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Polycyclic Aromatic Hydrocarbons (PAHs) in Road Dust Collected from Myanmar, Japan, Taiwan, and Vietnam

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Abstract

In this study, we determined the concentrations of polycyclic aromatic hydrocarbons (PAHs) in road dust from Myanmar, Japan, Taiwan, and Vietnam. PAHs were detected in urban and rural areas of Myanmar at mean concentrations of 630 ng/g dry weight and 200 ng/g dry weight, respectively. PAHs were also detected in road dust from Vietnam (mean 1700 ng/g) and Taiwan (2400 ng/g). PAH diagnostic ratios suggested that fossil fuel vehicular exhaust and biomass combustion are major sources of PAHs in road dust in Myanmar. Road dust samples from Japan, Taiwan, and Vietnam had similar PAH diagnostic ratios, implying that PAH sources are similar. We assessed the human health risks posed by PAHs in road dust using carcinogenic equivalents (CEQs) and incremental lifetime cancer risk (ILCR). Mean CEQs were decreased in the order Taiwan (173 ng/g) > Vietnam (162 ng/g for Hanoi) > Myanmar (42 and 31 ng/g for Yangon and Pathein, respectively) > Japan (30 ng/g for Kumamoto). Benz[*a*]pyrene, fluoranthene, and benzo[*b*]fluoranthene, the predominant PAHs, contributed > 70% of total CEQs. High ILCR values were found for Taiwan (5.9×10^{-4} and 9.9×10^{-4} for children and adults, respectively) and Vietnam (6.5×10^{-4} and 9.2×10^{-4} for children and adults, respectively, in Hanoi), indicating that PAHs in road dust pose cancer risks to the inhabitants of Taiwan and Hanoi. To our knowledge, this is the first report to identify PAH pollution in the environment and to evaluate the human health risks of these PAHs in Myanmar.

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous pollutants that have been detected in a wide range of environmental matrices (Yunker et al. 2002; Wang et al. 1999; Nakata et al. 2014). PAHs have petrogenic and pyrogenic sources. Low molecular-weight PAHs and alkylated PAHs are found at high concentrations in mineral oils, making oil spills important petrogenic contributors of PAHs to the environment. Complex PAH mixtures containing high molecular weight PAHs are produced by pyrogenic sources through the incomplete combustion of organic material, such as coal, petroleum, and wood (Yunker et al. 2002). It is important to identify the sources of PAH emissions, to develop methods for controlling PAH pollution in the environment, and to minimize health risks to humans.

There are public health concerns about exposure to PAHs, because many of these compounds are carcinogenic and mutagenic. The U.S. Environmental Protection Agency (EPA) has classified 16 PAHs as priority pollutants (USEPA 1993). Benzo[*a*]pyrene (BaP), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene, and chrysene (Chry) are classed as carcinogenic or potentially carcinogenic chemicals by the International Agency for Research on Cancer. Several high molecular weight PAHs, including BaP, can bind to the aryl hydrocarbon receptor, which is associated with tumor production and increased oxidative stress; these PAHs are used as markers when evaluating the risks posed by PAHs

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to humans (Lin et al. 2002; Villeneuve et al. 2002). There are three main pathways through which humans are exposed to PAHs: ingestion, inhalation, and dermal contact. Incremental lifetime cancer risks (ILCRs) for PAHs, as defined by the USEPA (1991), have been used to evaluate the cancer risks posed to humans via exposure to PAHs through these pathways.

Monitoring studies of PAH contamination in road dust have been performed in developed and developing countries. Mean PAHs levels in road dust collected from Iran and Egypt were 330 ng/g (Saeedi et al. 2012) and 680 ng/g dry weight (dw) (Hassanien and Abdel-Latif 2008), respectively. In China, PAHs levels in road dust are 2400 ng/g dw in Shanghai (Jia et al. 2017), 3900 ng/g in Lanzhou (Jiang et al. 2014), and 4800 ng/g in Guangzhou (Wang et al. 2011). However, little information is available on the concentrations and distributions of various environmental pollutants in Myanmar, including PAHs and persistent organic pollutants.

Heavy metal pollution in Myanmar has been investigated in several recent studies. High arsenic concentrations (50–630 µg/L) have been found in well water in the Lower Ayeyarwady Basin of western Myanmar (Van Geen et al. 2014). Bacquart et al. (2015) determined the concentrations of 21 metals in 18 drinking water samples and found that concentrations of arsenic, fluoride, iron, manganese, and uranium in water from most wells in Myingyan Township in central Myanmar were higher than health-based reference values. Wai et al. (2018) determined heavy metal concentrations in human urine from Myanmar and suggested that telomere shortening occurs because of exposure to arsenic and cadmium. Concentrations of fine particles with a diameter of 2.5 µm or less (PM2.5) in the air of downtown Yangon City in Myanmar have recently been published; PM2.5 concentrations were higher than the US EPA national ambient air quality standard of 35 µg/m^3 at all sampling sites (Yi et al. 2018). PM2.5 pollution caused by traffic and PAH concentrations in road dust have been found to be related. High molecular weight PAHs have been identified at high concentrations in PM2.5 and particulate matter with a diameter of 10 µm or less (PM10) (Khan et al. 2017; Alves et al. 2017), but no data are available for PAH concentrations in Myanmar.

Road dust is a suitable matrix for monitoring PAH pollution. Road dust is a complex mixture of particles in the exhaust emitted from motor vehicles, particles produced from vehicle tires, liquids (e.g., lubricating oils and fuel) that have spilled or leaked from vehicles, and particles produced by road surface erosion. High concentrations of PAHs and other toxic chemicals have been found in road dust. In previous studies, PAH concentrations and distribution have been determined in road dust from Australia (Nguyen et al. 2014), China (Wang et al. 2011), Korea (Lee and Dong 2010), Tokyo (Takada et al. 1991; Khanal et al. 2018), and Vietnam (Tuyen et al. 2014). Road dust from urban and industrial areas in these countries has generally been found to be severely polluted with PAHs.

In this study, we determined PAH concentrations in samples of road dust and sediment collected in Myanmar during 2014 and 2016. We sought to investigate the concentrations, distributions, and sources of PAHs in the environment in Myanmar and to assess the risks posed by PAHs to the inhabitants of that country. Road dust samples collected in Japan, Taiwan, and Vietnam between 2012 and 2018 were also analyzed to assess PAH pollution and the toxicological implications of PAH exposure in different parts of Asia.

Materials and Methods

Chemicals Analyzed

We analyzed the concentrations of 19 PAHs: acenaphthylene, acenaphthene, fluorene, phenanthrene (Phe), anthracene, fluoranthene (Flth), pyrene (Py), benz[*a*]anthracene, Chry, BbF, benzo[*k*]fluoranthene, benzo[*e*]pyrene, BaP, perylene (Pery), indeno[*1,2,3-cd*]pyrene (IcdP), benzo[*g,h,i*]perylene (BghiP), dibenz[*a,h*]anthracene (DahA), picene, coronene, and dibenzothiophene. Naphthalene was detected in some samples but also in every blank sample, so naphthalene data were excluded from interpretation.

Sample Collection

Fifty-one road dust samples were collected in Myanmar on three occasions during 2014 and 2016. Samples were collected from the cities of Yangon and Pathein (urban areas) and Bagan, Chaungthar, Myingyan, and Wundwin towns (rural areas), as well as from the suburbs of these towns and cities. Yangon was previously the capital city of Myanmar and has a population of more than four million people. Twenty-two sediment samples were also collected near the Myanmar road dust sampling sites on two occasions during 2014 and 2015 to investigate the present status of pollution and potential sources of PAHs in the country (Table SI-1). Road dust samples were also collected from Hanoi and Halong cities in Vietnam during 2012 ($n=9$), Kumamoto City in Japan during 2017 ($n=16$), and Tainan City in Taiwan during 2018 ($n=10$). The sampling site locations are shown in Fig. 1, and information on the road dust and sediment samples is given in Tables SI-1 and SI-2, respectively. Each road dust sample was collected from the edge of a road, adjacent to the asphalt, using a clean brush and dustpan. Sediment samples were collected from a river or lake using an Ekman–Berge grab sampler. Each sample was placed in a clean plastic bag and stored at − 20 °C until analysis.

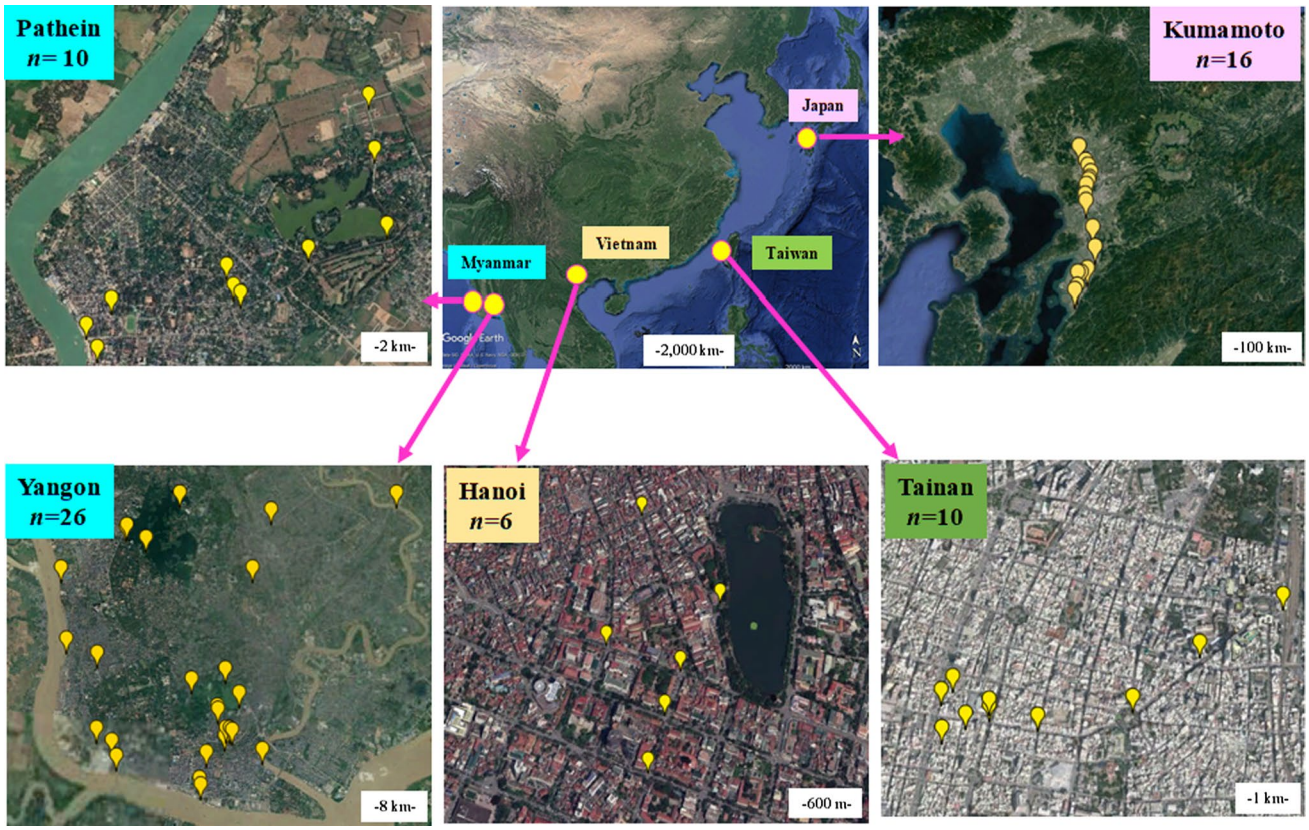

Fig. 1 Maps showing road dust sampling sites in Myanmar, Japan, Taiwan, and Vietnam

Analytical Procedures

PAH concentrations in the samples were determined using a previously described procedure (Nakata et al. 2014). Each road dust sample was passed through a 500-µm sieve, then 3–10 g of the sample was extracted using a 1:1 v/v mixture of dichloromethane and *n*-hexane, with ultrasonication. The extract was evaporated to a small volume, then deuterated PAH surrogate standards (acenaphthene-d_{10}, phenanthrene-d_{10}, chrysene-d_{12}, and perylene-d_{14}) were added. The extract was then cleaned using gel permeation chromatography (Bio-Beads S-X3; Bio-Rad Laboratories, Hercules, CA) using a 1:1 v/v mixture of dichloromethane and hexane as the mobile phase at a flow rate of 5 mL/min. After concentration of the eluent, the sample was spiked into a silica gel chromatography column (Wakogel C200; FUJIFILM Wako Pure Chemical Corporation, Japan) using hexane as the mobile phase for cleaning. The eluate was evaporated to < 100 µL using a rotary evaporator and then under a gentle steam of nitrogen; then, ^{13}C-pentachlorobiphenyl was added to act as an internal standard. Sediment samples were not passed through a sieve but were otherwise processed following the same procedure. PAH concentrations in the extracts were determined using a 7890A gas chromatograph coupled to a 5975C mass spectrometer (Agilent Technologies, Santa Clara, CA). Separation was achieved using a BPX column (length 60 m, ID 0.25 mm, film thickness 0.25 µm; Trajan Scientific and Medical, Ringwood, Australia). The mass spectrometer was used in selected ion monitoring mode with the parameters shown in Table SI-3. The gas chromatograph oven temperature program started at 80 °C, which was held for 1 min, then increased at 20 °C/min to 160 °C, then increased at 3 °C/min to 280 °C, which was held for 15 min. The carrier gas was helium, and the flow rate was 1 mL/min. Procedural blanks, spiked blanks, and matrix-spiked samples were analyzed.

Total organic carbon (TOC) content of the samples was determined using a previously described method (Nakata et al. 2014). Each road dust or sediment sample (approximately 5 g dw) was digested in hydrochloric acid solution (1.0 M, 30–50 mL) to remove inorganic carbon. The sample was centrifuged at 2500 rpm for 5 min, and the supernatant was removed. The solid residue was dried at 80 °C and analyzed using a JM1000CN Macro Corder instrument (J-Science Lab Co., Ltd., Kyoto, Japan). Statistical analyses were performed using Excel Statistics version 5.0 software (Esumi, Tokyo, Japan) to investigate differences in the PAH profiles of samples from different countries and areas.

Quality Assurance and Quality Control

Procedural blanks and spiked blanks were analyzed to assess contamination and quantification errors, and surrogate standards were used to assess PAH recovery. The acenaphthene-d_{10}, phenanthrene-d_{10}, chrysene-d_{12}, and perylene-d_{14} recoveries were 52% ± 11%, 75% ± 10%, 114% ± 14%, and 130% ± 19%, respectively. Only naphthalene was detected in the procedural blanks. Marine sediment standard reference material IAEA-383 (International Atomic Energy Agency, Vienna, Austria) was analyzed to assess the accuracy and precision of the method. As shown in Table SI-4, the determined and expected individual PAH concentrations agreed well. PAH quantification limits were 0.04–0.2 ng/g.

Cancer Risk Assessment

We assessed the risks posed to humans by exposure to PAHs by calculating ILCR using a method published by the USEPA (1991). The ILCR for ingestion, dermal contact, and inhalation was calculated using Eqs. 1, 2, and 3, respectively.

$$\mathrm{ILCR_{Ingestion}} = \frac{\mathrm{CS} \times \left(\mathrm{CSF_{Ingestion}} \times \frac{\sqrt[3]{\mathrm{BW}}}{70}\right) \times \mathrm{IR_{Ingestion}} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT} \times 10^6}, \quad (1)$$

$$\mathrm{ILCR_{Dermal}} = \frac{\mathrm{CS} \times \left(\mathrm{CSF_{Dermal}} \times \frac{\sqrt[3]{\mathrm{BW}}}{70}\right) \times \mathrm{SA} \times \mathrm{AF} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT} \times 10^6}, \quad (2)$$

$$\mathrm{ILCR_{Inhalation}} = \frac{\mathrm{CS} \times \left(\mathrm{CSF_{Inhalation}} \times \frac{\sqrt[3]{\mathrm{BW}}}{70}\right) \times \mathrm{IR_{Ihalation}} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT} \times \mathrm{PEF}}. \quad (3)$$

In the equations, CS is the BaP-equivalent concentration in dust (μg/kg). The carcinogenic potency of each PAH relative to BaP (Larsen and Larsen 1998) was used to calculate the BaP-equivalent concentration of all PAHs. $\mathrm{CSF_{Ingestion}}$, $\mathrm{CSF_{Dermal}}$, and $\mathrm{CSF_{Inhalation}}$ are carcinogenic slope factors based on the carcinogencity of BaP (7.3, 25, and 3.9 mg/kg/day, respectively) (USEPA 2012; Knafla et al. 2006; OEHHA 2009). BW and EF are body weight and exposure frequency, respectively (BW: 16.8 kg for children and 57.7 kg for adults) (Dang et al. 2010); ED is the exposure duration (6 years for children and 30 years for adults) (USEPA 2004); $\mathrm{IR_{inhalation}}$ is the inhalation rate (10 m^3/day for children and 20 m^3/day for adults) (Wang et al. 2011, USEPA 2002); $\mathrm{IR_{ingestion}}$ is the dust ingestion rate (100 mg/day for children and 50 mg/day for adults) (USEPA 2011); SA is the dermal exposure area (2800 cm^2 for children and 5700 cm^2 for adults) (USEPA 2004); AF is the dermal adherence factor (0.2 mg/cm^2 for children and 0.07 mg/cm^2 for adults) (USEPA 2004); ABS is the dermal absorption fraction (0.13 for children and adults) (USEPA 2004); AT is the average lifespan (25,550 days) (Ferreira-Baptista and De Miguel 2005); and PEF is the particle emission factor (1.36×10^9 m^3/kg) (USEPA 2002). The detailed values used for the parameters are shown in Table SI-5. The risks posed to children and adults were calculated separately. The total risk was defined as the sum of the ILCRs for the different exposure routes.

Results and Discussion

Concentrations and Distributions of PAHs

The mean and maximum PAH concentrations and TOC contents for road dust samples from Japan, Myanmar, Taiwan, and Vietnam are shown in Table 1. High concentrations of PAHs were found in road dust samples from urban areas of Myanmar, particularly Yangon City. The highest PAH concentrations were found in samples from, in decreasing order, near Yangon zoo (site RD-33: 4100 ng/g dw), east of Yangon Central Station (RD-31: 1800 ng/g dw), and near the mouth of the Yangon River (RD-22: 1300 ng/g dw; Fig. 2). These sites were all in downtown Yangon and are strongly affected by traffic congestion, suggesting that emissions from motor vehicles may be major source of PAHs to road dust in Yangon. Low PAH concentrations were found in samples collected at sites RD-26 (84 ng/g dw), RD-44 (103 ng/g dw), and RD-35 (107 ng/g dw), although these sites were also in downtown Yangon. The differences in concentrations could be explained by the lower TOC content in the samples from less-polluted sites (mean TOC content 0.40%) than in samples from more-polluted sites (mean TOC content 1.2%). We found a significant relationship between TOC and PAH concentrations in road dust collected from Myanmar, except for RD-33, owing to exceptional high concentration ($r = 0.466$, $p = 0.013$; Fig. SI-1). The mean PAH concentration in road dust from Pathein City was 530 ng/g dw, which was comparable to the mean concentration in road dust from Yangon City (630 ng/g dw). High PAH concentrations were found in the samples from sites RD-8 (1400 ng/g dw) and RD-9 (1300 ng/g dw) in downtown Pathein City. The lowest concentration of PAHs was found in road dust from Pathein University (RD-1: 83 ng/g dw), probably because the traffic density is low in that area and the sample TOC content was low (0.24%). The Yangon–Pathein Highway in western Myanmar is the principal road between Yangon and Pathein. The mean PAH concentration in dust from the Yangon–Pathein Highway was 460 ng/g dw, with the highest concentration found in dust from a bridge crossing the Ayeyarwady River (1400 ng/g dw).

Lower PAH concentrations were found in the dust samples from rural areas and small towns in Myanmar. The

Table 1 Polycyclic aromatic hydrocarbon (PAH) concentrations in road dust samples collected from Myanmar, Japan, Taiwan, and Vietnam

Country	Myanmar ($n=51$)														Vietnam ($n=9$)				Japan ($n=16$)		Taiwan ($n=10$)	
Name of city	Yangon		Pathein		Yangon–Pathein		Chaungthar		Bagan		Wundwin		Myingyan		Hanoi		Halong		Kumamoto		Tainan	
Year	2014–2016		2014		2014–2016		2014		2016		2015		2016		2012		2012		2017		2018	
Number	26		10		5		2		3		2		2		6		3		16		10	
	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum	Mean	Maximum
TOC%	1.5	3.8	0.37	1.2	1.6	4.6	0.62	0.65	0.29	0.62	0.27	0.39	0.88	1.1	3.6	6.3	2.5	5.3	1.7	3.0	4	9.2
PHE	37	170	50	110	34	54	27	54	13	28	16	25	29	35	110	300	46	99	94	840	260	1000
FLTH	130	680	140	360	72	160	100	130	31	69	32	39	46	42	240	650	47	110	110	690	580	2600
PY	120	540	87	230	95	250	72	93	28	63	30	43	44	40	260	620	39	90	110	500	570	2400
BaA	47	350	29	97	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	94	240	17	42	15	110	110	810
CHRY	57	270	55	130	54	200	37	47	12	27	15	20	11	14	130	270	29	63	26	130	130	570
BbF	42	500	27	120	28	110	ND	ND	ND	ND	ND	ND	5.2	10	120	250	31	66	22	130	87	490
BkF	8.5	57	12	55	7.7	35	ND	ND	0.7	2.1	11	12	ND	ND	51	120	6.9	21	11	71	47	290
BaP	21	340	11	66	1.9	9.5	ND	ND	4.2	12	4.9	5.8	2.5	4.9	80	220	13	31	16	98	100	820
PERY	11	100	7.1	19	13	52	1.9	3.8	0.8	2.4	0.9	1.5	3.1	4.1	37	100	4.4	11	6.1	26	28	160
IcdP	32	480	32	130	ND	ND	ND	ND	ND	ND	7.1	9.6	ND	ND	94	220	15	33	16	96	39	140
BghiP	41	340	26	92	50	170	29	35.0	ND	ND	9.1	13	ND	ND	160	270	27	53	6.4	100	110	520
16PAHs[1]	560	3600	480	1200	350	1000	270	360	89	200	130	170	140	150	1400	3300	290	650	450	2900	2100	9800
Total PAHs	630	4100	530	1300	460	1400	290	390	100	230	130	180	150	160	1700	3900	360	800	520	3200	2400	11,000
FLTH/FLTH + PY	0.51	0.60	0.59	0.65	0.45	0.48	0.58	0.59	0.53	0.56	0.53	0.62	0.51	0.51	0.47	0.51	0.52	0.55	0.46	0.58	0.47	0.58

TOC total organic carbon content; *PHE* phenanthrene; *FLTH* fluoranthene; *PY* pyrene, *BaA* benz[*a*]anthracene; *CHRY* chrysene; *BbF* benzo[*b*]fluoranthene; *BkF* benzo[*k*]fluoranthene; *BaP* benzo[*a*]pyrene; *PERY* perylene; *IcdP* indeno[*1,2,3-cd*]perylene, BghiP = benzo[*ghi*]perylene, *ND* not detected

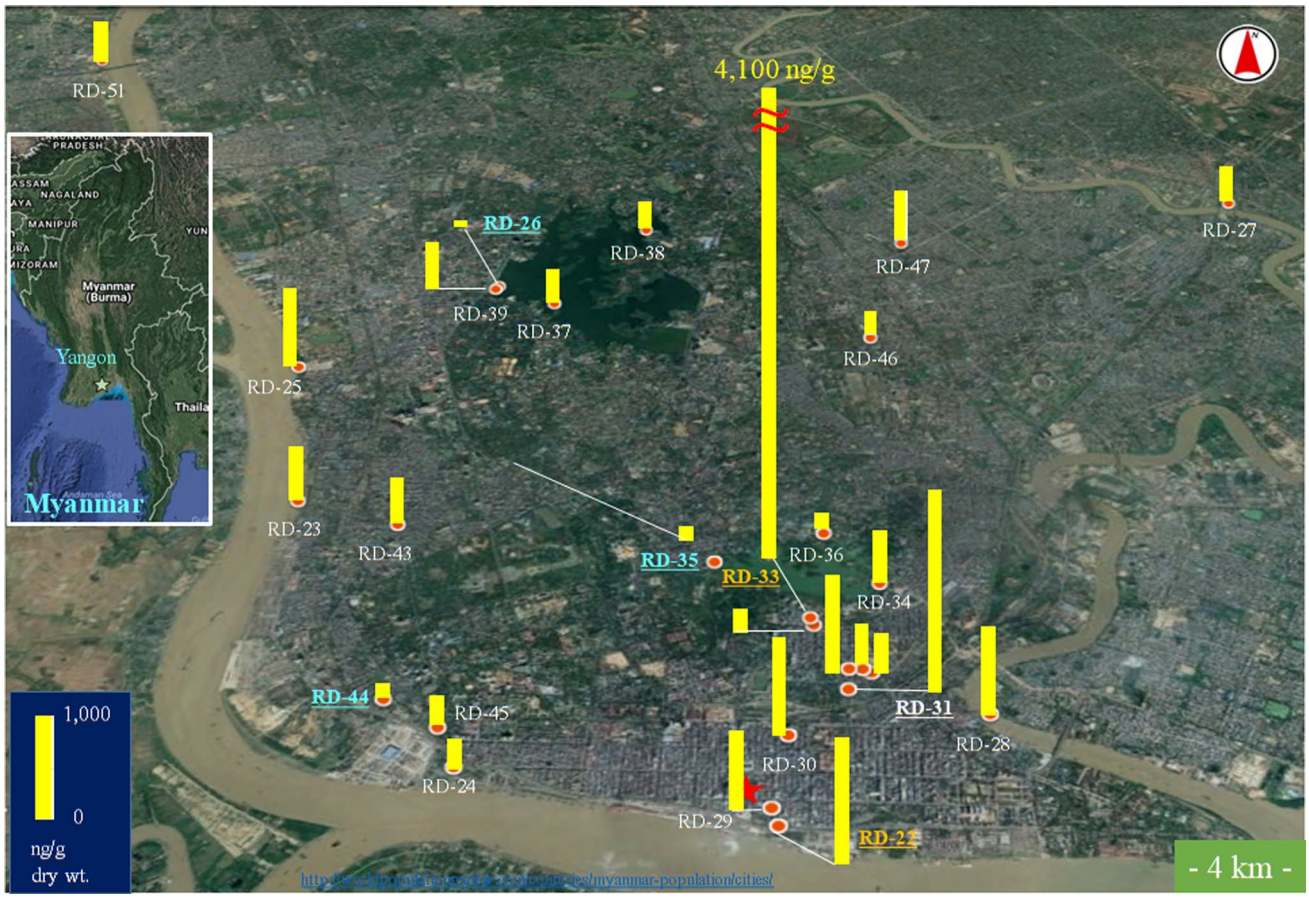

Fig. 2 Concentrations and distribution of polycyclic aromatic hydrocarbon (PAHs) in road dust collected from Yangon City, Myanmar

mean PAH concentrations in samples from Bagan, Chaungthar, Myingyan, and Wundwin were 100, 290, 150, and 130 ng/g dw, respectively. This may be due to the lower populations and traffic densities in these areas. Flth and Py were the predominant PAHs in dust samples from Yangon, contributing 25% ± 6.1% and 24% ± 6.6% of the total PAH concentrations, respectively (Fig. 3). Chry and Phe also made large contributions to the total PAH concentrations. The PAH profiles were similar in nearly all samples, implying that the sources of PAHs in road dust are similar in urban and rural areas of Myanmar.

As for road dust samples, high PAH concentrations were found in sediment samples from urban parts of Yangon. The mean PAH concentration in sediment samples from Yangon was 280 ng/g dw (Table 2). High PAH concentrations were found in sediment from Inya Lake (SD-6: 1020 ng/g dw) and Kandawgyi Lake (SD-5: 890 ng/g dw dw) in downtown Yangon. PAH concentrations in sediment are divided into four categories: (a) a low degree of pollution, 0–100 ng/g dw; (b) moderate degree of pollution, 100–1000 ng/g dw; (c) high degree of pollution, 1000–5000 ng/g dw, and (d) very high degree of pollution, > 5000 ng/g dw (Baumard et al. 1998). The sediment samples from Myanmar were all in the category low degree of pollution for PAHs. In addition, a significant correlation was seen for the mean concentrations of 16 PAHs, except low molecular weight compounds, between road dust and sediment in Pathein ($r = 0.919$, $p < 0.001$) but not in Yangon ($r = 0.427$, $p = 0.221$; Fig. SI-2). This implies that road dust is a major source of PAH contamination in the sediment of Pathein, and there are several sources of PAHs in Yangon.

The dominant PAHs in sediment samples from Inya and Kandawgyi lakes were Flth, Py, IcdP, and BghiP, suggesting that motor vehicle emissions were important sources of PAHs for sediment in these lakes. However, Pery was an important component of the PAHs in sediment from other sampling sites in Yangon, contributing 38–63% of the total PAH concentrations (Fig. 3). Similar profiles were found in samples from Pathein. Pery has biogenic sources, as it is produced during diagenesis from natural precursors (Hite et al. 1980). The low PAH concentrations and predominance of Pery in the sediment from many sampling sites of Yangon indicated that the sampling sites had low to moderate levels of PAH pollution.

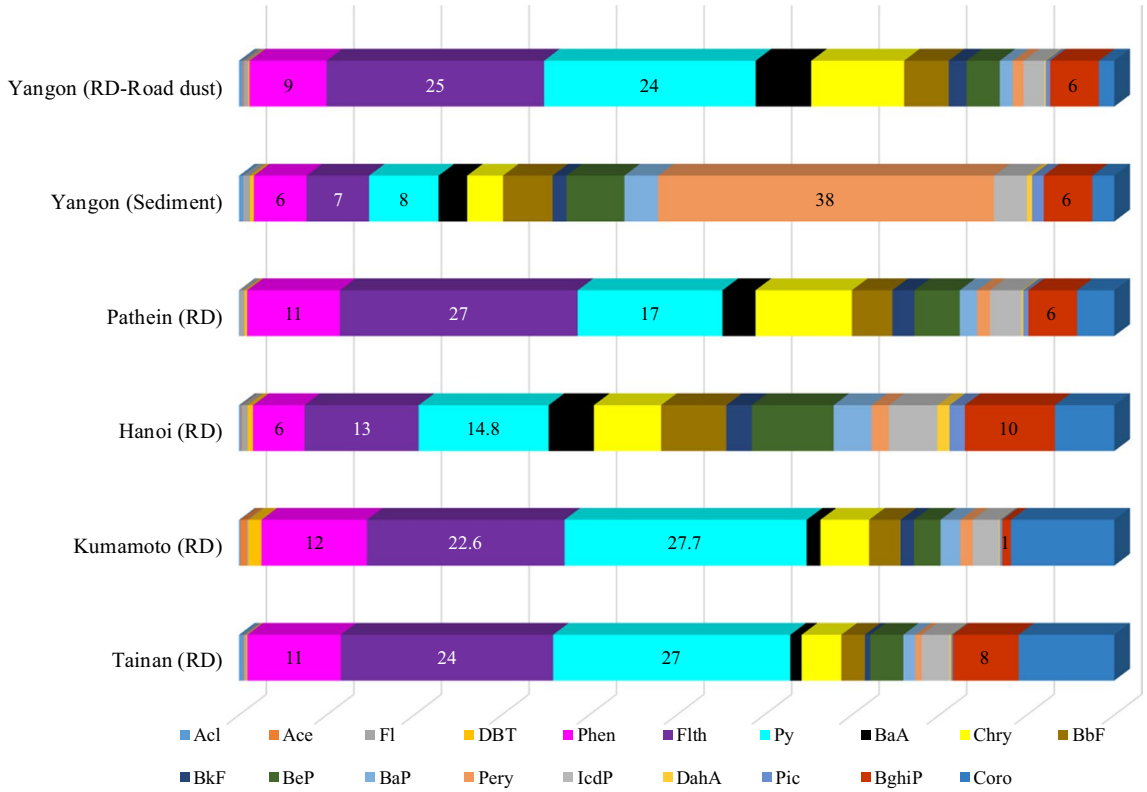

Fig. 3 Composition of PAHs in road dust and sediment samples from Myanmar, Japan, Taiwan, and Vietnam. *Acl* acenaphthylene; *Ace* acenaphthene; *Fl* fluorene; *DBT* dibenzothiophene; *Phen* phenanthrene; *Flth* fluoranthene; *Py* pyrene; *BaA* benz[*a*]anthracene; *Chry* chrysene; *BbF* benzo[*b*]fluoranthene; *BkF* benzo[*k*]fluoranthene; *BeP* benzo[*e*]pyrene; *BaP* benzo[*a*]pyrene; *Pery* perylene; *IcdP* indeno[*1,2,3-cd*]pyrene; *DahA* dibenz[*a,h*]anthracene; *Pic* picene; *BghiP* benzo[*ghi*]perylene; *Coro* coronene

Table 2 PAH concentrations (ng/g dry weight) in the sediment samples from Myanmar

Name of city	Yangon		Pathein		Chaungthar	
Year	2015		2014		2014	
Number	8		10		4	
	Mean	MAX	Mean	MAX	Mean	MAX
TOC%	0.83	1.9	0.55	0.74	0.80	2.7
PHE	10	47	12	53	2.3	9.2
FLTH	23	150	4.9	16	2.5	9.8
PY	21	130	5.0	17	4.3	17
BaA	16	100	1.0	4.1	1.5	5.7
CHRY	15	86	1.9	4.1	2.2	8.4
BbF	26	110	1.7	4.8	3.0	12
BkF	10	40	ND	ND	ND	ND
BaP	19	74	1.3	4.8	1.6	6.3
PERY	30	49	29	45	0.80	2.5
IcdP	28	150	1.2	4.1	3.5	14
BghiP	25	131	1.3	4.0	4.1	16
16PAHs[a]	200	850	46	190	26	102
Total PAHs	280	1010	78	220	35	140

[a]Except for naphthalene

The mean PAH concentrations in road dust samples from Hanoi and Halong cities in Vietnam were 1700 and 360 ng/g dw, respectively (Table 1). The highest PAH concentration (4000 ng/g dw) was found in road dust from site RD-54, near Hoan Kiem Lake in downtown Hanoi. Hanoi, the capital of Vietnam, has approximately 7.7×10^6 inhabitants. High PAH concentrations (mean 1500 ng/g dw) have previously been found in road dust from Hanoi (Tuyen et al. 2014), and automobile exhaust fumes are assumed to be important sources of PAHs. The PAH concentrations were lower in road dust from Halong than in road dust from Hanoi, probably because of differences in the population and traffic densities in these cities. Phe, Py, and BghiP were the predominant PAHs in both Hanoi and Halong, implying that the sources of PAH are similar.

We analyzed a total of 16 road dust samples from Route 3, an arterial road in Kumamoto Prefecture of Japan. The mean PAH concentration was 520 ng/g dw (Table 1). This was lower than the mean PAH concentration of 3000 ng/g dw previously found in road dust from Tokyo, the capital of Japan (Khanal et al. 2018). However, high PAH concentrations were found in samples from sites RD-62 and RD-67 in Kumamoto City (3200 and 1100 ng/g dw, respectively), which have high traffic densities among the sampling sites. Low molecular weight PAHs (Py, Flth, and Phe) were the predominant PAHs in road dust samples, contributing 27%, 22%, and 12% of the total PAH concentrations, respectively (Fig. 3). These PAHs made similar contributions to the total PAH concentrations in road dust in Tokyo (Khanal et al. 2018).

The mean PAH concentration in road dust samples from Taiwan was 2400 ng/g dw, and the highest concentration (9400 ng/g dw) was found in the sample from site RD-84 (Table 1). High PAH concentrations were also found in samples from sites RD-86 (6000 ng/g dw) and RD-77 (3200 ng/g dw), which are on a main road in Tainan City. These concentrations were higher than those found in Japan and Myanmar but comparable to concentrations found in Hanoi City. Flth and Py were the predominant PAHs in road dust samples from Taiwan, contributing 24% and 27% of the total PAH concentrations, respectively. Phe and BghiP were also important PAHs, contributing 11% and 7.5% of the total PAH concentrations, respectively (Fig. 3). The profiles of road dust samples from different sites in Taiwan were nearly the same.

The PAH concentrations of the road dust samples analyzed in this study were compared with PAH concentrations found in other recent studies. PAH concentrations have been determined in road dust from Shanghai (mean 2400 ng/g dw; Jia et al. 2017), Lanzhou (3900 ng/g dw; Jiang et al. 2014), Xian (10,620 ng/g dw; Wei et al. 2015), and Guangzhou (4800 ng/g dw; Wang et al. 2011) in China. The mean PAH levels in road dust from Tehran, Iran and Cairo, Egypt were 330 ng/g (Saeedi et al. 2012) and 680 ng/g (Hassanien and Abdel-Latif 2008), respectively. These results indicate that PAH pollution is currently less serious in Myanmar and Japan than in other Asian countries.

Potential Sources of PAHs

Diagnostic ratios have been used to investigate the potential sources of PAHs in environmental samples. The Flth to Flth + Py ratio (Flth/Flth + Py) is a common diagnostic ratio. A Flth/Flth + Py ratio > 0.5 indicates diesel emissions, and a Flth/Flth + Py ratio < 0.5 indicates gasoline emissions (Ravindra et al. 2008). Yunker et al. (2002) found Flth/Flth + Py ratios > 0.50 for kerosene, grass, coal, and wood combustion but Flth/Flth + Py ratios < 0.5 for fuel and crude oil combustion and for automobile emissions. The Flth/Flth + Py ratios for vehicle emissions and crude oil combustion are similar (0.41–0.49) and closer to 0.50 than the Flth/Flth + Py ratio for diesel exhaust, suggesting that unburned diesel reduces the proportion of Flth in diesel exhaust (Sjogren et al. 1996; Schauer et al. 1996; Wang et al. 1999). An IcdP/IcdP + BghiP ratio > 0.5 indicates wood combustion, and an IcdP/IcdP + BghiP ratio of 0.62 indicates coal combustion (Grimmer et al. 1983; Yunker et al. 2002).

The mean Flth/Flth + Py ratios for most road dust samples from Myanmar were > 0.50 (Table 1). The highest Flth/Flth + Py ratio (0.59) was for Pathein, followed by 0.58 for Chaungthar, 0.53 for Bagan and Wundwin, and then next 0.51 for Myingyan and Yangon. High IcdP/IcdP + BghiP ratios were found for sites RD-8 (0.59), RD-31 (0.57), and RD-33 (0.58), at which the PAH concentrations were high. The Flth/Flth + Py ratio in sediment from site SD-6, which had the highest PAH concentration in Yangon, was 0.54. All of these sampling sites were near main roads with heavy traffic, and these results indicated that pyrogenic emissions from diesel vehicles may be important sources of PAHs.

A study of PM2.5 concentrations in the air of Yangon reported that the highest concentrations (164 ± 52 μg/m^3) were found in a township; this was assumed to be because of smoke produced by burning dried vegetation and tea/food shops that use wood or charcoal stoves (Yi et al. 2018). No information is available on traffic congestion at the sampling sites, but the high PM2.5 and PAH concentrations in road dust suggest that there are various sources of PAHs in Myanmar.

The mean Flth/Flth + Py ratios for road dust samples from Hanoi in Vietnam were 0.47 ± 0.03 (i.e., these were similar and mostly < 0.50). The mean Flth/Flth + Py ratios for road dust from Japan and Taiwan were 0.46 ± 0.07 and 0.47 ± 0.08, respectively. The IcdP/IcdP + BghiP ratios for samples from Hanoi were 0.35 ± 0.06 (< 0.50). These results indicated that petrogenic fuel combustion by vehicles is the predominant PAH source in these countries. Diagnostic ratios for Japan and Vietnam determined in previous studies (Tuyen et al. 2014; Khanal et al. 2018) were similar to the ratios for our samples.

Cancer and Health Risk Assessment

We calculated the theoretical carcinogenic equivalents (CEQs) of PAHs by multiplying the concentrations in road dust by the appropriate carcinogenic potencies relative to BaP (Durant et al. 1996; Larsen and Larsen 1998). The carcinogenic potencies of individual PAHs and CEQ values are shown in Table 3.

Mean CEQs were high in urban areas of Myanmar (41 and 31 ng/g dw for Yangon and Pathein, respectively) but < 10 ng/g dw at rural sites (Table 3). The contributions of individual PAHs to the CEQ values for most samples from Myanmar decreased in the order BaP > Flth > BbF. In contrast, high CEQs were found for road dust from Tainan in Taiwan (173 ng/g dw) and Hanoi in Vietnam (162 ng/g dw). As for Myanmar, BaP and Flth were the predominant contributors to the total CEQs for samples from Japan, Taiwan, and Vietnam. However, BbF and IcdP were also important contributors to the total CEQs for samples from Vietnam. CEQs have previously been determined for road dust from Hanoi in Vietnam (mean 117 ng/g dw; Tuyen et al. 2014), Beijing in China (129 ng/g dw; Wang et al. 2010), Tehran in Iran (29 ng/g dw; Saeedi et al. 2012), and Cairo in Egypt (7.0 ng/g dw; Hassanien and Abdel-Latif 2008). In summary, the CEQs for road dust from Myanmar were comparable to CEQs for road dust from less-polluted areas in other countries.

In the carcinogenic risk assessment, an ILCR between 10^{-6} and 10^{-4} was assumed to indicate a potential carcinogenic risk, ILCR > 10^{-4} a high degree of carcinogenic risk (Liao and Chiang, 2006), and an ILCR ≤ 10^{-6}

Table 3 Carcinogenic equivalents (as ng/g benzo[*a*]pyrene) in road dust samples

	Carcinogenic potencies	Myanmar							Vietnam		Japan	Taiwan
		Yangon	Pathein	Yangon–Pathein	Chaungthar	Bagan	Wundwin	Myingyan	Hanoi	Halong	Kumamoto	Tainan
PHE	0.0005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.054	0.0	0.0	0.13
FLU	0.05	6.7	7.2	3.6	5.0	1.5	1.6	2.3	12	2.3	5.7	29
PYR	0.001	0.12	0.087	0.095	0.072	0.0	0.0	0.0	0.26	0.0	0.11	0.57
BaA	0.005	0.24	0.14	0.0	0.0	0.0	0.0	0.0	0.47	0.084	0.074	0.54
CHR	0.03	1.7	1.6	1.6	1.1	0.35	0.46	0.33	3.9	0.88	0.79	4.0
BbF	0.15	6.3	4.0	4.1	0.0	0.0	0.0	0.78	18	4.7	3.4	13
BkF	0.15	1.3	1.9	1.2	0.0	0.11	1.6	0.0	7.6	1.0	1.6	7.0
BeP	0.002	0.081	0.063	0.12	0.0	0.0	0.0	0.0	0.30	0.064	0.0	0.28
BaP	1	21	11	1.9	0.0	4.2	4.9	2.5	80	12	16	102
IcdP	0.1	3.2	3.2	0.0	0.0	0.0	0.71	0.0	9.4	1.5	1.6	3.9
DahA	1.1	0.61	0.66	0.0	0.0	0.0	0.0	0.0	26	6.3	1.3	10
BghiP	0.02	0.81	0.52	1.0	0.6	0.0	0.18	0.0	3.2	0.53	0.13	2.2
Total		42	31	14	6.8	6.2	9.5	5.9	162	30	31	173

Table 4 Estimated incremental lifetime cancer risk values calculated using PAH concentrations found in road dust samples from Myanmar, Japan, Taiwan, and Vietnam

Conc. (BaP-EQ)	Myanmar												Vietnam				Japan		Taiw an	
	Yangon		Pathein		Yangon–Pathein		Chaungthar		Bagan		Wundwin		Myingyan		Hanoi		Halong		Kumamoto		Tainan	
	42		31		14		6.8		6.2		9.5		5.9		162		30		31		173	
	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult
LCRs-ingestion	4.8E−05	5.2E−05	3.5E−05	3.9E−05	1.6E−05	1.7E−05	7.8E−06	8.6E−06	7.1E−06	7.8E−06	1.1E−05	1.2E−05	6.8E−06	7.4E−06	1.8E−04	2.0E−04	3.4E−05	3.8E−05	3.6E−05	3.9E−05	2.0E−04	2.2E−04
LCRs-dermal	1.2E−04	1.9E−04	8.8E−05	1.4E−04	3.9E−05	6.1E−05	1.9E−05	3.0E−05	1.8E−05	2.8E−05	2.7E−05	4.2E−05	1.7E−05	2.6E−05	4.6E−04	7.2E−04	8.5E−05	1.3E−04	8.9E−05	1.4E−04	4.9E−04	7.7E−04
LCRs-inhalation	1.9E−09	8.2E−09	1.4E−09	6.1E−09	6.1E−10l	2.7E−09	3.1E−10	1.3E−09	2.8E−10	1.2E−09	4.3E−10	1.9E−09	2.7E−10	1.2E−09	7.3E−09	3.2E−08	1.3E−09	5.9E−09	1.4E−09	6.1E−09	7.8E−09	3.4E−08
Total	1.7E−04	2.4E−04	1.2E−04	1.8E−04	5.4E−05	7.8E−05	2.7E−05	3.9E−05	2.5E−05	3.6E−05	3.8E−05	5.4E−05	2.4E−05	3.4E−05	6.5E−04	9.2E−04	1.2E−04	1.7E−04	1.2E−04	1.8E−04	6.9E−04	9.9E−04

was assumed to indicate an acceptable degree of carcinogenic risk (Chiang et al. 2009; Peng et al. 2011). For Myanmar, high ILCR values were found for urban areas of Yangon (1.7×10^{-4} for children and 2.4×10^{-4} for adults) and Pathein (1.2×10^{-4} for children and 1.8×10^{-4} for adults); low ILCR values were found for rural areas, such as Bagan (2.5×10^{-5} for children and 3.6×10^{-5} for adults), Chaungthar (2.7×10^{-5} for children and 2.7×10^{-5} for adults) and Wundwin (3.8×10^{-5} for children and 5.4×10^{-5} for adults), as shown in Table 4 and Fig. 4. Similar results were found for Vietnam, where the ILCRs were five times higher for Hanoi than for Halong. The highest ILCR values were for Tainan (5.9×10^{-4} for children and 9.9×10^{-4} for adults). These results suggest that PAH exposure leads to a high degree of carcinogenic risk for inhabitants of Hanoi and Tainan.

Dermal exposure contributed 71–78% of the total (ingestion, dermal contact, and inhalation) ILCR (Table 4). Ingestion contributed 22–29% of the total ILCR, and inhalation contributed 0.004% or less of the total ILCR. The results obtained in this study lead us to conclude that PAH contamination is less severe in Myanmar than in other Asian countries and is unlikely to harm human health.

Conclusions

We determined the PAH concentrations in road dust from four Asian countries: Myanmar, Japan, Taiwan, and Vietnam. The PAH concentrations were higher in road dust from urban areas (e.g., Pathein and Yangon) than from rural areas in Myanmar. PAH diagnostic ratios indicated that fossil fuel combustion in vehicles and biomass combustion are important sources of PAHs in both urban and rural areas of Myanmar. High PAH concentrations were found in road dust from urban areas of Taiwan and Vietnam, in agreement with the results of previous studies. CEQ values calculated using PAH concentrations in road dust suggested that BaP, Flth, and BbF are the main contributors to health risks posed by PAHs to people in Myanmar, Japan, Taiwan, and Vietnam. ILCR values indicated that PAHs in road dust pose low levels of carcinogenic risk to inhabitants of Myanmar and Japan but high levels of carcinogenic risk to people living in urban areas of Taiwan and Vietnam. Environmental monitoring studies have been carried out in Asian countries, but to date, little information on PAH concentrations in environmental media has been available for Myanmar. To our knowledge, this is the first report to identify PAH pollution concentrations and distributions in environmental matrices collected from Myanmar.

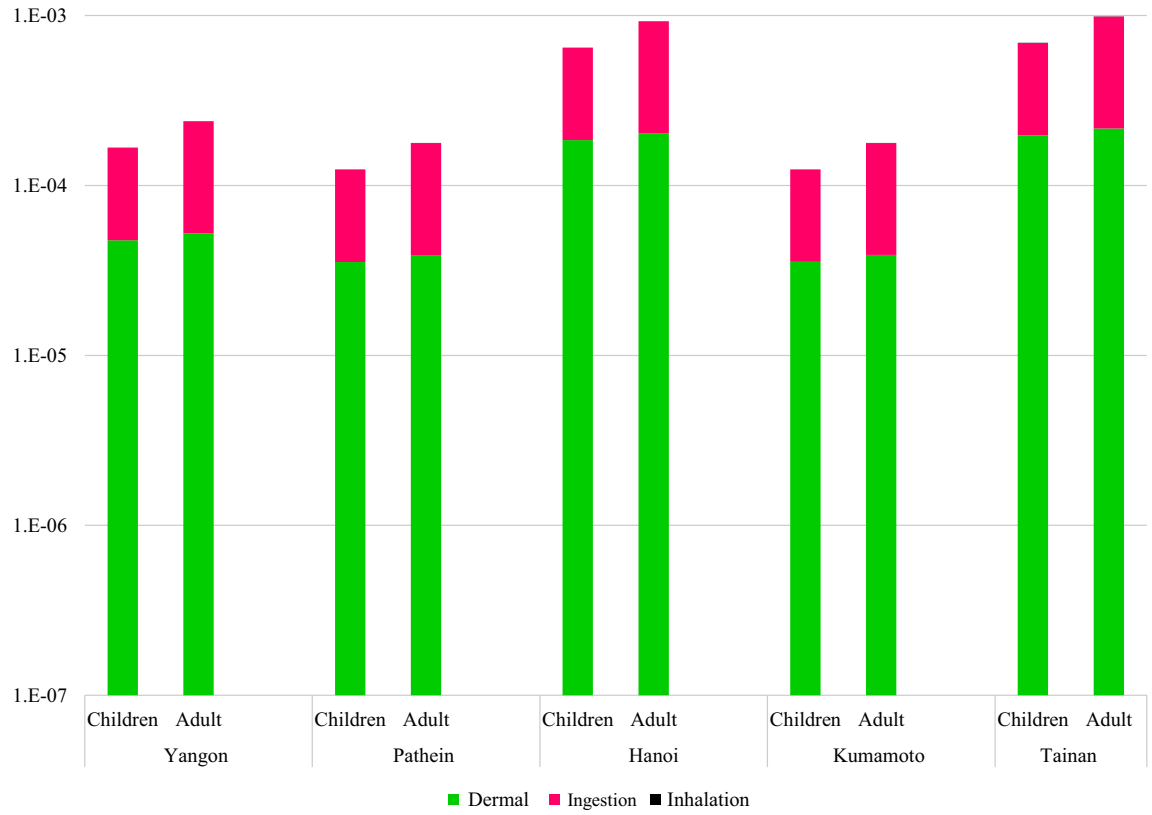

Fig. 4 Estimated incremental lifetime cancer risk (ILCR) values calculated using PAH concentrations in road dust samples from Myanmar, Japan, Taiwan, and Vietnam

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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