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Waste to Biofuel by Torrefaction Technology

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***Abstract*—**Torrefaction is one of waste to energy (WTE) technologies developing in Taiwan recently, which can reduce the moisture and impurities and increase the energy density of biowaste effectively. To understand the torrefaction characteristics of different biowaste and the influences of different torrefaction conditions, four typical biowaste were selected to carry out the torrefaction experiments. The physical and chemical properties of different biowaste prior to and after torrefaction were analyzed and compared. Experimental results show that the contents of elemental carbon and caloric value of the four biowaste were significantly increased after torrefaction. The increase of combustible and caloric value in bamboo was the greatest among the four biowaste. The caloric value of bamboo can be increased from 1526 kcal/kg to 6104 kcal/kg after 300°C and 1 hour torrefaction. The caloric value of torrefied bamboo was almost four times as the original. The increase of elemental carbon content in wood was the greatest (from 41.03% to 75.24%), and the next was bamboo (from 47.07% to 74.63%). The major parameters which affected the caloric value of torrefied biowaste followed the sequence of biowaste kinds, torrefaction time, and torrefaction temperature. The optimal torrefaction conditions of the experiments were bamboo torrefied at 300°C for 3 hours, and the corresponding caloric value of torrefied bamboo was 5953 kcal/kg. This caloric value is similar to that of brown coal or bituminous coal.

***Keywords*—**Torrefaction, waste to energy, calorie, biofuel.

I. Introduction

TORREFACTION is one of the thermal treatment methods for biomass, which can remove the moisture and impurities of biomass. Most important, it can reduce the biomass volume and increase the energy density of biomass effectively [1], [2]. Torrefaction can be treated as a mild pyrolysis or a high temperature drying process without oxygen. The major products of biomass torrefaction are solid fuels (biocarbon), which can be reused as fuel coals in the power plant or steel manufacture and reduce the emissions of CO_2 and fly ash. Kiel [3] studied the physical and chemical properties of biomass during torrefaction process and found that the moisture, CO_2, CO, acetic acid, other volatiles, char, and gum were released out of the biomass sequentially as the heating temperature and time were increased. The final products of biomass torrefaction were the biocarbon. The compositions and characteristics of biocarbon were similar to those of lignite and charcoal, and their energy densities were increased with the rising temperature and time of biomass torrefaction [4].

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Cellulose, hemicellulose and lignin are the major fiber compositions in common plants and biomass, they are quite different in physical, chemical, and structural properties. As a biomass was torrefied, these three components were decomposed and different reactions occurred. When the temperature was lower than 250°C, hemicellulose was dried and decomposed while cellulose and lignin weren't. As the temperature increased to above 250°C, the volatiles and organic polymers in cellulose and lignin were decomposed or removed. The weight of biomass was decreased obviously. With the increasing temperatures, more and more cellulose and lignin were decomposed and carbonized. During the torrefaction of biomass, the effect of temperature on the decomposition of hemicellulose was more significant than those of cellulose and lignin. The volume of biomass can be reduced with torrefaction by 30% [5], [6].

II. Experimental Procedures

Four biomass samples were selected to represent the common biowaste in our environment, they were wood (*Acacia confusa* Merr.), bamboo (*Phyllostachys edulis*), rice straw, and waste paper (corrugated paper). The wood and bamboo samples were taken from the backyard of our school, the rice straw samples were taken from a farm in Changhua county, and the corrugated paper samples were taken from a convenience store in Taichung city. The physical and chemical properties of each sample, including the contents of moisture, combustible, ash, cellulose, hemicellulose, lignin, and the chemical element compositions and calorific value, were analyzed by following the standard methods in Taiwan or referring to the related studies [7].

The experiment series of different parameters were designed by Taguchi method L16 orthogonal arrays [8]. The investigated parameters were different biowaste (wood, bamboo, straw, paper), torrefaction temperatures (200, 300, 400, 500°C), and torrefaction time (1, 2, 3, 4 hrs). There were sixteen experiments carried out in this study (as shown in Table I). The variations of physical and chemical properties of biowaste prior to and after torrefaction experiments were compared and studied, including the contents of moisture, combustible and ash, elemental composition, caloric value, and fiber compositions (cellulose, hemicellulose, and lignin).

The torrefaction experiments were carried out with nitrogen as carrier gas in a programmable logic temperature-controlled oven. The torrefaction temperature was controlled at 200-500°C. The weight variations of each biowaste was monitored and recorded before and after torrefaction.

TABLE I
EXPERIMENTAL CONDITIONS

Run	Sample	Temp. (^oC)	Time (hr)
1	wood	200	1
2	wood	300	2
3	wood	400	3
4	wood	500	4
5	Bamboo	200	2
6	Bamboo	300	1
7	Bamboo	400	4
8	Bamboo	500	3
9	Rice straw	200	3
10	Rice straw	300	4
11	Rice straw	400	1
12	Rice straw	500	2
13	Corrugated paper	200	4
14	Corrugated paper	300	3
15	Corrugated paper	400	2
16	Corrugated paper	500	1

III. RESULTS AND DISCUSSIONS

A. Characteristics of Different Biowaste Prior to Torrefaction

Table II shows the contents of moisture, combustible, ash, cellulose, hemicellulose, lignin, the chemical element compositions and calorific value of different biowaste prior to torrefaction. The moisture contents in common biowaste are higher, so the net calorific values of biowaste are usually much lower than their dry-base gross calorific values. Bamboo had the highest moisture content (51.67%) among the four biowaste, the next were rice straw (33.39%) and wood (25.00%). The net calorific values of the four biowaste followed the sequence of corrugated paper (3051.74 kcal/kg), wood (2374.52 kcal/kg), rice straw (1779.96 kcal/kg), and bamboo (1525.79 kcal/kg). Rice straw had the highest ash content (19.38%); the others had ash content lower than 10%. Corrugated paper had the highest combustible content (85.99%), the next were wood (73.35%), bamboo and rice straw had similar combustible content (47%). Because the moisture content of biowaste can be removed by torrefaction, it is useful to take the dry-basis compositions of biowaste into account. The dry-basis combustible contents of biowaste followed the sequence of wood (97.80%), bamboo (97.37%), corrugated paper (92.04%), and rice straw (70.91%). The dry-basis gross calorific vales of biowaste were bamboo (4020.54 kcal/kg), wood (3564.75 kcal/kg), corrugated paper (3517.64 kcal/kg), and rice straw (3152.40 kcal/kg). These data were expected to have significant relationships to the energy content of torrefied biowaste.

The analysis results of lignocellulose compositions showed that corrugated paper had the highest cellulose content (64.15%), the next were wood, bamboo, and rice straw. Corrugated paper also had the highest hemicellulose content (94.19%). The contents of hemicellulose and lignin in wood, bamboo, and rice straw were all near 40%. The major elements in biowaste are carbon, hydrogen, and nitrogen. Bamboo had the highest carbon content (47.07%), and also had the highest dry-base calorific value (4020.54 kcal/kg). The carbon content in biowaste should have significant relationship to the calorific value of torrefied biowaste.

TABLE II
CHARACTERISTICS OF DIFFERENT BIOWASTE PRIOR TO TORREFACTION

	Wood	Bamboo	Rice straw	Corrugated paper
Moisture (%)	25.00	51.67±2.36	33.39±4.78	6.67
Ash (%)(wet-basis)	1.65±0.08	1.27	19.38±0.38	7.44±0.14
Combustible (%) (wet-basis)	73.35	47.06	47.23	85.99
Ash (%)(dry-basis)	2.20	2.63	29.09	7.96
Combustible (%) (dry-basis)	97.80	97.37	70.91	92.04
Nitrogen (%)	2.66±0.14	1.901±0.11	2.68±0.08	1.59±0.09
Carbon (%)	41.03±0.63	47.07±0.14	37.95±0.13	38.52±0.09
Hydrogen (%)	3.70±0.02	4.17±0.02	3.77±0.01	3.82±0.02
Cellulose (%)	33.59±1.49	54.62±0.74	36.39±0.69	64.15±3.75
Hemicellulose (%)	43.55±10.41	39.52±23.86	35.19±30.40	94.19±3.58
Lignin (%)	35.52±0.74	37.1±5.77	41.88±4.53	21.7±1.62
Gross calorific value (kcal/kg)	3564.75±26.2	4020.54±41	3152.40±39	3517.64±3.9
Net calorific value (kcal/kg)	2374.52	1525.79	1779.96	3051.74

B. Characteristics of Different Biowaste after Torrefaction

Table III shows the contents of combustible, ash, carbon, hydrogen and calorific value of different biowaste after torrefaction. The torrefaction temperatures were 200-500 ^oC, and torrefaction time was 1-4 hrs. The combustible contents and calorific values of torrefied biowaste were increased obviously, due to the moistures and impurities in biowaste being completely removed during torrefaction. The combustible content of wood was increased from 73.35% to 95.92%, and the calorific value was increased from 2374.52 kcal/kg to 5331.66 kcal/kg after torrefaction at 500oC for 4 hrs. The calorific value was increased by 2957.14 kcal/kg, which is almost double as the calorific value prior to torrefaction. The carbon content of wood was also increased from 41.03% to 75.24%. The carbon content of torrefied biowaste was highly related to the calorific value.

The combustible content of torrefied bamboo was increased from (47.06%) to (98.28%). The increase of torrefied bamboo's calorific value was larger than that of wood, because bamboo had higher moisture content than wood. After torrefaction at 300^oC for 1hr, the calorific value of bamboo increased from 1525.79 kcal/kg to 6104.24 kcal/kg. The calorific value was increased by 4578.45 kcal/kg, which is almost quadruple as the calorific value prior to torrefaction. The carbon content of bamboo was increased from 47.07% to 74.63%, which was related to the increase of calorific value.

The combustible content of rice straw was increased from 47.23% to 74.46%, and the carbon content and calorific value were mildly increased from 1779.96 kcal/kg to 2696.74 kcal/kg. The calorific value was increased by 916.78 kcal/kg, which is almost 1.5 times as the calorific value prior to torrefaction. The combustible content of corrugated paper was slightly increased from 85.99% to 96.88% after 200^oC torrefaction. When the temperature rose to 400^oC and 500^oC, the combustible and carbon contents as well as calorific value were all decreased because of the paper being completely decomposed.

TABLE III
CHARACTERISTICS OF DIFFERENT BIOWASTE AFTER TORREFACTION

Run	Sample	Ash (%)	Combustible (%)	Calorific value (kcal/kg)	Carbon (%)	Hydrogen (%)
1	wood	16.17	83.83	3096.718	44.17±0.27	3.16±0.09
2	wood	4.08	95.92	5064.291	67.81±0.14	2.53±0.20
3	wood	5.68	94.33	5009.802	68.05±0.51	1.97±0.01
4	wood	25.91	74.10	5331.66	75.24±0.09	1.84±0.02
5	Bamboo	1.72	98.28	4535.171	55.67±0.39	3.39±0.18
6	Bamboo	4.86	95.14	6104.24	74.63±0.03	2.99±0.05
7	Bamboo	6.53	93.47	5017.367	72.00±0.04	2.04±0.03
8	Bamboo	13.54	86.46	5399.413	74.05±0.08	1.88±0.02
9	Rice straw	25.54	74.46	2524.723	40.91±0.08	2.59±0.05
10	Rice straw	40.77	59.23	2696.735	41.37±0.03	1.96±0.09
11	Rice straw	40.79	59.21	2599.855	41.14±0.04	1.59±0.04
12	Rice straw	53.14	46.86	2013.793	42.42±0.36	1.24±0.07
13	Corrugated paper	3.12	96.88	3192.381	43.08±0.11	3.32±0.15
14	Corrugated paper	24.01	75.99	2108.479	42.36±0.07	1.53±0.03
15	Corrugated paper	50.86	49.14	675.067	21.91±0.1	1.11±0.05
16	Corrugated paper	69.52	30.48	340.152	11.95±0.04	0.59±0.06

C. Influences of Different Torrefaction Conditions

The influences of different operation parameters on the calorific values of torrefied biowaste were investigated by using Taguchi orthogonal arrays method and signal-to-noise ratio (S/N ratio). The investigated parameters were different biowaste (wood, bamboo, straw, paper), torrefaction temperatures (200, 300, 400, 500°C), and torrefaction time (1, 2, 3, 4 hr). All the results of sixteen experiments were analyzed with statistic software MINITAB and the S/N ratio of each parameter were obtained. The results (Fig. 1) indicated that the influence of different parameters on torrefied biowaste followed the sequence of kinds of biowaste, torrefaction time, and torrefaction temperature. The best kind of biowaste was bamboo, the next were wood, rice straw, and corrugated paper. The best torrefaction time was 4 hr, the next were 3, 2, and 1 hrs. The best torrefaction temperature was 300°C, the next were 200, 400, and 500°C. Therefore, the best torrefaction condition in this study was bamboo torrefied at 300°C for 4 hrs. To verify the best condition, additional experiment was conducted and the calorific value of torrefied bamboo was 5952.88 kcal/kg. This value was similar to calorific value of brown coal or bituminous coal.

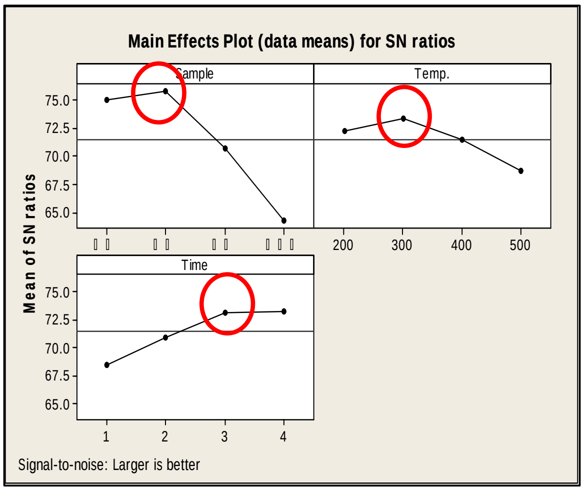

Fig. 1 S/N ratios of different operation parameters

IV. CONCLUSION

Experimental results illustrated that the calorific values of different biowaste can be increased by torrefaction. Torrefaction is a potential technology for recycling biowaste to biofuel. The influence of different operation parameters on the calorific values of torrefied biowaste followed the sequence of the kinds of biowaste, torrefaction time, and temperature. The best biowaste is bamboo, the best torrefaction time is 3 hours, and the best torrefaction temperature is 300°C.

The contents of carbon, combustible, and moisture in biowaste had higher relationships to the calorific values of torrefied biowaste. The increases in the combustible content and caloric value of torrefied bamboo were the highest among the four biowaste. The caloric values of bamboo can be increased from 1526 kcal/kg to 6104 kcal/kg after 300 °C and 1 hour torrefaction, which was almost four times as the original waste. The elemental carbon content of wood was increased from 41.03% to 75.24% after torrefaction, and that of bamboo was increased from 47.07% to 74.63%. The optimal torrefaction conditions of this study were bamboo torrefied at 300 °C for 4 hours. The corresponding caloric value of torrefied bamboo was 5953 kcal/kg.

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