6 wt%, suggesting its lignocellulosic constituents. The content of fixed carbon in the sample was about 18.4 wt%. By contrast, the ash content was only 6.7 wt%, which was significantly lower than those (i.e., over 10 wt%) in crop residues such as rice straw and rice husk (Ebeling and Jenkins 1985), but higher than those of hardwoods (Tillman 1978).

As summarized in Table 1, the ultimate analyses revealed high contents of carbon and oxygen in the driftwood sample, supporting the lignocellulosic structure for this wood waste. It is well known that pure cellulose, having the general formula $(C_6H_{10}O_5)_n$, has carbon and oxygen contents of 44.4 and 49.4 wt%, respectively. It can be seen that the driftwood sample contained the contents of carbon and oxygen with 59.4 and 34.6 wt%, which are in approximate agreement with data for woody biomass (Klass 1998). Furthermore, the molar ratio of hydrogen to carbon (H/C) is 1.67 for cellulose, $(C_6H_{10}O_5)_n$, and 1.6 for hemicellulose, $(C_5H_8O_4)_n$. In this regard, the molar ratios of H/C for the driftwood sample was only 1.11, indicating that the major organic constituents may be a mixture of cellulose, hemicellulose, lignin, and hydrocarbons.

Concerning the generation of gases from the driftwood sample, it should be remarked that the nitrogen concentration is relatively high in the biomass sample (Tillman 1978). As a result, fuel-bound nitrogen will contribute to the emissions of nitrogen oxides (NOx) from biomass combustion facilities, where they could have a need for installing NOx control systems. Just like common biomass fuels, their sulfur contents were very low compared with that of coal. It should be therefore expected that sulfur oxides (SOx) would not be emitted in a large extent due to extremely low concentrations of sulfur in the driftwood sample. With the widespread use of biomass resources as fuels, the most controversial pollutants from combustor or boiler emissions are the categories of polychlorinated organics including dioxins and chlorinated aromatics, which may be formed as a result of incomplete combustion of chlorine-containing biomass (Demirbas 2008). These compounds are of concern mainly due to their high toxicity.

From the standpoint of conversion of biomass to energy and synfuels, the heating value of biomass is a very important property. For driftwood, its higher heating value (HHV) was 18.71 ± 0.94 MJ/kg on a dry basis. The result was slightly higher than 17.5 MJ/kg for cellulose (Klass 1998). As compared to hydrocarbon fuels, the heating value of driftwood was obviously lower than those of coal and fuel oil (i.e., about 28 and 36 MJ/kg, respectively) because of its high levels of oxygen and ash, as listed in Table 1.

Thermochemical Characteristics of Driftwood-based Biochar

From the standpoint of energy use of biochar in replacement of coal, its heating value is the most important fuel property. From the data in Table 1, it can be seen that the calorific value (i.e., 25.47 MJ/kg) of biochar from driftwood was slightly lower than those (i.e., about 28 MJ/kg) of fossil coal (Harvey 2010). As compared to the calorific value of driftwood (18.71 MJ/kg, listed in Table 1), an increase of 36% was obtained for the resulting driftwood-based biochar in the brick-made kiln. The experimental results have demonstrated that the biochar derived from driftwood may be used as a solid fuel charcoal with high energy content and organic carbon, especially in fixed carbon (i.e., 82.4 wt%). It is well known that the fixed carbon is the carbon found in the material that is left after volatile materials are driven off. Therefore, it is usually used as an estimate of the amount of coke that can be generated from coals or coal-like materials (e.g., biocoal and biochar).

It is well known that the thermochemical properties of solid fuel can be defined in terms of its proximate and ultimate (elemental) analyses. As a preliminary demonstration, the chemical composition of a resulting biochar was determined. In the proximate analysis, the volatile matter, ash, and fixed carbon of driftwood-based biochar sample were about 13, 4, and 83 wt% on a dry basis, respectively. On the other hand, the ultimate analysis was found to be around 80.0, 1.9, 0.5, 16.0, and 0.0 wt% for carbon, hydrogen, nitrogen, sulfur and oxygen within the biochar sample. These analyses showed that the driftwood-based biochar was very similar to commercial coal. In contrast to its environmental and energy benefits, corrosive elements in driftwood-based biochar could be released to the atmosphere during combustion. In this regard, the content of nitrogen in the biochar was relatively low, about 0.5 % by weight, in comparison with most of coals having nitrogen contents below 2 wt% (Bustin et al. 1993). It should be noted that fuel-bound nitrogen would contribute to nitrogen oxides (NOx) emission from biomass combustion facilities, where they could have a need for installing NOx control systems.

Environmental and Economical Benefit Analysis of Utilizing Driftwood

In Taiwan, industrial scrap wood was being reused as auxiliary fuel in the utilities (e.g., boiler and incinerator). Its environmental benefit of mitigating CO_2 emissions has been analyzed in the previous study (Tsai 2010a). As a result, utilizing driftwood as an energy source should be one of the best demonstrated waste management methods based on both environmental and economic benefits. With respect to the benefits of mitigating emissions of greenhouse gases (GHG) to the environment, a simple method (Tier 1 method) adopted by the Intergovernmental Panel on Climate Change (IPCC) was used to estimate equivalent GHG (i.e., CO_2, CH_4 and N_2O) emissions from the utilization of driftwood as an energy source and its equivalent oil output (IPCC 2006). According to the IPCC methodology, this method is based on the quantities of biomass fuel combusted and average default emission factors (seen in Table 2). Therefore, the amount of driftwood was first converted to energy activity (output) units (i.e., TJ or GJ) based on its clean-up amount (i.e., 1.0 million tons) during the Typhoon Morakot in Taiwan as follows:

Energy output (TJ) = Amount (Mg) × Heating value (GJ/Mg)
= 1,000,000 Mg × 18.7 GJ/Mg
= 1.87×10^{7} GJ
= 1.87×10^{4} TJ
≒ 1.0×10^{9} kW-h (based on power efficiency of 20% in Taiwan's MSW incinerator) (Tsai 2010b)
≒ 3.1×10^{6} barrels oil equivalent (based on heat value of 6 GJ/barrel)

The anthropogenic GHG emissions from energy combustion activity were thus obtained by multiplying levels of activity (in TJ) by default emission factors (e.g., kg N_2O/TJ), as listed in Table 2.

Table 2. Environmental Benefits of Utilizing Driftwood as Biomass Energy in terms of Greenhouse Gases (GHG) Emission Mitigation [a]

GHG	Coal		Oil		Driftwood		Net mitigation (Mg)	
	DEF [b]	Emission (Mg)	DEF [b]	Emission (Mg)	DEF [b]	Emission (Mg)	Driftwood vs. coal	Driftwood vs. oil
CO_2	94,600	1,769,020	73,300	1,370,710	(0) [c]	0	- 1,769,020	- 1,370,710
CH_4	1	19	3	56	30	561	+ 542	+ 505
N_2O	1.4	26	0.6	11	4	75	+ 49	+ 64

[a] The calculation of GHG emissions was on a basis of energy output of 1.87 × 10^4 TJ from driftwood.
[b] DEF denotes default emission factors (in kg/TJ) (IPCC 2006).
[c] The value in the parenthesis means that the emission of CO_2 from driftwood can be considered to be "zero" because the biomass energy is close to "carbon neutral".

In order to encourage the energy use from the cogeneration (CHP or power generation) in Taiwan, current promotion regulations on waste-to-energy utilization are mainly based on the Energy Management Law (EML). According to the Article 10 of the newly revised EML, the power sector may ask the local vertical integrated utilities to purchase its surplus electricity at a rational fee. The current rate of purchasing electricity energy is close to 2.0 NT$//kWh, or 0.07 US$ /kWh (MOEA 2011). As a result, the economic benefits of generating electricity from co-combusting driftwood with coal or municipal solid waste can be further estimated as follows:

$$\begin{aligned}\text{Economic gain (US\$)} &= \text{Power (kW-h)} \times \text{Purchase fee (US\$ /kWh)}\\ &= 1.0 \times 10^{9}\ \text{kW-h} \times 0.07\ \text{US\$ /kW-h}\\ &\fallingdotseq 7.0 \times 10^{7}\ \text{US\$}\end{aligned}$$

On the other hand, the combustion of biomass fuels will inevitably increase the emissions of non-CO_2 GHG (i.e., CH_4 and N_2O), which are closely dependent on the type of fuel and the technology used. According to the data on 100 year time horizon-global warming potentials (GWP), the GWP values for CH_4 and N_2O are 23 and 296, respectively (IPCC 2006). Furthermore, the net emissions of GHG from the combustion of driftwood in terms of equivalent CO_2 can be quantitatively analyzed in comparison with those by fossil fuels (i.e., coal and oil) as follows:

1. Driftwood vs. coal

$$\begin{aligned}\text{Net } CO_2 \text{ equivalent emission (Mg)} &= \text{Net } CO_2 \text{ mitigation} + [\text{Net } CH_4 \text{ mitigation} \times \text{GWP-}CH_4] + [\text{Net } N_2O \text{ mitigation} \times \text{GWP-}N_2O]\\ &= -1{,}769{,}020 + (542 \times 23) + (49 \times 296)\\ &\fallingdotseq -1.7 \times 10^{6}\ \text{Mg}\end{aligned}$$

2. Driftwood s vs. oil

$$\begin{aligned}\text{Net } CO_2 \text{ equivalent emission (Mg)} &= \text{Net } CO_2 \text{ mitigation} + [\text{Net } CH_4 \text{ mitigation} \times \text{GWP-}CH_4] + [\text{Net } N_2O \text{ mitigation} \times \text{GWP-}N_2O] \\ &= -\ 1{,}370{,}710 + (505 \times 23) + (64 \times 296) \\ &\fallingdotseq -\ 1.3 \times 10^{6} \text{ Mg}\end{aligned}$$

CONCLUSIONS

1. Driftwood obviously comprised a large percentage of volatile matter at about 70 wt%. On the other hand, the molar ratio of hydrogen to carbon (H/C) for the woody waste was only 1.1.
2. The nitrogen concentration was slightly high, compared to other biomass resources, suggesting that the design of nitrogen oxides (NOx) emission control system for biomass-to-heat facilities will arouse concern.
3. The results of a preliminary benefit analysis showed that a total energy output of 1.87×10^{4} TJ/year (about three million barrels oil equivalent) can be gained on a basis of driftwood of one million tons in Taiwan, which is equivalent to the economic gains of 7.0×10^{7} US$ resulting from the power generation of co-combusting driftwood with municipal solid waste in the CHP system. Moreover, the net CO_2 equivalent mitigation emissions for using driftwood as biomass fuel have been calculated at 1.7×10^{6} and 1.3×10^{6} Mg (tons) in comparison with coal and oil, respectively.

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