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Assessing the potential environmental impact of woody biomass using quantitative universal exergy

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A B S T R A C T

At the same time of supplying tremendous energy, woody biomass also releases tremendous emissions in the forms of CO_2, NO_2, SO_2, and ash, causing serious environmental impact. This work investigates the potential environmental impact (PEI) of woody biomass using the quantitative universal exergy for the first time. The PEI of woody biomass is expressed using the chemical exergy of the potential (theoretical) emission gases (CO_2, NO_2, and SO_2) and ash components (mineral oxides) that produced from woody biomass, and this method is then used to study the PEIs of sixty four woody biomass samples. The results show that the PEIs are between 318.49 kJ/kg and 1078.81 kJ/kg, which are mainly attributed to CO_2 (52.73%–99.37%) and ash (0.18%–35.93%), followed by NO_2 (0.16%–8.75%) and SO_2 (0%–3.99%). The results also indicate that woody biomass generally results in less PEI (318.49–1078.81 kJ/kg) than coal (1325–1437 kJ/kg), and this dominance is more obvious when carbon neutral is taken into consideration. The content included in this study not only details the PEIs of the abundantly available woody biomass resources, but also demonstrates how to assess the PEIs of a fuel. Also, the method detailed in this study can be further applied to assess the PEI of a fuel utilization unit or process when the actual amounts of actual emissions are determined.

1. Introduction

The woody biomass on the earth was about 8.621 Gm^3 in 2016 (Li et al., 2017). If 1 m^3 of woody biomass yields 7.2 GJ of energy (Lauri et al., 2014), the 8.621 Gm^3 of woody biomass could supply 62.07 EJ of energy, which is about 87% of the primary renewable energy the world consumes (Zhang et al., 2015a). Although woody biomass is mainly used as an energy resource and the abundant woody biomass can supply tremendous energy, it can at the same time release tremendous emissions such as CO_2, NO_2, SO_2, and ash, causing serious environmental impact (Dincer et al., 2004; Yuan et al., 2017).

The emissions released from woody biomass have been widely studied and assessed. Ehrig and Behrendt (2013) studied the CO_2 emission from co-firing of wood pellets imported from different countries (Australia, Canada, Russia). Moroń and Rybak (2015) detailed the NO_x and SO_2 emissions from co-firing of brown coal with wood pellets as affected by different atmospheres (air, oxy, oxy + H_2O). Cereceda-Balic et al. (2017) determined the emission factors for the gases of CO_2, NO_x, and SO_2 generated from the combustion of hardwood and softwood. Kopczyński et al. (2017) detailed the SO_x and NO_x emissions and ash properties during the co-combustion of Ziemowit hard coal and raw or torrefied woody biomass. Generally, the emissions released from woody biomass would cause negative environmental impacts, e. g. the released CO_2 and CH_4 would result in greenhouse effect and cause global warming (Lin and Ahmad, 2017), the released NO_x and SO_x would form acid rain and kill plants (Kopczyński et al., 2017), the metals included in wood ash would deteriorate the soil quality for plant growth (Jones and Quilliam, 2014) and cause health risk on the human body (Orecchio et al., 2016), etc.

The environmental impacts of emissions from woody biomass have been widely assessed. Dwivedi et al. (2011) calculated the environmental impacts of the imported American wood pellets. Murphy et al. (2015) detailed the greenhouse gas (GHG) emissions of timber products from Irish wood processing industry. Nakano

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et al. (2018) studied the environmental impacts of greenhouse gas emissions of the Japanese round wood industry. Bais-Moleman et al. (2017) assessed the greenhouse gas emissions of wood product cascading in the European Union. Sánchez-García et al. (2017) analyzed the greenhouse gas emissions from a wood-fired power plant in Spain. Linkosalmi et al. (2016) specified the environmental information of wood-based furniture manufacturing processes (furniture industry) in Finland. Kim and Song (2014) analyzed the environmental impacts of the systems used for wood waste recycling. Handler et al. (2014) studied the environmental impacts of round wood supply chain options. Generally, the environmental impacts of woody biomass were mainly focused on greenhouse gas emissions, and the methods used were mainly life cycle assessment/analysis. On the other hand, the environmental impacts of ash components from woody biomass were not considered.

Exergy is a measure of energy quantity and quality, and it is widely used to study energy resources (Esen and Yuksel, 2013), units (Esen et al., 2007), and processes (Zhang et al., 2012). Exergy is also a measure of difference between a matter and its environment (Wall, 1986), and it is effective in measuring the potential the matter impacts the environment (Rosen and Dincer, 2001). Therefore, exergy was identified as relationship between a matter and its environmental impact (Dincer, 2000), and it has been widely used as a universal quantitative method to assess the PEIs of emissions (Ji et al., 2009), pollutants (Sciubba, 1999), energy systems (Caliskan, 2015), and transportation sectors (Dai et al., 2014). However, the environmental impact of woody biomass has not been assessed based on the quantitative universal exergy.

This work investigates the potential environmental impact (PEI) of woody biomass using the quantitative universal exergy for the first time. The specific objectives are: (a) to determine the PEI of woody biomass, and (b) to analyze the contributions to the PEI.

2. Materials and method

2.1. Materials

The materials used in this study include sixty four woody biomass samples, whose basic properties have been reported (Zhang et al., 2015a; 2016a,b). The C, N, and S elements and ash contents in woody biomass are the main causes for the PEIs, they are therefore detailed in this work. Table 1 shows the percentages of C, N, S, and ash for the woody biomass samples. Generally, the woody biomass samples have high contents of C (18.96–53.40%) whereas low contents of N (0.02–2.10%) and S (0–0.40%). Table 2 shows the molar contents of mineral oxides in the woody biomass ash. The mineral oxides mainly include SiO_2 (0–22.657 mol/kg), CaO (1.427–11.501 mol/kg), MgO (0.288–11.382 mol/kg), K_2O (0–4.958 mol/kg), Na_2O (0–3.792 mol/kg), P_2O_5 (0–2.051 mol/kg), Al_2O_3 (0.009–1.754 mol/kg), SO_3 (0–1.681 mol/kg), Fe_2O_3 (0–0.985 mol/kg), MnO (0–0.510 mol/kg) and TiO_2 (0–0.498 mol/kg).

Table 1
C, N, S, and ash contents of woody biomass (Zhang et al., 2015 a; Zhang et al., 2016 a).

No.	Wood	Origin	C (%)	N (%)	S (%)	Ash (%)
Softwood						
1	Pine	Sweden	50.60	0.10	0.01	0.40
2	Pine	Finland	49.80	0.29	0.01	0.58
3	Pine	Finland	50.01	0.38	0.03	1.64
4	Pine	Finland	51.21	0.38	0.03	1.52
5	Pine	Finland	47.94	0.09	0.00	0.09
6	Pine	U.S.A	51.20	0.25	0.01	0.22
7	Pine	U.S.A	31.34	0.06	0.00	1.30
8	Pine	U.S.A	26.68	0.05	0.05	1.50
9	Pine	Canada	45.42	0.13	0.01	1.50
10	Pine	Germany	41.32	0.16	0.08	1.87
11	Pine	N	53.40	0.10	0.10	2.90
12	Spruce	Sweden	49.90	0.20	0.01	0.60
13	Spruce	Finland	47.28	0.38	0.03	2.22
14	Fir	U.S.A	45.89	0.27	0.00	0.45
15	Fir	N	18.96	0.02	0.01	0.15
16	Conifer	Sweden	46.53	0.43	0.00	1.09
17	Miscanthus	Greece	41.15	1.20	0.25	5.91
18	Cardoon	Greece	43.02	0.76	0.17	11.37
19	Cytisus	Spain	19.93	0.84	0.04	0.56
20	Cedar	N	46.21	0.09	0.01	0.90
21	Christmas tree	N	32.08	0.32	0.25	3.24
Hardwood						
22	Willow	Finland	48.51	0.39	0.03	1.15
23	Willow	Greece	46.25	0.68	0.31	1.78
24	Willow	N	45.86	0.89	0.12	2.17
25	Willow	N	45.41	0.45	0.06	1.08
26	Willow	N	44.92	0.55	0.06	1.54
27	Willow	N	44.07	0.32	0.03	0.85
28	Willow	N	43.54	0.32	0.04	0.94
29	Willow	N	44.03	0.58	0.08	1.33
30	Willow	N	42.66	0.62	0.05	1.48
31	Willow	N	41.43	0.54	0.05	0.95
32	Poplar	Greece	45.91	0.74	0.03	1.64
33	Poplar	U.S.A	47.05	0.22	0.05	1.16
34	Poplar	Spain	39.89	0.35	0.06	2.77
35	Poplar	N	47.39	0.55	0.02	1.49
36	Poplar	N	46.72	0.56	0.02	2.51
37	Oak	Spain	46.81	0.53	0.02	3.54
38	Oak	N	49.70	0.20	0.10	5.30
39	Oak	N	44.24	0.03	0.01	0.27
40	Eucalyptus	U.S.A	44.89	0.13	0.03	0.48
41	Eucalyptus	N	41.71	0.26	0.00	4.22
42	Citrus	Greece	47.00	1.00	0.03	2.80
43	Olive	Greece	48.20	0.70	0.03	1.50
44	Paulownia	Greece	45.78	0.34	0.24	0.85
45	Pepper	Finland	34.38	2.10	0.40	18.05
46	Salix	Sweden	43.06	0.44	0.00	1.68
47	Ulexeuropaeus	Spain	26.05	0.92	0.05	0.83
Others (not detailed or not known)						
48	Wood	Spain	47.21	0.20	0.05	0.68
49	Wood	Sweden	45.79	0.08	0.01	0.46
50	Wood	Spain	37.73	0.36	0.04	14.02
51	Wood	Dutch	41.47	1.19	0.07	2.46
52	Wood	U.S.A	32.06	0.26	0.01	0.69
53	Wood	N	34.39	0.27	0.02	0.54
54	Demolition	Finland	45.69	0.86	0.07	1.49
55	Demolition	Germany	47.87	0.61	0.02	3.53
56	Demolition	N	42.13	0.52	0.11	11.94
57	Park waste	Dutch	47.04	0.24	0.04	3.06
58	Park waste	Dutch	35.88	0.81	0.17	15.58
59	Forest residue	Sweden	33.93	0.49	0.00	0.84
60	Forest residue	N	25.70	0.53	0.06	2.03
61	Composting	Dutch	30.63	0.92	0.13	29.73
62	Painted	Dutch	44.86	0.40	0.04	1.87
63	Wood waste	Sweden	33.05	0.15	0.01	0.54
64	Furniture waste	N	43.85	0.25	0.03	3.17

N indicates not detailed or not known.

2.2. Potential emissions from woody biomass

Energy contained in woody biomass is mainly released during the thermochemical conversion processes (liquefaction, pyrolysis, gasification, and combustion). A general equation can be used to describe the thermochemical processes for woody biomass conversion:

$$\text{Woody biomass} \rightarrow \text{heat} + \text{products} \quad (1)$$

If the woody biomass is completely converted, the products are mainly CO_2, NO_x, SO_x, H_2O, and ash (Cereceda-Balic et al., 2017). Sometimes, the other intermediate products would be formed, e. g. alcohol, butanol, CH_4, CO, H_2, etc. Although these intermediate