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Characteristics of particulate-bound polycyclic aromatic hydrocarbons emitted from industrial grade biomass boilers

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ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are carcinogenic or mutagenic and are important toxic pollutants in the flue gas of boilers. Two industrial grade biomass boilers were selected to investigate the characteristics of particulate-bound PAHs: one biomass boiler retro-fitted from an oil boiler (BB1) and one specially designed (BB2) biomass boiler. One coal-fired boiler was also selected for comparison. By using a dilution tunnel system, particulate samples from boilers were collected and 10 PAH species were analyzed by gas chromatography–mass spectrometer (GC–MS). The total emission factors (EFs) of PAHs ranged from 0.0064 to Q3 0.0380 mg/kg, with an average of 0.0225 mg/kg, for the biomass boiler emission samples. The total PAH EFs for the tested coal-fired boiler were 1.8 times lower than the average value of the biomass boilers. The PAH diagnostic ratios for wood pellets and straw pellets were similar. The ratio of indeno(1,2,3-*cd*)pyrene/[indeno(1,2,3-*cd*)pyrene + benzo(*g*,*h*,*i*)perylene] for the two biomass boilers was lower than those of the reference data for other burning devices, which can probably be used as an indicator to distinguish the emission of biomass boilers from that of industrial coal-fired boilers and residential stoves. The toxic potential of the emission from wood pellet burning was higher than that from straw pellet burning, however both of them were much lower than residential stove exhausts.

Introduction

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous pollutants, and some of them are carcinogenic and/or mutagenic (Ames et al., 1975; Epstein et al., 1979). In addition to natural processes, PAHs mainly originate from coal and wood burning, petrol and diesel oil combustion, industrial processes and so on (Bamford and Baker, 2003; Chen et al., 2006; Yunker et al., 2002). In the atmosphere, the partitioning of PAHs between the particulate and gas phases depends on the vapor pressure as well as air conditions such as ambient temperature, and nature of the aerosol such as origin and properties, because they are semi-volatile organic compounds. However, carcinogenic 5- and 6-ring PAHs are mostly associated with particulate matter (Bamford and Baker, 2003; Araki et al., 2009).

The energy consumption in China has kept rapidly increasing in the past decades. China has become the largest consumer of energy in the world, with the primary energy consumption accounting for 22.4% of the world in 2013. Currently, in China, coal is the biggest energy contributor, accounting for 67.4% of the total consumption in 2013

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(BP Statistical Review of World Energy, 2013). Biomass is organic material with intrinsic chemical energy content and is composed of a wide variety of forestry and agricultural resources, industrial processing residues, and municipal solid and urban wood residues. China is a leading agricultural nation and the amount of crop residue was found to be 802.32 million tons in 2009 (Song et al., 2014). Among the crop residue resources, process residue is an important contributor in China; the total process residue quantity in China from 2007 to 2009 was evaluated at 88.62 million tons annually, which was equivalent to 49.34 million tons of standard coal (Guo et al., 2012). Due to the large resource amount and renewable characteristics, biomass is expected to play a more important role in the energy structure of China in the future.

Much of the previous research on emission factors (EFs) in relation to coal or biomass combustion has focused on small residential stoves, mainly because of their wide usage in China. Due to the low combustion efficiency and lack of control measures, emissions from small residential stoves usually result in serious indoor and outdoor air pollution (Chen et al., 2006; Zhi et al., 2008; Yang et al., 2010; Shen et al., 2012). Bignal et al. (2008) investigated the PAH emission from a woodchip-fired 50 kW domestic boiler. Olsson and Kjällstrand (2006) reported a study on PAH concentrations relative to other organic emissions in two modes (flaming and glowing) of a 30 kW boiler. The above studies involved relatively small biomass boilers where raw fuel with high moisture content was used for burning. It was reported that high moisture content usually leads to high PAH release (Bignal et al., 2008). On the other hand, due to its higher combustion efficiency and lower emissions, the industrial grade biomass boiler has been promoted in China in recent years. Some researchers reported PAH EFs for some industrial coal-fired boilers (Yang et al., 1998; Li et al., 1999; Dyke et al., 2003), however data from industrial biomass boilers were not included. In addition, the use of processed crop residues (dry pellets) is also gradually expanding in China, which has much lower moisture than that of raw biomass fuels and is expected to have lower emissions of PAHs, as well as other incomplete combustion byproducts. Currently, data on the emission profile, especially PAHs, of industrial grade biomass boilers using local processed biomass fuels in China are scarce.

In order to diagnose the relative contributions of various sources and devise effective control strategies, accurate inventories are often compiled based on the strengths of emission activities and EFs. Generally, EFs will vary depending on fuel category, fuel origin, stove type, combustion conditions, dilution technologies and so on. Some studies have reported the PAH EFs for some domestic coal and biomass under particular combustion conditions (Chen et al., 2005; Tao et al., 2006). However, reports concerning the biomass combustion from industrial boilers in China are rare.

In this research, EFs of particulate-bound PAHs exhausted from two types of industrial biomass boiler were investigated. Two types of pelletized biomass fuels were tested respectively. Additionally, the PAH EFs of the emission from one industrial coal-fired boiler were also studied for comparison.

1. Methods

1.1. Biomass boilers and coal-fired boiler

Currently, in China, some of the biomass boilers are specially designed for biomass combustion, while others are retro-fitted from original coal or oil burning boilers. In this study, two biomass boilers were selected, one of which was retro-fitted from an oil-fired boiler (BB1) and another was specially designed (BB2). For comparison, emission from a coal-fired boiler (CB) with similar power was also investigated. The detailed information of these boilers is listed in Table 1. These boilers operated intermittently according to the requirements of heat supply or hot water supply. In the case of heat supply, the boilers usually are used from 15th November to 15th March of the next year, and the average working time is about 10 h/day.

1.2. Fuel

Two kinds of biomass fuels were purchased from a local market: wood pellets and straw pellets. The shape of the pellets was stick-form with diameter of 0.6–0.8 cm and length of 3–5 cm. The same wood pellets were used as the test fuel for the burning experiments of both BB1 and BB2. A bituminous coal (Datong, Shanxi Province) with block-form and less than approximately 4 cm in size was also tested for comparison. Analytical characteristics of the tested fuels are shown in Table 2. The proximate and elemental analyses were conducted at China Coal Research Institute. The proximate analysis was conducted according to the Chinese national standard methodologies (GB/T212-, 2008) and the elemental analysis was conducted using an elemental analyzer (CE-440, Exeter Analytical Inc., USA) for each test. Compared with coal, the tested biomass fuels showed higher percentages of volatile compounds and oxygen but lower moisture, heating value, carbon content and sulfur content.

1.3. Sampling

Sampling was undertaken in January 2010. The dilution sampling system used in this study has been reported in detail elsewhere (Geng et al., 2013) and is briefly summarized here. Gases were first extracted and two-stage diluted from the flue by a dilution system (FPS 4000, Dekati Ltd., Finland) which is widely used (Giechaskiela et al., 2005; Mathis et al., 2004; Vaaraslahti et al., 2004). The temperature of flue gas could be subsequently cooled to room temperature (about 20 °C) and the dilution ratio was controlled at 14 to 20. Then PM_{10} samples were collected by a double-channel cyclone PM sampler on quartz fiber filters (47 mm diameter, Advantec, Japan) for the boilers at normal operation conditions. The sampling time duration was about 150 min for each sample and a total of 4 samples were collected. In order to evaluate particulate matter (PM) removal rate, PM_{10} samples were respectively collected before and after precipitation, and a good removal rate was confirmed (Geng et al., 2013). On the other hand, PAHs in the samples collected after precipitation were analyzed and are reported in this paper.

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Table 1 – Information of boilers.

	Model	Power (MW)	Precipitator	Fire grate	Application
Biomass-fired boiler 1 (BB1)	DZW2.1-0.7/95/70-M	2.1	Bag filter	Reciprocating bar	Heat supply for residential or office building
Biomass-fired boiler 2 (BB2)	CDZL1.4-0	1.4	Water film scrubber	Chain grate	Heat supply for office building or vegetable greenhouses
Coal-fired boiler (CB)	IRZL-2.0-0	2.0	Water film scrubber	Chain grate	Heat or hot water supply for office building

1.4. PAH analysis

Since only particle samples were collected in this study, some 2- or 3-ring PAHs that mainly exist in the gas phase were not appropriate for the discussion in this study. Therefore, ten PAH species having relatively lower saturated vapor pressure were analyzed and investigated (Table 3). The pretreatment and analysis were conducted by Beijing Center for Physical & Chemical Analysis, according to methods EPA-610 and EPA-TO13A and described briefly here. The PM_{10} filter samples were extracted ultrasonically three times with 150 mL of dichloromethane (DCM), and each extraction lasted 30 min. Surrogate deuterated PAHs (chrysene-d_{12}, pyrene-d_{12}, SUPELCO, USA) were added prior to the extraction. The extracts were concentrated on a rotary evaporator and fractionated using silica–alumina column chromatography. The PAH fractions were then concentrated and an internal standard (hexa-methylbenzene, SUPELCO, USA) was added for quantification of individual PAHs by gas chromatography–mass spectrometer (GC–MS) (Varian GC-431 coupled with Varian 240-MS, USA).

1.5. Calculation of emission factors

The fuel-mass based PAH-EF is expressed in units of milligrams (mg) of PAH emitted per kilogram (kg) of fuel burned. The EF (mg/kg) of species X on a fuel-mass basis can be calculated using the following equation:

$$EF_X = \frac{[X] \times D \times Q \times T}{M} \quad (1)$$

where, [X] (mg/m^3) is the concentration of species X on the sample filter, Q (m^3/min) is the flow rate of the flue gas in stack, *T* (min) is the sampling time, *D* is the dilution factor and *M* (kg) is the weight of fuel burned during the sampling time.

1.6. Quality assurance and quality control

Quartz-fiber filters were baked at 800 °C in an oven for 2 h to remove organic materials adsorbed on them. A laboratory blank sample was processed with the same procedure as the real samples and no detectable PAHs were present. Field blanks were analyzed and no significant contamination was found. The relative correlation for the standard curve (standard solution including six concentration levels: 0, 10, 50, 100, 500 and 1000 ng/mL) was higher than 0.995 and the relative standard deviation of the response factor was less than 15%.

2. Results and discussion

2.1. Emission factors

EFs of the identified 10 PAHs in particulate samples were calculated on a fuel-weight basis and are shown in Table 4. The total EFs of PAHs ranged from 0.0064 to 0.0380 mg/kg, with an average of 0.0225 mg/kg, for the biomass boiler emission samples. The total PAH EFs for the tested coal-fired boiler was 1.8 times lower than the average value of biomass boiler. The difference in the values between PAH EFs for the biomass and coal may be due to the different volatile contents of the fuels. The volatile content of biomass was 75.8% (wood pellets, air dried basis) and 57.0% (straw pellets, air dried basis) while that for coal was only 31.4% (Table 2). At the same time, the total PAH EFs for BB1 with wood pellets was 3.6 times higher than that of BB1 with straw pellets (Table 4).

Table 2 – Analytical characteristics of the tested fuels (air-dried basis).

		Biomass		Coal
		Wood pellet	Straw pellet	Bituminous
Proximate analysis (air dry basis)	Moisture (%)	2.6	2.6	3.8
	Volatile matter (%)	75.8	57.0	31.4
	Ash (%)	5.2	25.2	10.6
	Fixed carbon (%)	16.3	15.2	54.1
	Higher heating value (MJ/kg)	20.3	14.4	26.5
	Lower heating value (MJ/kg)	19.1	13.5	25.6
Elemental analysis (air dry basis)	Carbon (%)	46.9	35.8	66.9
	Hydrogen (%)	5.5	4.2	3.9
	Nitrogen (%)	0.1	0.9	0.8
	Oxygen (%)	39.5	31.1	13.1
	Sulfur (%)	0.1	0.1	0.9

Table 3 – Investigated polycyclic aromatic hydrocarbons (PAHs).

No	Name	Abbreviation	Rings	Formula
1	Fluoranthene	FLA	4	$C_{16}H_{10}$
2	Pyrene	PYR	4	$C_{16}H_{10}$
3	Benz(*a*)anthracene	BaA	4	$C_{18}H_{12}$
4	Chrysene	CHR	4	$C_{18}H_{12}$
5	Benzo(*b*)fluoranthene	BbF	5	$C_{20}H_{12}$
6	Benzo(*k*)fluoranthene	BkF	5	$C_{20}H_{12}$
7	Benzo(*a*)pyrene	BaP	5	$C_{20}H_{12}$
8	Indeno(1,2,3-*cd*)pyrene	IcdP	6	$C_{22}H_{12}$
9	Dibenz(*a*,*h*)anthracene	DahA	5	$C_{22}H_{14}$
10	Benzo(*g*,*h*,*i*)perylene	BghiP	6	$C_{22}H_{12}$

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Table 4 – PAH emission factors for biomass boiler and coal-fired boiler (based on fuel mass) (units: mg/kg).

	BB1 wood pellet	BB1 straw pellet	BB2 wood pellet	CB bituminous
FLA	0.0062	0.0013	0.0001	0.0044
PYR	0.0061	0.0012	0.0001	0.0014
BaA	0.0011	0.0004	0.0096	0.0006
CHR	0.0015	0.0006	0.0154	0.0011
BbF	0.0017	0.0008	0.0079	0.0022
BkF	0.0013	0.0006	0.0028	0.0007
BaP	0.0009	0.0004	0.0012	0.0006
IcdP	0.0007	0.0002	0.0001	0.0003
DahA	0.0013	0.0002	0.0006	0.0003
BghiP	0.0025	0.0008	0.0003	0.0013
Sum (10-PAH)	0.0231	0.0064	0.0380	0.0128

PAH: polycyclic aromatic hydrocarbon.

Additionally, the volatile content was found to be 1.3 times higher in the tested wood than that in the tested straw (Table 2). High volatile content usually leads to incomplete combustion, which results in more PAH emission (Chen et al., 2005). Therefore, the different PAH EFs for BB1 with wood pellets and BB1 with straw pellets, which were tested in the same boiler, may also be due to the different percentages of volatile content between the two tested biomass fuels.

The concentrations of benzo(*a*)pyrene (BaP) from the tested biomass fuels were 0.86 $\mu g/m^3$ (BB1 with wood pellets), 0.38 $\mu g/m^3$ (BB1 with straw pellets) and 1.24 $\mu g/m^3$ (BB2 with wood pellets). In Beijing, the standard maximum concentration limit of BaP is 0.3 $\mu g/m^3$ (DB11/501-2007). The BaP concentration from the emission of the studied biomass burning was 0.3 to 3.1 times higher than the standard value, which indicated that the pollution of biomass combustion from the industrial boiler to the atmosphere was serious. Therefore, a more efficient precipitation system should be employed to reduce PAH emissions. In addition, the concentration of BaP from the tested bituminous coal emission was 0.56 $\mu g/m^3$, which was at the same level as the biomass emission.

As shown in Fig. 1, good correlation between the BaP EFs and total PAH EFs was observed (R^2 = 0.9991). This finding was probably due to the similar generation mechanism for the tested PAH species. Therefore, the EFs of the total PAHs can be derived from the EFs of BaP by multiplying by the slope in Fig. 1, which can be used to estimate the total PAH EFs when the BaP value is available.

A comparison of studies reporting 10-PAH EFs and BaP EFs for each tested fuel is shown in Table 5, with some data cited from other reports. The BaP EFs for the tested fuels in this study were at a similar level compared with the data obtained from a study on the coal burning emission from the industrial boiler and power plant boiler (Cui et al., 1993). Also, both the 10-PAH EFs and BaP EFs were much higher in the emission from the residential stoves than those from the industrial boiler, regardless of the fuel types, which was because the precipitation systems installed after the industrial boiler can effectively precipitate the emitted dust. Another reason is that the oxygen supply during the burning process of a residential stove is much more insufficient than that of a boiler, which leads to much higher amounts of incomplete combustion byproducts such as PAHs. Additionally, Shen et al. (2013) reported that the PAH EFs of wood pellet burning were lower than those of straw pellets, which was similar to the result obtained in this study.

2.2. PAH diagnostic ratio

A number of PAH diagnostic ratios, including FLA/(FLA + PYR), BaA/(BaA + CHR), IcdP/(IcdP + BghiP) and BbF/(BbF + BkF) (FLA, PYR, BaA, CHR, IcdP, BghiP, BbF, and BkF refer to Table 3), are often used as source-specific indicators for PAH source identification (Watson, 1984; Yunker et al., 2002; Galarneau, 2008; Katsoyiannis et al., 2007; Zhang et al., 2008). For example, it was reported that IcdP/(IcdP + BghiP) larger than 0.5 indicated emission from coal combustion, while a ratio smaller than 0.5 indicated petroleum combustion (Yunker et al., 2002). Four frequently-used PAH diagnostic ratios were calculated and shown in Table 6, compared with some results from the literature. Each of the four PAH diagnostic ratios showed similar levels for wood pellets and straw pellets in this study, and similar characteristics were also found in Shen et al. (2013). However, the ratios of IcdP/(IcdP + BghiP) for both wood pellets and straw pellets were lower than those of the reference data in Table 6 for the two biomass fuels, which were at a similar level compared to the value for coal in this study. Therefore, IcdP/(IcdP + BghiP) can probably be used as one of the reference indicators to discriminate between the exhausts of industrial boilers and

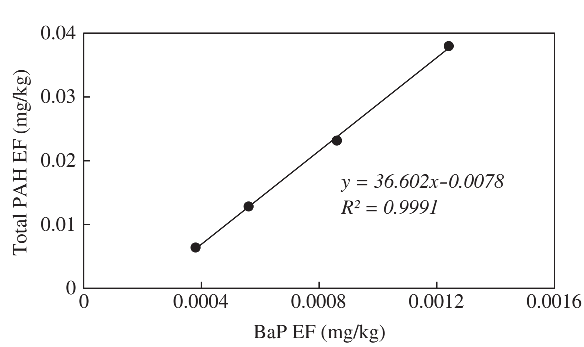

Fig. 1 – Correlation of benzo(a)pyrene emission factors (BaP EFs) with the total polycyclic aromatic hydrocarbon (PAH) EFs.

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Table 5 – Comparison of PAH emission factors (EFs) with some reported values.

Boiler/stove	Fuel	Size	PAH EFs (mg/kg)		References
			10-PAH	BaP	
BB1	Wood pellet	PM_{10}	0.0231	0.0009	This study
BB1	Straw pellet	PM_{10}	0.0064	0.0004	
BB2	Wood pellet	PM_{10}	0.0380	0.0012	
CB	Bituminous coal	PM_{10}	0.0128	0.0006	
Industrial boiler	Blended bituminous coal	$PM_{2.5}$	–	0.0002–0.0097	Cui et al., 1993
Power plant boiler	Blended bituminous coal and coal briquette	$PM_{2.5}$	–	0.0003	
Residential stove	Anthracite coal	$PM_{2.5}$	–	0.32–20	
Residential stove	Bituminous coal and honeycomb briquette	PM_{10}	69.00–160.00	1.05–2.46	Geng et al., 2014
Residential stove	Bituminous coal	TSP	398	34.9	Liu et al., 2009
Residential stove	Wood pellet	TSP	1.71	0.04	Shen et al., 2013
	Straw pellet	TSP	2.7	0.11	

10-PAH refers to the sum of FLA, PYR, BaA, CHR, BbF, BkF, BaP, IcdP, DahA and BghiP. TSP: total suspended particulate matter; PAH: polycyclic aromatic hydrocarbon; FLA: fluoranthene; PYR: pyrene; BaA: benz(a)anthracene; CHR: chrysene; BbF: benzo(b)fluoranthene; BkF: benzo(k)fluoranthene; BaP: benzo(a)pyrene; IcdP: indeno(1,2,3-cd)pyrene; DahA: dibenz(a,h)anthracene; BghiP: benzo(g,h,i)perylene.

residential stoves. Additionally, the diagnostic ratios for the tested coal sample were generally comparable to those reported in Shen et al. (2011), although in our study FLA/(FLA + PYR) was a little higher than the maximum value in the reference.

2.3. Potential toxicity risk

To assess the potential toxicity risk to ecosystems and human beings, a sum of 7 carcinogenic PAH components ($\sum PAH_7$, BaA, CHR, BbF, BkF, BaP, IcdP and DahA (dibenz(*a*,*h*)anthracene)), BaP-equivalent carcinogenic power (BaPE), and 2,3,7,8-tetrachlorodibenzodioxin (TCDD)-based total toxicity potency (TEQ) have been utilized in many studies (Cecinato, 1997; Larsen and Larsen, 1998; Bosveld et al., 2002; Bhargava et al., 2004; Lu et al., 2008; Liu et al., 2009). At the same time, PAHs are considered to be the main cause of indirect-acting mutagenicity (Gibson, 1983; Durant et al., 1996). We had previously assayed the indirect-acting mutagenicities of PAHs by the Ames test (Yang et al., 2010), and the results were used for the mutagenicity evaluation in this study. The original parameters for the calculation are listed in Table 7 and the calculated results for the potential risk of PAHs in the burning emissions of the tested fuels are listed in Table 8. In addition, the values listed in Table 8 for BaPE, TEQ and indirect-acting mutagenicities represent the results of each PAH species multiplied by each corresponding EF value. In this study, BB2 with wood pellets showed the highest values of $\sum PAH_7$, BaPE, TEQ and indirect-acting mutagenicities among the tested fuels, while BB1 with straw pellets showed the lowest toxicities. The above result was consistent with the PAH EFs for each fuel. In addition, compared with data from some other reports (Chen et al., 2005, 2006; Geng et al., 2014), the toxicity of the PAHs for the emission from the industrial boilers is much lower than that from residential stoves due to the much lower amount of PAH emission. However, due to their long-term operation, the PAH emission from industrial biomass boilers may still be more important than that from residential stoves.

3. Conclusions

Using a dilution system, particulate samples from industrial boiler combustion with two types of biomass fuels and coal were collected to analyze for 10 kinds of PAHs. The total PAH EFs for the tested coal-fired boiler were lower than the average value for the biomass boilers, and the EFs for BB1 with wood pellets were higher than that for BB1 with straw pellets. These results might be due to the different volatile contents of the

Table 6 – PAH diagnostic ratios for the tested fuels.

	This study (industrial boilers)			References (residential stoves)		
	Wood pellet [a]	Straw pellet [b]	Coal [c]	Wood pellet [d]	Straw pellet [d]	Coal [e]
FLA/(FLA + PYR)	0.46	0.52	0.76	0.56	0.54	0.32–0.70
BaA/(BaA + CHR)	0.41	0.43	0.36	0.36	0.40	0.27–0.56
IcdP/(IcdP + BghiP)	0.26	0.20	0.21	0.50	0.45	0.23–0.63
BbF/(BbF + BkF)	0.66	0.59	0.76	0.53	0.55	0.60–0.89

PAH: polycyclic aromatic hydrocarbon; FLA: fluoranthene; PYR: pyrene; BaA: benz(a)anthracene; CHR: chrysene; BbF: benzo(b)fluoranthene; BkF: benzo(k)fluoranthene; IcdP: indeno(1,2,3-cd)pyrene; BghiP: benzo(g,h,i)perylene.

[a] Average values of BB1 and BB2 with wood pellet.
[b] Value of BB1 with straw pellet.
[c] Value of coal-fired boiler (CB).
[d] Shen et al., 2013.
[e] Shen et al., 2011.

Table 7 – Parameters for the toxicity risk evaluation of each PAH species.

PAH	BaPE	TEQ	Indirect-acting mutagenicities* (revertant/mg)
FLA	–	0.00000001	1.8
PYR	–	–	<0.1
BaA	0.06	0.00001	2.0
CHR	–	0.0001	<0.1
BbF	0.07	–	7.8
BkF	0.07	–	3.8
BaP	1	0.0001	16.1
IcdP	0.08	–	0.8
DahA	0.6	0.0001	5.0
BghiP	–	0.00000001	0.3

BaPE: benzo(a)pyrene-equivalent carcinogenic power for PAHs (Cecinato, 1997); TEQ: total toxicity potency for PAHs, base on 2,3,7,8-tetrachlorodibenzo-dioxin (TCDD) in vitro assays (Bosveld et al., 2002); PAH: polycyclic aromatic hydrocarbon; FLA: fluoranthene; PYR: pyrene; BaA: benz(a)anthracene; CHR: chrysene; BbF: benzo(b)fluoranthene; BkF: benzo(k)fluoranthene; BaP: benzo (a)pyrene; IcdP: indeno(1,2,3-cd)pyrene; DahA: dibenz(a,h) anthracene; BghiP: benzo(g,h,i)perylene.

* Indirect-acting mutagenicities of PAHs *in vitro* assays (*Salmonella typhimurium* TA100 strain with S9 mix) (Yang et al., 2010).

fuels, since high volatile content usually leads to incomplete combustion, which results in more PAH emission. Compared with the reference data, total PAH EFs were much higher in the emission of the residential stoves than those from the industrial boilers whatever the fuel type, which was mainly due to the installed precipitation systems for the industrial boilers. The BaP concentration from the emission of the studied biomass burning was 0.3 to 3.1 times higher than the standard value (DB11/501-2007), indicating the environment pollution risk of using industrial biomass boilers. Good correlation between BaP EFs and the total PAH EFs was observed, indicating the usefulness of BaP values for the estimation of the total PAH amount. The investigated PAH diagnostic ratio for both wood pellets and straw pellets showed similar levels. However, the ratios of IcdP/(IcdP + BghiP) for the two biomass fuels in this study were lower than those of the reference data from residential stoves, which can probably be used as an indicator for industrial boiler and residential stove exhausts. Based on the toxic risk calculation, the toxicity of the PAHs for the emission from the industrial boilers was much lower than that from residential stoves due to the much lower amount of PAH emission.

Table 8 – Potential toxicity risk of PAHs for each tested fuels.

	BB1 wood pellet	BB1 straw pellet	BB2 wood pellet	CB bituminous
$\sum PAH_7$ (mg/kg)	0.0084	0.0031	0.0375	0.0058
BaPE*	0.0012	0.0005	0.0026	0.0008
TEQ**	0.0003	0.0003	0.0030	0.0009
Indirect-acting mutagenicities (revertant/mg)	1.6E-06	6.8E-07	4.5E-06	9.1E-07

$\sum PAH_7$ is the sum of 7 carcinogenic PAH species; indirect-acting mutagenicities are calculated by indirect-acting mutagenicities of PAHs in vitro assays.
PAHs: polycyclic aromatic hydrocarbon; BaPE: benzo(a)pyrene-equivalent; TEQ: total toxicity potency.
* Calculated by BaPE.
** Calculated by TEQ.

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