Bamboo-Derived Fuel from *Dendrocalamus latiflorus*, *Phyllostachys makinoi*, and *Phyllostachys pubescens* Waste

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Bamboo is used as a raw material for producing chopsticks, artifacts, utensils, plywood, fiberboard, and decorated multi-layered panels. The manufacturing process generates a large amount of bamboo residual waste. In this study, bamboo-derived fuels were prepared from the residual waste of *Dendrocalamus latiflorus, Phyllostachys makinoi,* and *Phyllostachys pubescens*. The combustion behaviors of bamboo-derived fuels were also investigated. The characteristics of derived fuels made from bamboo waste with engine oil waste showed that the ash content was less than 5% and that the calorific value reached 5,000 kcal/kg, which was higher than derived fuels standards. Additionally, the derived fuel of bamboo waste had a high combustion efficiency and low nitrogen, sulfur, and chlorine emission levels, which were lower than the derived fuels standards. Thus, bamboo-derived fuel prepared from *Dendrocalamus latiflorus, Phyllostachys makinoi,* and *Phyllostachys pubescens* waste mixed with engine oil waste is a suitable fuel alternative.

Keywords: Bamboo waste derived fuel; Ma bamboo; Makino bamboo; Moso bamboo; Combustion

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INTRODUCTION

Bamboo stands are endemic in South and East Asia. Bamboo's fast growth and adaptability in various soil and climate conditions make it a good candidate as a renewable resource (Vogtländer *et al.* 2010). Bamboo stands cover 152,300 hectares, which is roughly 7.2% of the overall forest area in Taiwan. Ma bamboo, Makino bamboo, and Moso bamboo are the important bamboo species. Bamboo is conventionally used as the raw material for producing artifacts, utensils (disposable chopsticks), plywood, fiberboard, decorated multi-layered panels, and building materials in Taiwan and many Asian countries (Nguyen *et al.* 2012). The manufacturing process generates a large amount of residual bamboo waste, which is an environmental threat that needs disposal and utilization. The waste products from bamboo processing may be suitable biomass energy fuel when using established feedstock handling equipment (Scurlock *et al.* 2000). Alternatively, Taiwan uses over 45 billion pairs of single-use chopsticks annually according to the Environmental Protection Administration, Taiwan (2014). The manufacture of disposable chopsticks consumes large amounts of trees and bamboo plants each year. Additionally, this waste represent an appreciable amount of rubbish that is not recycled. Thus, the utilization of this waste could represent a marketable resource of bioenergy.

Many methods including acid treatment, hydrolysis, pyrolysis, gasification, thermal, and fuel methods have been adopted for processing bamboo waste biomass (Asada *et al.* 2011; Chiang *et al.* 2012; Wang 2012; Cheng and Chang 2013; Bada *et al.* 2014; Jiang *et al.* 2014; Liu *et al.* 2014; Qin *et al.* 2015; Shen *et al.* 2014). Bamboo waste biomass has been used to produce fuels, activated carbon, carbon fibers, syngas, glucose, methane, and bioethanol. Refuse-derived fuels (RDFs) are an innovation of waste-to-energy technology created by shredding and drying out combustible waste. Previous studies have shown that raw bamboo (*Bambusa multiplex*) has the highest fuel value and the lowest ignition temperature (Bada *et al.* 2014). Additionally, co-firing bamboo biomass with coal for electricity generation is a near-term, low-risk, low-cost, renewable energy technology for reducing CO_2 and SO_2 air emissions (Al-Mansour and Zuwala 2010; Berndes *et al.* 2010; Bada *et al.* 2014). Biomass, when blended with coal, should enhance coal pyrolysis or gasification (Cheng *et al.* 2014; Bada *et al.* 2015) and minimise the risks of slagging and fouling (Fryda *et al.* 2014). However, little information is available about using bamboo waste as a RDF biomass. The direct utilization of bamboo waste is limited by its high moisture content and volatile matter, which makes controlling its combustion more difficult (Liu *et al.* 2013, 2014). The moisture content in the biomass has been found to be a predominant factor for the increase of particulate matter emissions (Chao *et al.* 2008).

According to the statistical data of the Ministry of Transportation and Communications, Taiwan, there were 7,367,522 cars and 14,195,123 motorcycles in 2013 (Ministry of Transportation and Communications 2013). The amount of engine oil waste generated from cars and motorcycles is about 115 million liters annually in Taiwan. Engine oil waste has been collected and used as boiler fuels or base oils in the past. Engine oil waste has high heating value, which can be turned into valuable fuel products by treating, refining, purifying, and distilling processes. However, these processes increase the need for electrical energy consumption and capital equipment costs. Thus, the combination of bamboo waste and engine oil waste to produce a refuse-derived fuel will help to repurpose disposable waste materials and to provide an alternative fuel that is cost-effective and has environmental benefits.

This study focuses on the production of fuel from bamboo waste generated from manufacturing chopsticks, artifacts, utensils, plywood, fiberboard, and decorated multi-layered panels, as well as disposable chopsticks in Taiwan. Engine oil waste was added to bamboo waste to be processed as a refuse-derived fuel.

EXPERIMENTAL

Materials

The *Dendrocalamus latiflorus*, *Phyllostachys makinoi*, and *Phyllostachys pubescens* waste used in this study were collected from a bamboo processing plant located at Nan-Tou county in Taiwan (Fig. 1). The dried bamboo waste was chipped, ground, and sieved through a 40-mesh sieve before use in batch experiments. The engine oil waste was obtained from a vehicle maintenance and repair plant located at Yunlin county in Taiwan. The basic characteristics of bamboo waste and engine oil waste were analyzed by an

Elementar Vario EL III elemental analyzer (CHN-OS Rapid, German), a three-component analysis (ASTM D3174-02 2002), a thermogravimetric analyzer (PerkinElmer Pyris Diamond, USA and Shimadzu DTG-60, Japan), and calorific value analysis (ASTM D5865-13 2013). Additionally, the chemical components of the bamboo waste, such as cellulose, lignin, solvent extractives, and ash, were analyzed in accordance to TAPPI T203 cm-09 (2009), TAPPI T222 om-11 (2011), TAPPI T 204 cm-07 (2007), and TAPPI T211 om-07 (2007), respectively.

Fig. 1. Bamboo product and bamboo waste

Bamboo Waste Refuse-Derived Fuel (RDF) Production

The main aim of this study was to turn bamboo waste into an energy resource by the granulation process and add value to the bamboo waste. Figure 2 is a flow diagram of the study. The hydraulic machine was used for granulation process to form pellets. The engine oil waste was used as the binder to produce a hard granular bamboo waste RDF. Different ratios (5:1, 10:1, and 20:1) of bamboo waste-to-engine oil waste was used to analyze the impact on its granulation. The diameters of pellet grains produced during the granulation process were 2 mm, 7 mm, and 13 mm. The granulation parameters of the experiment included the pressure (700, 800, and 900 psi) and time (3, 5, and 7 min). The characteristics of the bamboo waste-derived fuel were analyzed to evaluate the combustion efficiency and to determine compliance with the derived fuels standards (ASTM E0856-83R04 2006). The tubular furnace was used for combustion tests. The gaseous emissions (CO and CO_2) from biomass combustion were measured. The modified combustion efficiency (CE) is the ratio of the carbon dioxide to the carbon dioxide and monoxide (CE = $\Delta CO_2/(\Delta CO_2+\Delta CO)$) (Yokelson *et al.* 1996).

RESULTS AND DISCUSSION

Characteristics

The chemical constituents of the bamboo waste are shown in Table 1. Bamboo waste contained 64.96 to 68.22% holocellulose, 26.19 to 28.80% lignin, and 1.73 to 2.96% ash. The α-cellulose and lignin content was similar to other woody biomasses but appreciably different from agricultural wastes (*e.g.*, bagasse, corn stalks, corn cobs, corn stover, wheat straw, rice straw, switchgrass, olive husk, and olive pomace) (Ioelovich 2015). The characteristics of Ma bamboo, Makino bamboo, and Moso bamboo wastes are shown in Table 2. The water content of the bamboo waste was approximately 6.85 to 7.90%, whereas the ash content was 1.50 to 2.73%. The combustible content was about 89.37 to 91.52%. The water and ash contents were relatively low compared with the European standard limits of 10% and 5%, respectively, for RDF. The carbon content in the bamboo waste was about 43.9% to 45.25% of the total. The amounts of nitrogen (< 1.0%), sulphur (< 0.2%), and chlorine (< 0.15%) were relatively low compared with other refuse-derived fuels. Thus, the emissions of acidic gaseous pollutants, such as NOx and SOx, should be negligible during the co-combustion of bamboo waste refuse-derived fuels. The calorific values of the bamboo wastes ranged between 4,139 to 4,356 cal/g and were higher than non-edible biomasses (2,627 to 3,344 cal/g) (Ioelovich 2015). The bamboo waste can be used as a feedstock for refuse-derived fuels (fuel pellets). The refuse-derived fuels made from renewable bamboo waste has potential as a green energy resource. Compared with the fuel quality requirements, the bamboo waste has a lower calorific value than coal fuel (5,000 cal/g) designed for power plant broilers at Taipower (Taiwan Power Company 2015). Thus, the high carbon content and high calorific value of engine oil waste was used as the binding agent.

Table 1. Chemical Analysis of Bamboo Waste

Bamboo Waste	Holocellulose (%)	α-Cellulose (%)	Lignin (%)	Extractives (%)	Ash (%)
Ma	65.52±2.37	42.27±2.72	26.19±1.49	2.93±1.27	2.96±0.83
Makino	68.22±2.63	46.31±1.52	28.78±1.71	1.69±1.19	1.75±0.52
Moso	64.96±2.43	41.08±1.43	28.80±1.93	4.30±1.42	1.73±0.41

Data provided as the mean ± standard deviation

Table 2. Three-Component, Elemental Analysis, and Calorific Value (dry based) of Bamboo Waste and Engine Oil Waste

Property	Bamboo Waste			Engine Oil Waste
	Ma	Makino	Moso	
Moisture (%)	6.85 ± 1.22	7.90 ± 1.53	6.98 ± 1.78	6.40 ± 2.13
Ash (%)	2.68 ± 0.71	2.73 ± 1.05	1.50 ± 0.24	12.63 ± 5.25
Combustible Portion (%)	90.47 ± 4.60	89.37 ± 3.59	91.52 ± 4.53	80.97 ± 6.59
C (%)	44.22 ± 1.91	43.90 ± 1.47	45.25 ± 2.04	82.83 ± 5.61
H (%)	6.10 ± 0.43	6.06 ± 0.55	5.71 ± 0.38	13.63 ± 1.28
O (%)	45.63 ± 1.05	41.47 ± 1.80	43.89 ± 1.65	1.37 ± 0.09
N (%)	0.07 ± 0.02	0.06 ± 0.01	0.08 ± 0.02	0.07 ± 0.01
S (%)	N.D.	N.D.	N.D.	N.D.
Cl (%)	N.D.	N.D.	N.D.	N.D.
Calorific Value (cal/g)	4,139 ± 84	4,285 ± 102	4,356 ± 115	10,459 ± 214

Data provided as the mean ± standard deviation

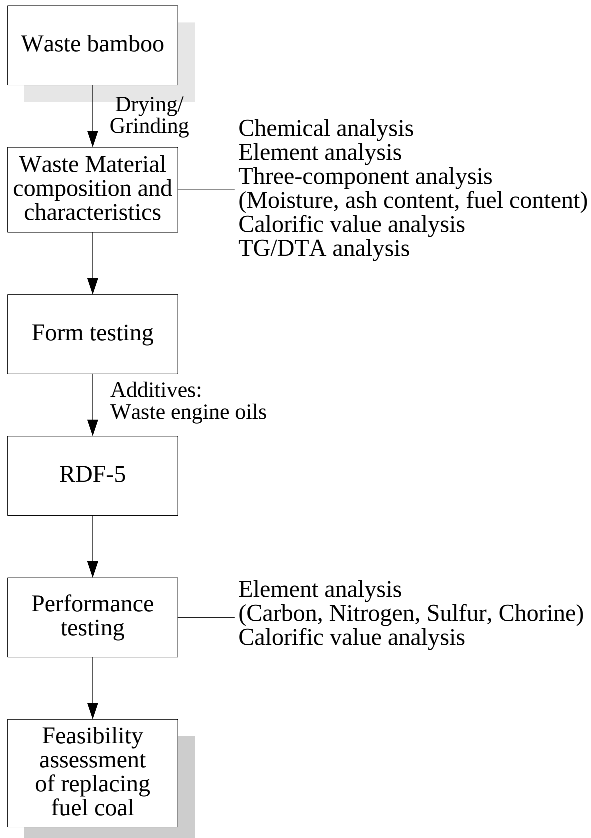

Fig. 2. Flowchart of the study

Figure 3 shows the results of thermogravimetric and derivative thermogravimetric analyses of bamboo waste and engine oil waste. The overall exothermal reaction temperature was about 291.52 and 394.6 °C for Ma bamboo waste, 287.6 and 395.6 °C for Makino bamboo waste, and 317.8 and 438.5 °C for Moso bamboo waste. At 500 °C, the weight of the Ma, Makino, and Moso bamboo waste was reduced by 98.5, 98.8, and 98.8%, respectively. The overall exothermal reaction temperature was at 337.1 °C for the engine oil waste. Figure 4 shows the results of the thermogravimetric and differential thermal analyses of Ma bamboo waste with engine oil waste. The overall exothermal reaction temperature was about 359.95 and 478.97 °C for Ma bamboo waste with 5% engine oil waste, 364.56 and 483.76 °C for Ma bamboo waste with 10% engine oil waste, and 377.43 and 461.76 °C for Ma bamboo waste with 20% engine oil waste. The first exothermal peak of bamboo waste with engine oil waste is expected to rise as the amount of engine oil waste content increased. Thus, the utilization of engine oil waste should enhance the calorific value of bamboo waste.

Bamboo Waste RDF with Engine Oil Waste

The characteristics of bamboo waste refuse-derived fuels mixed with engine oil waste are shown in Table 3. Carbon dioxide was the dominant gas released during combustion, which was similar to woody biomass (Cheng *et al.* 2014). The concentrations of sulphur and nitrogen released from bamboo waste were lower than other wood and herbaceous biomasses (Carpenter *et al.* 2014). The production of toxic SOx and NOx emissions during fuel combustion or co-firing were expected to be low. The corrosion and ash deposition problems with toxic chlorine emissions are not expected to be of concern. The results also revealed that the bamboo waste refuse-derived fuels mixed with engine oil waste had an increased calorific value. Thus, the utilization of engine oil waste as a binding agent is feasible. This is a solution to the problem of engine oil disposal in factories, and it also enhances the combustion property of the refuse-derived fuel. Comparing the quality standard requirements, calorific value, moisture, and ash content of coal fuel designed for power plant broilers in Taipower (Taiwan Power Company 2015), the bamboo waste-engine oil waste mixture was well within the standard requirements. Hence, the fuel derived from the mixture of bamboo waste and engine oil waste has the potential to be used in power broilers for electricity generation.

The combustion efficiency of the bamboo waste refuse-derived fuels were relatively stable and were over 97% in the laboratory-scale test unit. Thus, the bamboo waste refuse-derived fuel mixed with engine oil waste improves the calorific value of bamboo waste, which makes it more valuable for energy recovery; additionally, this combination achieves waste material disposal and cost reduction.

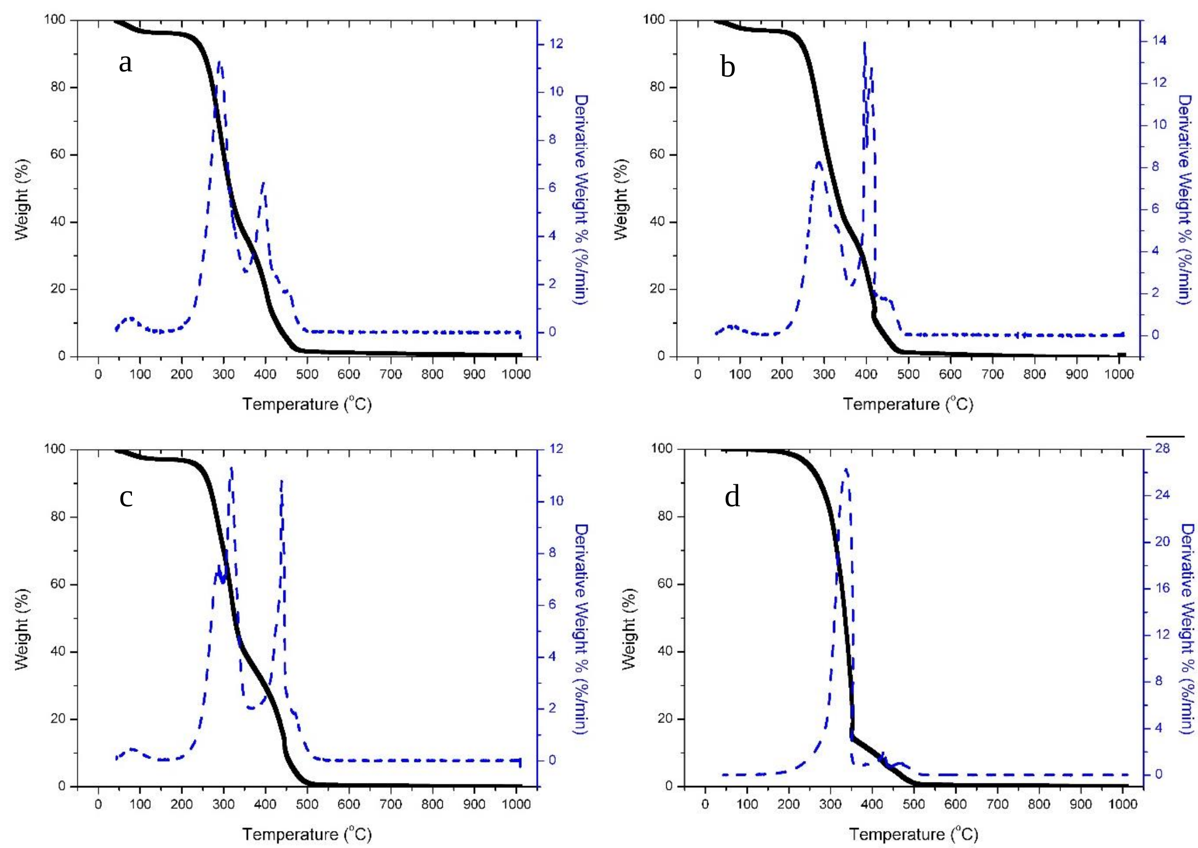

Fig. 3. TGA/DTG curves of (a) Ma, (b) Makino, and (c) Moso bamboo waste, and (d) engine oil waste

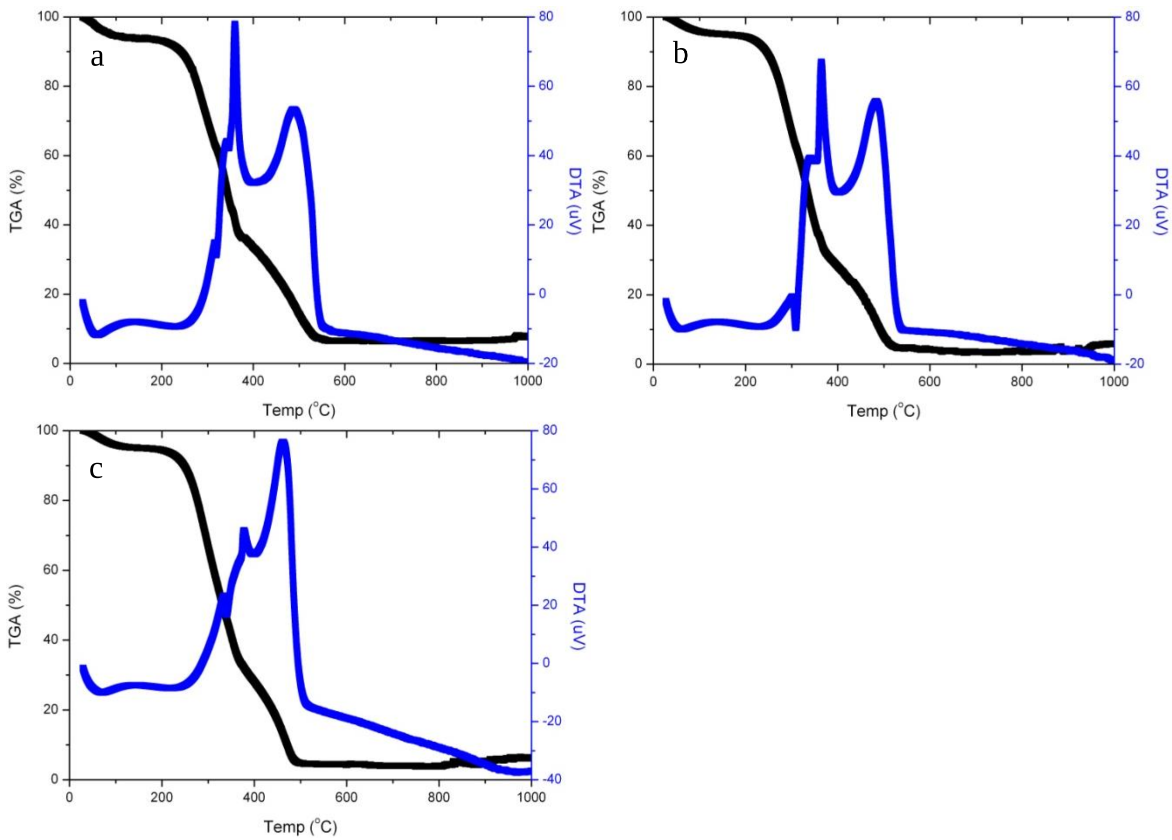

Fig. 4. TGA/DTA curves of Ma bamboo waste with (a) 5%, (b) 10%, and (c) 20% of engine oil waste

Table 3. Calorific Value and Combustion Efficiency of Bamboo Waste Refuse Derived Fuels Mixed with Engine Oil Waste

Bamboo Waste	Ma	Ma with Engine Oil Waste			Makino	Makino with Engine Oil Waste		
(%)	100	20	10	5	100	20	10	5
C	44.51±0.57	51.24±0.96	47.80±0.71	46.05±0.35	43.85±0.30	50.68±1.04	47.13±0.85	44.86±1.01
N	0.07±0.01	0.07±0.01	0.07±0.01	0.07±0.01	0.07±0.01	0.07±0.01	0.07±0.01	0.07±0.01
S	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cl	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Calorific value (cal/g)	4,139±84	5,263±210	4,720±129	4,400±80	4,285±102	5,498±67	4,850±72	4,537±81
CE (%)	97.5	97.4	98.3	97.1	97.9	98.1	97.6	97.8

CONCLUSIONS

1. The bamboo derived fuels were prepared from the wastes of *Dendrocalamus latiflorus*, *Phyllostachys makinoi*, and *Phyllostachys pubescens*. In order to increase the plasticity during the granulation process, engine oil waste was used as the binding agent. The characteristics of derived fuel made from bamboo waste with 20% engine

oil waste showed that the ash content is less than 5% and the calorific value reached 5,000 cal/g (which is higher than the derived fuels standards).

2. The first exothermal peak of bamboo waste with engine oil waste is expected to rise as the amount of engine oil waste content increased.
3. The bamboo waste derived fuel has a high combustion efficiency and low nitrogen, sulfur, and chlorine emissions (which are lower than the derived fuels standards).
4. The bamboo derived fuel prepared from the waste of *Dendrocalamus latiflorus, Phyllostachys makinoi*, and *Phyllostachys pubescens* mixed with engine oil waste is suitable alternative fuel.

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