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An experimental analysis on property and structure variations of agricultural wastes undergoing torrefaction

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HIGHLIGHTS

- ▶ Coffee residue, sawdust and rice husk undergoing torrefaction are investigated.
- ▶ A high-volatile bituminous coal and a low-volatile one are also regarded for comparison.
- ▶ Coffee residue is the most active biomass to torrefaction.
- ▶ Torrefied wastes approach the high-volatile coal as increasing temperature and duration.
- ▶ Torrefaction is conducive to the applications of biomass in industrial furnaces.

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ABSTRACT

Three agricultural wastes, consisting of coffee residue, sawdust and rice husk, undergoing torrefaction are investigated to evaluate the potential of biomass as solid fuel. Two different torrefaction temperatures (240 and 270 °C) and durations (0.5 and 1 h) are considered in the study, and the properties and structures of the raw and torrefied wastes are extensively investigated by means of proximate, elemental, fiber, calorific, thermogravimetric, SEM and FTIR analyses. A high-volatile bituminous coal and a low-volatile one are also regarded for comparison. By virtue of more hemicellulose contained in the coffee residue, it is the most active biomass to torrefaction and its higher heating value (HHV) is improved up to 38%. The empirical atomic formula of the raw wastes is expressed by $CH_{1.54-1.76}O_{0.65-0.89}$ and it changes to $CH_{1.02-1.57}O_{0.26-0.64}$ after undergoing torrefaction. The torrefied biomasses approach high-volatile coal when the torrefaction temperature and duration increase. From fuel point of view, the improved properties and changed molecular structure are conducive to the applications of biomass in industrial furnaces such as boilers and blast furnaces.

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1. Introduction

According to the statistics of International Energy Agency (IEA), the development of renewable energy in the world has grown at an average annual rate of 1.7% [1]. Renewable energy sources include solar, wind, biomass, geothermal, hydropower and ocean energies. In these renewable energy sources, biomass is the largest one which approximately accounts for 10% of the world's annual energy consumption in comparison to 21%, 27% and 33% from natural gas, coal and petroleum oil, respectively [2]. In currently developing bioenergy systems, biomass can be consumed directly from the solid state; it can also be converted into liquid biofuels and gas fuels such as biogas or synthesis gas (syngas). When one is concerned with solid biomass, it is always desirable to utilize agricultural wastes, which are abundant worldwide, as alternatives to fossil fuels [3]. For example, it has been reported that Taiwan produced around 5 million metric tons of agricultural wastes in 2009 [4].

Biomass has been considered as a carbon neutral fuel in that the net carbon emissions from burning biomass are zero. However, raw biomass is generally characterized by its higher moisture content and volatile matter as well as lower heating value and energy density [5] compared to fossil fuels. Besides, it is difficult to grind biomass into small particles stemming from its lignocellulosic nature. By virtue of higher volatile matter in raw biomass, this results in less char to be produced and burned in combustors. For these reasons, the potential of raw biomass serves as an alternative fuel of coal is restricted. Nevertheless, the aforementioned drawbacks can be resolved through the pretreatment methods. Among the pretreatment methods, torrefaction is a promising technique to upgrade solid biomass [6–10]. Torrefaction is a thermal pretreatment process where

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raw biomass is heated in an inert atmosphere at the temperature range of 200–300 °C [11–13], and nitrogen is the most commonly used purge gas to provide a non-oxiding environment.

It is well known that the principal and basic constituents in biomass are hemicellulose, cellulose and lignin [14,15]; small amount of extractives are also contained in biomass. Hemicellulose is a branched polymer, whereas cellulose is a straight chain polymer. Both hemicellulose and cellulose are densely packed by layers of lignin. On account of inherent difference in the structures of hemicellulose, cellulose and lignin, their decomposition temperatures are in the ranges of 200–315, 315–400 and 160–900 °C, respectively [16]. Accordingly, it has been reported that torrefaction has a significant impact upon hemicellulose, whereas cellulose and lignin are affected by the pretreatment to a certain extent, depending mainly on torrefaction temperature and duration [7]. Some studies have outlined the impact of torrefaction temperature on the properties of torrefied biomass. For example, in the study of Yan et al. [17], they pointed out that an increase in torrefaction temperature resulted in a decrease in the mass yield of loblolly pine, but led to an increase of carbon content in the treated solid biomass. Chen et al. [18] investigated the torrefaction of a woody biomass at the conditions of light (220 °C), mild (250 °C) and severe (280 °C) torrefactions. They highlighted that the severe torrefaction was able to increase the calorific value of the wood up to 40%. But over 50% of mass was lost from the pretreatment. Rousset et al. [19] also studied bamboo torrefied at the three different temperatures. They found that the energy yield was larger than the mass yield and increasing temperature intensified this difference.

Reviewing past studies indicates that when torrefaction is employed to pretreat biomass, some of the oxygen and hydrogen in raw biomass are consumed from the thermal degradation. Meanwhile, biomass experiences partial carbonization. The O/C and H/C ratios in torrefied biomass are reduced, thereby increasing its heating value [17,20,21]. It has also been reported that the ignitability, reactivity and grindability of torrefied biomass are better compared to their parent one [20,22,23]. The advantages of torrefaction have been addressed in a number of published papers. However, some information from the torrefaction of solid agricultural wastes remains insufficient, especially in their molecular structures. To provide a deep insight into the technique of torrefaction, this study is intended to investigate the impact of torrefaction temperature and duration upon the properties of three agricultural wastes. Particular emphasis is placed on the variations of ultimate analysis results and internal structure of lignocelluloses due to the reactions of hemicellulose, cellulose and lignin.

2. Experimental

2.1. Reaction system

The schematic of the reaction system is displayed in Fig. 1. The experimental system was made up of a nitrogen cylinder, a rotameter, a reactor and a product gas treatment unit. The steel cylinder was used to supply nitrogen for providing a non-oxidizing environment. The volumetric flow rate of nitrogen was controlled by the rotameter. The reactor comprised a quartz tube, a tube furnace and a temperature controller. Tested samples were placed in the tube which was situated in the furnace. A temperature probe (thermocouple) was mounted in the furnace beside the quartz tube to detect the temperature. The power of the furnace was controlled by the temperature controller. A conical flask was employed as the product gas treatment unit to remove tars and clean the exhaust gas stemming from torrefaction.

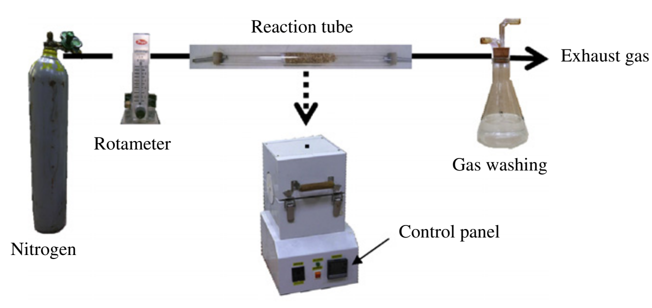

Fig. 1. A schematic of experimental system.

2.2. Experimental procedure and analyses

Three different agricultural wastes, including coffee residue, sawdust and rice husk, were tested. The coffee residue was obtained from coffee beans; the sawdust was from the sawing of woods and the rice husk was collected from the treatment of rice in Taiwan. The wastes were preliminarily ground by a shredder and sieved by vibrating screens. On account of intrinsic difference in the wastes, the particle sizes of the coffee residue and sawdust were controlled between 100 and 200 mesh (i.e. 75–150 μm). On the other hand, the particle sizes of the rice husk were located between 40 and 100 mesh (i.e. 150–385 μm). The sieved biomasses were dried in an oven at 105 °C for 24 h to prepare the experimental samples. Subsequently, the samples were placed

Table 1
Proximate analysis and fiber analysis of three solid wastes (wt.%).

Raw material	Coffee residue	Sawdust	Rice husk
Proximate analysis			
Moisture	14.50	12.90	11.51
Volatile matter (VM)	68.80	61.36	61.13
Fixed carbon (FC)	14.94	13.96	16.37
Ash	1.76	11.78	10.99
Fiber analysis			
Hemicellulose	40.10	11.18	21.34
Cellulose	27.38	36.08	36.06
Lignin	6.00	28.66	21.16
Other	26.52	24.08	21.44

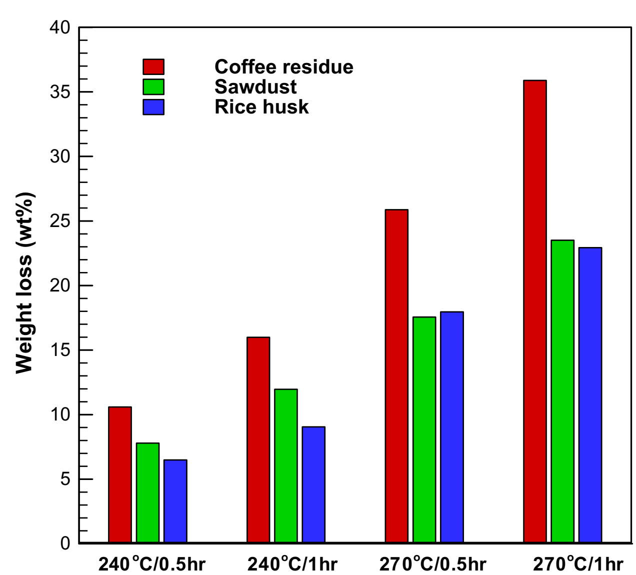

Fig. 2. Weight loss distributions of tested solid wastes at various torrefaction temperatures and durations.

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