

# A Review on the Atmospheric Concentrations of Polycyclic Aromatic Hydrocarbons (PAHs) in Asia Since 2000 - Part I: Data from Developed Countries

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## ABSTRACT

Among all hazardous air pollutants, polycyclic aromatic hydrocarbons (PAHs) are more significant owing to their carcinogenic, mutagenic and teratogenic properties. Many researchers worldwide have focused on determining the concentrations of PAHs in ambient air. However, the literature survey reveals that the seriousness of air pollution in Asia in terms of PAHs, compared to the rest of the world. Owing to the importance of PAHs in Asia, this paper reviews the concentrations of PAHs in Asia in recent years. For convenience, this paper describes the concentrations of PAHs in developed Asian countries reported during 2000-2011 as Part-I and in developing Asian countries as Part-II. The first section of this review provides a brief description of the properties, sources of PAHs and the health effects caused by their presence in the atmosphere. The ambient air PAH concentrations in both particle and vapor phases in developed Asian countries are then discussed. This study finds the ambient air concentrations of PAHs in developed Asian countries was higher than the Western countries but was lower than the developing Asian countries. The present review predicts the accurate toxicity due to the presence of PAHs in the atmosphere by calculating the Risk Weighted Concentration (RWC), regardless of the total amount of PAHs. The total data obtained during the literature survey is tabulated and presented as supplementary information to the readers.

**Key words:** PAHs, Ambient air, Urban areas, Developed Asian countries, Bezo(a)pyrene

## 1. INTRODUCTION

Environmental pollution is a major problem in the world in the 21<sup>st</sup> century due to urbanization and indus-

trialization. Air pollution dominates the others because the ease of spreading contaminants. Urbanization and industrialization has led to deterioration in air quality. The urban atmosphere is a complex and dynamic system containing a large range of interacting chemical species. Of these, polycyclic aromatic hydrocarbons (PAHs) have attracted considerable interest as they are multi-source and multi-pollutant mixtures that generally exist in many large densely populated or industrialized urban areas (Haemisegger *et al.*, 1985).

PAHs are classified into two types based on the number of fused rings present. Small PAHs contain up to six fused rings and large PAHs contain more than six fused rings. Most research has been carried out on small PAHs because of their availability ([en.wikipedia.org/wiki/polycyclic\\_aromatic\\_hydrocarbon](http://en.wikipedia.org/wiki/polycyclic_aromatic_hydrocarbon)). In another classification also based on the number of fused rings, PAHs are classified as light PAHs (containing up to four fused rings) and heavy PAHs (containing more than four fused rings). Heavy PAHs are more stable but more toxic than light PAHs (Wenzl *et al.*, 2006).

The United States Environmental Protection Agency (EPA) (ATSDR, 2005) listed 16 PAHs as priority pollutants. These PAHs were chosen for extensive studies because of i) the greater exposure of these PAHs to humans than the others, ii) availability of more information about these PAHs, and iii) these PAHs are more toxic to humans than the others.

Many researchers in worldwide have reported the concentrations of PAHs in ambient air. Some reports are discussed in this paper. Ciaparra *et al.* (2009) reported the concentrations of PAHs in ambient air at two integrated steelworks in the UK during 2005. They revealed a higher concentrations of PAHs at the closest point of the coke ovens. They also predicted that the concentrations of PAHs depend on the wind direction at a specific site.

Li *et al.* (2009) reported the concentrations and seasonal variations of PAHs associated with PM<sub>2.5</sub> in urban, suburban and rural ambient air monitoring sites in Atlanta during 2004. Their studies showed that PM<sub>2.5</sub>

bound PAH concentrations were more elevated at suburban sites near the highways, followed by the urban and rural sites. Vasilakos *et al.* (2007) reported the gas and particle phase PAH concentrations (in ng/m<sup>3</sup>) along with their sources in the atmosphere at two suburban areas (Koropi and Spata) in Athens, Greece, during winter and summer of 2003. Fourteen PAHs [Flu, Phe, Ant, Flt, Pyr, BaA, Chry, BbF, Benzo(e)pyrene (BeP), BaP, Perylene (Per), IcdP, DahA and BghiP] were found in their study sites. The total concentrations of these 14 PAHs in vapor phase was in the range of 6.89-124 ng/m<sup>3</sup>, whereas in particulate phase was between 0.44-13.2 ng/m<sup>3</sup>. The most abundant PAHs at these sites were Phe, Flu, Flt and Pyr. They observed a positive correlation for PAH concentrations with the concentration of nitric oxide and nitrogen dioxide, but a negative correlation exists with the concentration of ozone. Seasonal variation studies revealed the higher concentrations of PAHs in winter than in summer at both sampling sites. Based on the analysis of molecular diagnostic ratio, it was concluded that the vehicular traffic and wood burning near the sampling sites were the major sources for PAHs. Amodio *et al.* (2009) examined the particulate PAHs in two urban areas of Southern Italy. In both areas, they found higher concentrations of PAHs during winter. The impact of sources, meteorological conditions on the concentrations of PAHs in ambient air at their sampling sites was also described in their study. They observed a decrease in the concentrations of PAHs with increasing meteorological parameters such as ambient temperature and solar radiation. The concentrations of PAHs also decreased with increasing wind speed. The major sources for PAHs in their study sites were industrial and vehicular emissions. Sofowote *et al.* (2010) reported the gas and particle partitioning of PAHs at a sub-Arctic site in Canada. From August 2007 to October 2009, they collected gaseous and particulate phase PAHs on polyurethane foam (PUF) and glass fiber filters, respectively. Their partitioning studies revealed that in summer, the lower molecular weight PAHs showed higher partitioning into the particle-phase. This might be due to the impact of seasonal variations on the sources of lower molecular weight PAHs. During summer, local sources have more impact on the concentrations of PAHs than the long-range transportation of sources. The concentrations of PAHs and gas/particle partitioning are dependent on the source and photo transformation.

Similarly, in Asian countries, many researchers have reported the concentrations of PAHs in ambient air. Determination of the PAHs concentrations in ambient air has attracted increasing attention by Asian scientists since 2000. In addition, the concentrations of

PAHs reported in Western countries was much lower than that reported in Asian countries. In the 21<sup>st</sup> century, the ambient air quality has become a challenging issue particularly in Asian countries because most developing countries in the world are in Asia. This prompted a review of the concentrations of PAHs in Asian countries since 2000.

Asia is the world's most populated continent with more than 3.88 billion people. In contrast to the Western world, the lifestyle of Asians differs considerably according to the country ([http://en.wikipedia.org/wiki/Culture\\_of\\_Asia](http://en.wikipedia.org/wiki/Culture_of_Asia)). The different lifestyles of the Asians produce different emissions of PAHs in the atmosphere. The number of deaths caused by urban air pollution in most Asian countries is in the range of 150-400 per million population (Global health risks, WHO, 2009. <http://www.who.int/heli/risks/urban/urbanenv/en/>). This underscores the seriousness of air pollution in Asia. According to Zhang and Tao (2009), Asian countries, such as China and India, contributed approximately 38.5% of the total 16 EPA priority PAHs emission in the world during 2004. This prompted a review of the ambient concentrations of PAHs in Asian countries. In Western countries, particularly Western Europe, the industrial revolution occurred in the 18<sup>th</sup> century. On the other hand, most Asian countries were industrialized during the end of the 20<sup>th</sup> century and/or the early 21<sup>st</sup> century (<http://en.wikipedia.org/wiki/Industrialisation>). In Western countries, considerable data on the concentrations of PAHs in the atmosphere was published in the 1980s and 1990s. Most data published on the concentrations of PAHs in the atmosphere of Asian countries was available from the year 2000 onwards. Because of this, this paper reviewed the concentrations of PAHs in various cities of Asian countries since 2000. This study provides a clear picture of the air quality of various countries in Asia in terms of PAHs.

Some reviews on PAHs have been published but most focused on the sources or emission inventory (Zhang and Tao, 2009; Ravindra *et al.*, 2008; Baek *et al.*, 1991). Chang *et al.* (2006) reviewed the concentrations of PAHs in Asian countries, but their review was over a short period of five years and only six countries were included.

The significance of the PAHs in Asia prompted a review of the concentrations of PAHs in Asia since 2000. For convenience, this paper reports the concentrations of PAHs in developed Asian countries as Part-I and developing Asian countries as Part-II (Lakshmi Narayana *et al.*, 2012). The Asian countries were divided into two groups based on a recent report from the IMF (International Monetary Fund) ([http://en.wikipedia.org/wiki/List\\_of\\_countries\\_by\\_GDP\\_\(PPP\)\\_per\\_](http://en.wikipedia.org/wiki/List_of_countries_by_GDP_(PPP)_per_)

capita). Asian countries listed in the top 30 are considered developed countries and the remaining countries are considered developing countries. Japan, Hong Kong, Taiwan, Singapore and South Korea are listed in top 30 ranking in the latest IMF report and are considered developed countries. This paper describes the PAH concentrations in developed Asian countries reported during 2000-2011.

## 2. PROPERTIES, SOURCES AND HEALTH IMPLICATIONS OF PAHS

### 2.1 Properties and Sources of PAHs

PAHs generally exist as colorless, white solids with a faint and sometimes pleasant odor. PAHs are sparingly soluble in water but readily soluble in organic solvents owing to their lipophilic nature. The solubility of PAHs in water decreases with increasing number of aromatic rings. All PAHs are solids with relatively high boiling and melting points. PAHs are chemically inactive but bind to particulate matter in air (Skupinska *et al.*, 2004). The physical and chemical properties of PAHs, such as reactivity and stability, were reviewed extensively by Leach (1989). Their review, discussed about the thermodynamic stability, photo stability and reactivity of neutral and ionic PAHs. Three dimensional structures were more stable than the planar form of neutral benzenoid PAHs. Regarding the reactivity of PAHs, fully benzenoid molecules were expected to be less reactive. The reaction rates for the chemical attack of PAHs by atoms such as hydrogen, oxygen and nitrogen in interstellar media were generally unknown, but they are quite sensitive to the physical and chemical nature of the site attacked.

Identifying the major sources of emissions of PAHs and evaluating their physical and chemical characteristics are very important. Previously, it was considered that PAHs were formed only during the high temperature (973 K) pyrolysis of organic materials, but the discovery of complex mixtures of PAHs with a wide molecular weight range in fossil fuels showed that the pyrolysis of organic materials, even at low temperatures (373-423 K), can lead to their production (Mohanraj and Azeez, 2003). The amount and variety of PAHs produced from any process varies widely according to the types of raw materials and combustion conditions. The sources of PAHs can be classified into two types: i) natural and ii) anthropogenic sources. A part of the PAHs in the atmosphere arises from natural combustion such as forest fires and volcanic eruptions. The anthropogenic sources of PAHs can be divided into stationary combustion sources and mobile or transportation sources. In the transportation category, the major

concerns are conventional gasoline (Van metre *et al.*, 2006) and diesel engines, whereas the category of stationary sources encompasses a wide range of combustion processes including residential heating, industrial activities, incineration and power generation (Baek, 1988). Junko *et al.* (2001) reported the mobile sources of PAHs in a road way tunnel, because the highway tunnels are heavily exposed to the vehicle exhaust. Aluminum production is another source of PAHs in ambient air. Thrane (1967) reported the presence of PAHs in ambient air in residential areas near aluminum industries. Ravindra *et al.* (2008) revealed vehicular, wood/coal burning and industrial emissions to be significant sources of PAHs but this can vary according to the region. The contribution of domestic heating increases significantly during winter. Considerable variability was observed in the emission ratios of PAHs. Therefore, it is generally difficult to quantify the impact of several sources based only on PAHs (Marchand *et al.*, 2004). Another source of PAHs is waste incineration and power generation processes (Dyke *et al.*, 2003).

Srogi (2007) reviewed the sources of PAHs in ecosystems such as plants, air, water, food and soils. The air flow in indoor environment is limited, which results in an oxygen deficient atmosphere, and produces the PAHs during indoor straw combustion (Zhang *et al.*, 2008). Based on a literature survey, it is clear that the major anthropogenic sources of atmospheric PAHs are engine exhaust (gasoline and diesel), industrial processes (aluminum), power generation, waste incineration, indoor straw combustion, domestic heating and natural sources, such as volcanic eruptions and forest fires. More information about the sources of PAHs in the atmosphere can be found in many comprehensive review papers (Zhang and Tao, 2009; Elisabeth Galarneau, 2008; Mastral *et al.*, 2000; Sloss *et al.*, 1993; Baek *et al.*, 1991; Junk and Ford, 1980).

### 2.2 Health Effects and Toxicity of PAHs

PAHs are a major concern for environmental scientists worldwide because exposure to high concentrations is related to the carcinogenic risk, interference with the hormone system and depression of the immune system (Luch, 2005). Sundeeep (2007) examined relationship between exposure to ambient levels of PAHs during pregnancy and the prevalence of respiratory symptoms during the first year of life. He suggested that prenatal exposure to PAHs has a significant impact on the respiratory health of newborns.

According to the IARC (International Agency for Research on Cancer), tobacco smoke is a significant source of exposure to PAHs, whereas diet is the major source of exposure to PAHs in the non-smoking popu-

lation. The IARC (IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, 2010) classified the priority PAHs into three groups based on extensive studies on their carcinogenic nature. BaP is belongs to group 1 (carcinogenic to humans). DahA belongs to group 2A (probably carcinogenic to humans). Nap, BaA, BbF, BkF, Chry and IcdP are included in group 2B (possibly carcinogenic to humans). Acp, Ant, BghiP, Flt, Flu, Phe and Pyr are classified as group 3 (not classifiable according to their carcinogenicity to humans). Therefore, among the priority PAHs, eight PAHs are listed as carcinogenic (Table 1). On the other hand, exposure of humans to a single PAH does not occur because PAHs always exists as mixtures. This makes an assessment of the health consequences of PAHs exposure in humans difficult (Wenzl *et al.*, 2006). Denissenko *et al.* (1996) reported the direct etiological relationship between BaP and human lung cancer. PAHs also forms adducts with DNA and induce P53 mutations in human beings, which can result lung cancer (Alexandrov *et al.*, 2002). Chen and Liao (2006) performed risk assessment of human exposure to PAHs generated from industrial, traffic and rural settings in Taiwan. They provided the health risk assessment due to PAHs for three age groups: adults, children and infants. For adult (20-70 age) and children (5-19 age) age groups, inhalation ILCR (Inhalation, dermal, and total life time Cancer Risk) is higher than that of dermal contact, whereas for infants (0-1 age) the dermal contact ILCR value is higher than that of inhalation. According to them, an ILCR between  $10^{-6}$  and  $10^{-4}$  indicates a potential risk. Their study predicts the ILCRs between  $10^{-5}$  and  $10^{-4}$  for adults and children exposed to PAHs. This suggests a high potential car-

cinogenic risk to human at their sampling sites.

The Occupational Safety and Health Administration (<http://www.osha.gov/SLTC/coaltarpitchvolatiles/index.html>) set a limit of 0.2 mg of PAHs per cubic meter of air as the permissible exposure limit (PEL) on 8 h exposure period. According to the National Institute of Occupational Safety and Health (NIOSH), recommended exposure limit (REL) of PAHs in air is  $0.1 \text{ mg/m}^3$  over a 10 h exposure period.

### 3. AMBIENT AIR CONCENTRATIONS OF PAHS IN DEVELOPED ASIAN COUNTRIES

This section discusses the ambient air PAH concentrations reported since 2000 in developed Asian countries, such as Japan, Hong Kong, Taiwan, Singapore and South Korea. Table 2 provides a brief description of the papers reviewed from the developed Asian countries.

#### 3.1 Japan

Chetwittayachan *et al.* (2002) reported the real-time ambient concentrations of particle-bound PAHs (pPAH) on the roads of Tokyo and Bangkok. They used photoelectric aerosol sensor (PAS) to measure the total pPAH concentrations. They selected two sites in both Tokyo and Bangkok, one was a road side and other was general site, and measured the pPAH concentrations over seven consecutive days. Based on their results they concluded that at road side areas, the average concentrations of pPAHs during the sampling period were higher in Bangkok than in Tokyo, and vice versa for the

**Table 1.** Brief information about USEPA 16 prior PAHs.

No.	PAH	CAS No.	Molecular weight	IARC <sup>#</sup> classification	Unit risk* ( $\mu\text{g/m}^3$ ) <sup>-1</sup>
1	Naphthalene (Nap)	91-20-3	128.17	2B	3.40E-05
2	Acenaphthylene (Acy)	208-96-8	152.19	—	—
3	Acenaphthene (Acp)	83-32-9	154.21	3	—
4	Fluorene (Flu)	86-73-7	166.22	3	—
5	Phenanthrene (Phe)	1/8/1985	178.23	3	—
6	Anthracene (Ant)	120-12-7	178.23	3	—
7	Fluoranthene (Flt)	206-44-0	202.25	3	—
8	Pyrene (Pyr)	129-00-0	202.25	3	—
9	Benzo[a]anthracene (BaA)	56-55-3	228.29	2B	1.10E-04
10	Chrysene (Chry)	218-01-9	228.29	2B	1.10E-05
11	Benzo[b]fluoranthene (BbF)	205-99-2	252.31	2B	1.10E-04
12	Benzo[k]fluoranthene (BkF)	207-08-9	252.31	2B	1.10E-04
13	Benzo[a]pyrene (BaP)	50-32-8	252.31	1	1.10E-03
14	Indeno[1,2,3-cd]pyrene (IcdP)	193-39-5	276.33	2B	1.10E-04
15	Dibenz[a,h]anthracene (DahA)	53-70-3	278.35	2A	1.20E-03
16	Benzo[ghi]perylene (BghiP)	191-24-2	276.33	3	—

<sup>#</sup>IARC: International Agency for Research on Cancer

\*Unit Risk values taken from California EPA (California EPA, 1997)

**Table 2.** Brief description of the reviewed papers in developing Asian countries.

S. No.	Country	Site characteristics	Season (s)	No. of samples	Phase/Particle size	Analysis	Reference
1	Japan	Urban/Street side	All	136	Particle	HPLC/FLD	Wada <i>et al.</i> , 2001
		Industrial	Winter, Summer	–	Vapor and Particle	HPLC/FLD	Ohura <i>et al.</i> , 2004c
		Commercial, Industrial	Winter, Summer	28, 20	Particle	HPLC/FLD	Tang <i>et al.</i> , 2005
		Mountain area	All	27	Particle	HPLC/FLD	Tamamura <i>et al.</i> , 2007
		Residential	All	97	Particle/TSP	HPLC/FLD	Hien <i>et al.</i> , 2007
		Residential	All	21	Particle/PM <sub>10</sub>	GC/MS	Tham <i>et al.</i> , 2008
2	Hong Kong	University campus	All	33	Vapor and Particle	GC/MS	Lee <i>et al.</i> , 2001
		University campus	Winter, Summer	7-16	Particle/PM <sub>2.5</sub> , PM <sub>10</sub>	GC/MS	Guo <i>et al.</i> , 2003
3	Taiwan	Inside and out side the temple	–	6	Vapor and Particle	GC/MS	Lin <i>et al.</i> , 2002
		Road side	All	8-23	Particle/TSP	GC/MS	Chiang <i>et al.</i> , 2003
		Industrial	All	23	Vapor, Particle	GC/MS	Fang <i>et al.</i> , 2004b
4	South Korea	Industrial and Traffic	Winter, Spring	115	Particle/PM <sub>10</sub>	GC/FID	Son <i>et al.</i> , 2000
		Residential	Spring	5-8	Particle/PM <sub>10</sub> , TSP	GC/MS	Park <i>et al.</i> , 2001
		Urban	All	–	Particle/PM <sub>2.5</sub> , Vapor	GC/MS	Park <i>et al.</i> , 2002
		Residential, Commercial, Industrial	All	84	Particle/PM <sub>10</sub>	HPLC/UV-FLD	Choi and Baek, 2003
		Residential	Winter, Summer	14-15	Particle/PM <sub>2.5</sub>	GC/MS	Lee <i>et al.</i> , 2003
		Urban traffic	Winter, Summer, Spring	24	Particle/PM <sub>2.5</sub>	GC/MS	Han <i>et al.</i> , 2006
		Background	All	51	Particle	GC/MS	Lee <i>et al.</i> , 2006
		Residential	Spring, Summer, Autumn	19	Particle, Vapor	–	Park <i>et al.</i> , 2006a
		Urban traffic	–	35	Particle, Vapor	GC/MS	Park <i>et al.</i> , 2006b
	Urban traffic	All	86	Particle/PM <sub>10</sub>	GC/MS	Hong <i>et al.</i> , 2009	
5	Singapore	University campus	–	–	Vapor and Particle	GC/MS	He and Balasubramanian, 2009

general areas. They examined the diffusion of pPAHs in both cities. Tokyo has wide spread dispersion of pPAHs compared to Bangkok. They observed higher pPAH concentrations in both cities during the week-days than weekends. In their studies, they observed a strong positive correlation between the heavy duty vehicles and the pPAH concentrations in the early morning (0.00-8.00) in both cities with R<sup>2</sup> values of 0.752 and 0.776 in Tokyo and Bangkok, respectively. This suggests that the major source of pPAHs in both

cities was vehicular exhaust, particularly from heavy duty vehicles in the morning.

Ohura *et al.* (2004a) reported the indoor and outdoor concentrations of PAHs associated with particulate matter during summer and winter at Shizuoka. Airborne particles were collected and fractionated using a three-stage cascade impactor. The flow rate for sampling was 3.0 L/min. Airborne particles were divided into three fractions based on the size < 2.5 μm (PM<sub>2.5</sub>), 2.5-10.0 μm (PM<sub>2.5-10</sub>) and > 10 μm (PM<sub>>10</sub>). Teflon fiber

ring filters (47 mm) were used to collect the  $PM_{2.5-10.0}$  and  $PM > 10$  particles and Teflon fiber round filters (47 mm) were used for  $PM_{2.5}$  particles.  $PM_{2.5}$  particles accounted for 44-56% of the total suspended particulate matter. Regarding the PAHs associated with particulate matter, >80% of PAHs were associated with  $PM_{2.5}$ . Based on the ratios of the indoor to outdoor PAH concentrations, they concluded that the indoor PAHs were mostly from the outdoor sources. Therefore, most indoor particulate matter and PAHs concentrations is due to the transport of air from the outdoor to indoor environment. Therefore, the indoor BaP concentrations are affected strongly by the corresponding outdoor concentrations. Consequently, the risk assessment for the inhalation of PAHs was estimated roughly based on the outdoor BaP concentrations only. Based on their assessment of the carcinogenic risks associated with the inhalation of indoor PAHs, BaP made the greatest contribution (approximately, 51-64% of the total carcinogenic risk).

Ohura *et al.* (2004b) also studied the indoor and outdoor concentrations of PAHs as well as the factors affecting their concentrations in Shimizu. At their sampling sites, they observed higher concentrations of gaseous PAHs in summer and particulate PAHs in winter. As mentioned in the above paper they estimated the inhalation risk associated with carcinogenic PAHs using the toxic equivalency factors based on the potency of BaP. The same author (Ohura *et al.*, 2004c) also reported the ambient air concentrations of PAHs in two industrial cities, Fuji and Shimizu during summer and winter in 1999-2000. They found and measured the concentrations of thirty-nine PAHs at their sampling sites. In this study, it was observed that 2-3 ring and 5-7 ring PAHs were predominantly found in the vapor and particulate phases, respectively. But the 4-ring PAHs were mostly partitioned between the vapor and particulate phases. Regarding the sources of PAHs at these two industrial cities, principle component analysis was performed and concluded that the major sources of PAHs at the sampling site in Shimizu were paper making plants and traffic, but at the sampling site in Fuji the major principle source for PAHs was traffic.

In addition to the above mentioned papers, Tang *et al.* (2005) reported the ambient air PAH concentrations in Pan-Japan sea countries. They measured the atmospheric concentrations of PAHs in seven cities representing Pan-Japan sea countries i.e., Shenyang (China), Vladivostok (Russia), Kanazawa (Japan), Kitakyushu (Japan), Tokyo (Japan) and Sapporo (Japan) in winter and summer during 1997-2002. On the other hand, in Seoul, South Korea, they measured the PAHs concentrations in winter only. Along with the PAHs, they determined the concentrations of nitro PAHs in their study

sites. Similarly, Wada *et al.* (2001) reported the ambient air PAH and nitro PAH concentrations in Nagasaki from July 1997 to June 1998. Tamamura *et al.* (2007) reported the long range transport of PAHs in Asian dust from the eastern Asian continent to Kanazawa, Japan. Aerosol particles were collected during three Asian dust periods in 2003: March 11-19 and March 28 and April 9. The size of the Asian dust particles was mostly between 2.1-11  $\mu\text{m}$ . They observed a significant increase in the less volatile PAHs, such as BaP and BghiP, in the coarse particles during April 9<sup>th</sup> sampling. A significant increase in the ambient concentrations of PAHs was observed in Kanazawa during the Asian dust periods due to the transportation of dust particles originating from the loess regions in central and eastern China. The Asian dust particles originated from arid and semi-arid regions of Mongolia and northern China also shows a significant impact on the concentrations of PAHs in Kanazawa. Hien *et al.* (2007) performed a comparative study of the particle phase PAHs and their variability in the ambient air in Ho Chi Minh city, Vietnam and in Osaka, Japan during 2005-2006. Tham *et al.* (2008) reported the atmospheric concentrations of PAHs associated with particles in Hiroshima and the influence of meteorological conditions, such as ambient temperature, solar intensity, weekly rainfall, wind speed and humidity. Based on Pearson correlation analysis, they found a negative correlation for particulate PAHs with ambient temperature and solar intensity but showed a positive correlation with sulfur dioxide and nitrogen dioxide concentrations. Based on seasonal variation studies, they found that the concentrations of PAHs was higher in winter than in summer, particularly with 5-ring PAHs. On the other hand, the concentrations of carcinogenic PAHs was relatively unaffected by the seasons; their concentrations were constant throughout the year.

### 3.2 Hong Kong

A few authors (Ho and Lee, 2002; Ho *et al.*, 2002; Lee *et al.*, 2001) from Hong Kong characterized selective volatile organic compounds, PAHs and carbonyl compounds at a road side monitoring station (Hong Kong Polytechnic University). In all studies, ambient air samples were collected from 16<sup>th</sup> April 1999 to 30<sup>th</sup> March 2000. Based on monitoring for one year, they performed principle component analysis and factor analysis to identify the sources of the different VOCs and PAHs. They collected 33 samples during the above mentioned period, and analyzed 18 PAHs, including 16 EPA priority PAHs. They measured high concentration of naphthalene (a mean of 993  $\text{ng}/\text{m}^3$ ) at their sampling site and majority of naphthalene was in the

vapor phase. Principle component analysis showed that motor vehicle emissions were the major sources of PAHs, such as Phe, Flu, Flt and Pyr. Regarding seasonal variations, they found higher concentrations of PAHs during winter than in summer except for coronene. They assumed that the photochemical degradation of some PAHs during summer might result in a decrease in concentration in ambient air, and physical dispersion/transportation may explain the higher concentrations of PAHs during winter. The higher concentration of coronene in summer may be due to additional sources along with motor vehicle emissions. Guo *et al.* (2003) reported the PAHs concentrations in ambient air of Hong Kong Polytechnic University and Kwan Tong (an industrial site). They measured the PAHs associated with PM<sub>2.5</sub> and PM<sub>10</sub> during summer and winter in 2000-2001. Based on the diagnostic ratios of PAHs and principle component analysis, the major sources for PAHs at Hong Kong Polytechnic University were vehicular emissions with a small contribution from stationary combustions. On the other hand, the major sources at Kwan Tong site were gasoline and diesel engine emissions. Their ANOVA (Analysis of Variance) results showed that the ratios of PAHs in PM<sub>2.5</sub> to that in PM<sub>10</sub> at Hong Kong had a common pattern regardless of the speciation, seasonal variation and sampling sites. Ho and Yu (2004) introduced a new method called in-injection port thermal desorption for an analysis of n-alkanes and PAHs collected on aerosol filters. They measured the PAH concentrations at a roadside location of Hong Kong in the winter and summer of 2001. They analyzed the concentrations of PAHs (Phe, Flt, Pyr, BaA and Chry) in filters using solvent extraction and thermal desorption methods. They claimed that thermal desorption had advantages over solvent extraction, such as reduced labor and time by avoiding sample pre-treatment and requiring less filter material for analysis. Although they measured the concentrations of PAHs, they focused mainly on the concentrations of n-alkanes.

### 3.3 Taiwan

Fang *et al.* (2004a) measured the concentrations of PAHs in both the vapor and particulate phase in industrial, urban and rural areas of Taichung, Taiwan from August to December, 2002. Their results revealed high concentrations of PAHs at the industrial area followed by the urban and rural areas. The dry deposition fluxes of total PAHs also followed the same order (industrial > urban > rural area). The concentrations of total PAHs at the industrial site was 1.5 and 1.03 times higher than that in the gas and particle phases in the urban area, which was 2 and 1.05 higher than the gas and particle phases in the rural area. In all sampling

sites, combustion was the major source of PAHs. Based on the BaP equivalency results, they concluded that the health risk associated with gaseous phase PAHs were higher than that of the particulate phase PAHs at all sampling sites.

Fang *et al.* (2004b) examined the concentrations of PAHs in both gaseous and particulate phases at Taichung Industrial Park and Tunghai University during August 2002-July 2003. Principle component analysis showed that at Taichung Industrial Park area, industrial emissions were the source of PAHs, such as Ace, Acp, Chry, BbF and BeP. Diesel engine emissions were the major source of the PAHs, such as Flu, Phe, Ant and Pyr. At Tunghai University area, however, incineration emissions were found to be the major source of PAHs. Along with incineration, gasoline engine emissions also contribute to the generation of PAHs at this sampling area.

At the same sampling sites mentioned in the above paragraph, Fang *et al.* reported the concentrations of PAHs in both gaseous and particulate phases during August-December 2002 (Fang *et al.*, 2004c) and August 2002-March 2003 (Fang *et al.*, 2004d). Fang *et al.* (2004a-d) concluded that vehicular emissions, incinerator combustion and industrial emissions were the major sources of both gaseous and particulate phase PAHs in their sampling sites. Lin *et al.* (2002) performed a comparative study of PAH concentrations inside and outside of a Taiwanese temple in Tainan city. They measured higher concentrations of PAH inside the temple than outside. Chiang *et al.* (2003) reported the trend in concentrations of 14 PAHs (Phe, Flt, Pyr, 2,3-benzofluorene, BaA, triphenylene, Chry, BbF, BeP, BaP, Per, IcdP, DahA, and BghiP) over a seven year period (1990-1997) at Taipei city. During their long term study, they found that the BghiP concentration was predominant among the 14 PAHs examined. The magnitude of PAHs was not found in an ascending or descending order, but the ratios of total particulate PAHs to total suspended particulate matter decreased from the year 1990 to 1997. Based on factor analysis studies, they concluded that industrial emissions were the major sources for the PAHs, such as BaP, Per, BeP and BbF. Gasoline exhaust and oil combustions were the major sources for DahA, IcdP and BghiP. Seasonal comparison studies revealed the higher concentrations of carcinogenic PAHs in autumn and winter than the others. As for the detailed analysis of the ring distribution of PAHs, 6-ring PAHs that are in particulate phase accounted for more than 38% of the total PAHs, whereas 3-ring PAHs that are in vapor phase accounted for more than 50% of the total PAHs. Even though the concentrations of 3- and 4-ring PAHs was higher, the health risk was mostly associat-

ed with particulate phase 5- and 6-ring PAHs.

### 3.4 Singapore

He and Balasubramanian (2009) measured the particulate and vapor phase PAHs in ambient air at the National University of Singapore (NUS) between November and December 2006. The sampling site was located 67 m above sea level and in the vicinity of a highway and traffic intersection. The sampling site was influenced mainly by the emissions from urban vehicular traffic, chemical industries, major power plants and oil refineries. Ambient air samples were collected with a high volume sampler at a flow rate of 250 L/min (duration 24 h) using a quartz fiber filter (4" diameter) and polyurethane foam (PUF). The PAHs in the ambient air samples were analyzed by GC/MS. They measured the 16 EPA priority PAHs in the ambient air of the selected site. In this study, they observed high concentration of Pyr (7.3 ng/m<sup>3</sup>) followed in order by Phe (7.2 ng/m<sup>3</sup>) and Flt (5.6 ng/m<sup>3</sup>), and reported a total concentrations of 16 PAHs of 33.4 ng/m<sup>3</sup>. Approximately 80% of the total PAHs were in the vapor phase.

### 3.5 South Korea

In South Korea, Son *et al.* (2000) measured the concentrations of six PAHs (Flt, Pyr, BaA, Chry, BbF and BaP) associated with PM<sub>10</sub> in ambient air of Suwon city. They performed statistical analysis for the PAHs dataset using principal component analysis to identify qualitatively the potential sources of PM<sub>10</sub>. The major sources of atmospheric PAHs in Suwon city were found to be burning activities, such as refuse and field burning, coal burning and oil burning emissions in areas surrounding the study site. In this study, they observed higher concentration of BaP (mean: 1.04 ng/m<sup>3</sup>) than the remaining five PAHs at the same site. Park *et al.* (2001) reported the distribution patterns of PAHs between Yellow sand and non-Yellow sand periods in Seoul during March-April 2000. They observed that the concentrations of PAHs during a Yellow sand period was 140% higher than those of a non-Yellow sand period. The toxic PAHs originating from China was the major reason for the degradation of ambient air quality in Seoul. Park *et al.* (2002) measured the concentrations of PAHs in both the particulate and vapor phase in Seoul city during October 1998-December 1999. The total EPA 16 priority PAH concentrations in Seoul city during their sampling period ranged from 11-350 ng/m<sup>3</sup>. They observed high concentrations of PAHs during winter than in summer, and predicted high fuel consumption coupled with meteorological conditions (lower air temperature, lower mixing layer height) as possible reasons for the high concentrations

during winter.

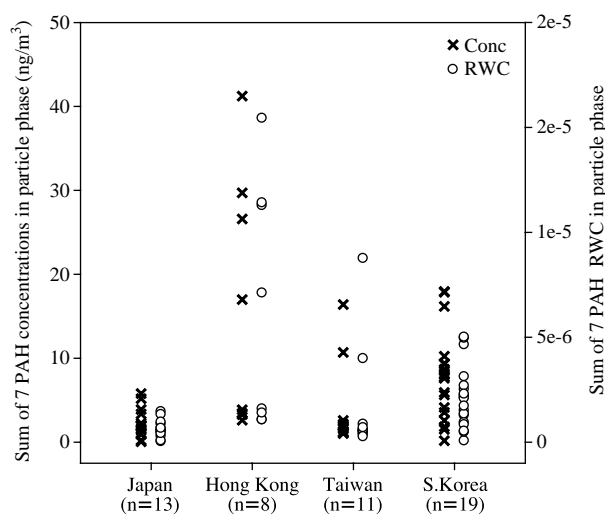
Choi and Baek (2003) determined the concentrations of PAHs associated with PM<sub>10</sub> in ambient air of different sites (residential, commercial, industrial and suburban) in Taegu metropolitan city during 1993-1994. They found that vehicular emissions in urban and suburban areas were likely to be a major contributor for atmospheric PAHs in the non-heating season, whereas the contributions of residential heating and local industrial oil burning emissions were significant in the heating season. Lee *et al.* (2003) reported the ambient PAHs during winter and summer of 2002 in Chongju city. In this study, they found that in the total PAHs mass, the concentrations of lower molecular weight PAHs (3-4 rings) were higher than that of high molecular weight PAHs (5-6 rings). They predicted the main contributor of PAHs in Chongju city to be vehicular emissions. Han *et al.* (2006) reported the concentrations of PAHs in the ambient air of Seoul metropolitan city during February-August 2005. They found that BaP concentration was 0.5 ng/m<sup>3</sup> in winter and ranged from 0.03-0.3 ng/m<sup>3</sup> in spring and summer, which indicates a decrease in concentration of BaP compared to the 1990's. Lee *et al.* (2006) examined the seasonal trend in particulate PAHs at Gosan (a background site) during 2001-2002. The measured annual mean particulate PAH concentrations of 3.17 ± 3.31 ng/m<sup>3</sup>, which was 3-15 times higher than those at the other background sites in the world to which they compared. They found that the PAH concentrations at Gosan were much higher when the air parcels moved from China. Park *et al.* (2006a) measured the concentrations of PAHs in Seoul area based on the emission sources. Their factor analysis studies showed that gasoline and diesel fueled cars emissions were the major sources of the PAHs, such as Chry, Pyr, IcdP, BbF, BkF and BghiP. Domestic and industrial combustions of liquid natural gas and BC (Bunker C) oil were the sources of PAHs, such as Phe and Ant. Municipal waste incineration was the major source of DahA and Ace. Park *et al.* (2006b) reported the concentrations of both the vapor phase and particulate phase PAHs in the urban atmosphere of Chongju city during October 1998-October 1999. They measured the concentrations of EPA priority 16 PAHs at the mentioned sampling site, and performed principle component analysis to determine the emission sources of individual PAHs. Based on a literature survey and their studies, they predicted vehicle emissions and coal combustions to be the major sources of BbF, BkF, IcdP, BghiP, Flt and Pyr. Oil combustion and municipal waste incineration were the sources of PAHs, such as Phe, Ant, Flt and Pyr. Hong *et al.* (2009) reported the ambient air concentrations of PAHs in Seoul city during September 2006-October 2007. The highest



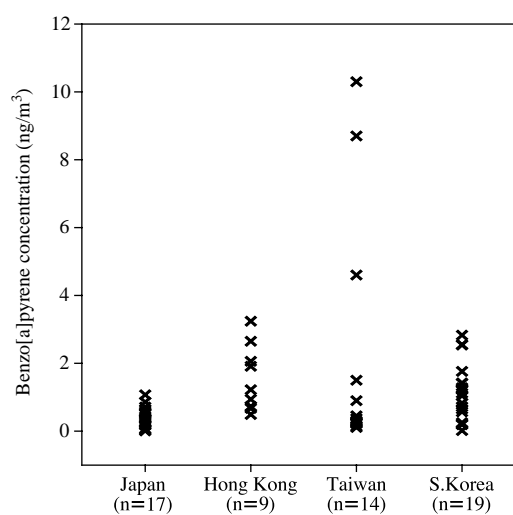
and lowest concentrations of PAHs was found in January and August, respectively. Their studies concluded the consumption of fossil fuels, temperature, mixing height and photochemical reactions to be the major factors affecting the concentrations of PAHs in Seoul metropolitan area. Park *et al.* (2007) reported the concentrations of PAHs bound with PM<sub>2.5</sub> in Seoul during November 1998-December 1999. They attributed the high concentrations during winter to increased fuel consumption for domestic heating, low boundary layer heights and low ambient temperature. Lee *et al.* (2008) examined the particulate PAHs concentrations at a background site, Mt. Halla site, Jeju Island in South Korea during March 1999-March 2002. They compared the concentrations of PAHs in Jeju Island with that at Gosan, another background site in South Korea. Based on their studies, they concluded that the concentrations of PAHs in Jeju Island was higher than at Gosan. Lee *et al.* (2011) reported the ambient air concentrations of PAHs in Seoul, the capital city of South Korea. The mean concentrations of PAHs during their study period was 26.6 ng/m<sup>3</sup>. They found that the concentrations of PAHs in Seoul was lower than in Chinese cities but higher than in Tokyo.

#### 4. DISCUSSION

Although the EPA suggests 16 PAHs as priority PAHs, the IARC included eight PAHs (BaP, DahA, Nap, BaA, BbF, BkF, Chry and IcdP) in their carcinogenic list. The California EPA predicts the unit risk values of these PAHs (Table 1). According to these unit risk values, it was concluded that DahA (unit risk 1.20E-03) and BaP (unit risk 1.10E-03) carry more risk to humans when they are present in the atmosphere. This highlights the importance of measuring these PAHs in the atmosphere than the others. On the other hand, the Nap concentrations were unclear, because the total concentrations and sum of the Risk Weighted Concentrations (RWC) of the seven PAHs (except Nap in the above eight PAHs) were calculated, and shown in Fig. 1. The RWC of each PAH was calculated by multiplying the reported ambient air mean concentration of each PAH in  $\mu\text{g}/\text{m}^3$  with the unit risk value of PAH in  $(\mu\text{g}/\text{m}^3)^{-1}$ . The unit risk value of each PAH was taken from the California EPA (1997) (Table 1). Fig. 1 shows that the sum of the seven PAH concentrations was higher in South Korea (17.96 ng/m<sup>3</sup>) than in Taiwan (16.40 ng/m<sup>3</sup>), but the sum of the RWCs of South Korea was lower (4.99e-6) than in Taiwan (8.74e-6). This suggests that the risk associated with these seven PAHs is higher in Taiwan than in South Korea even though South Korea has a higher sum of the concen-



**Fig. 1.** Sum of 7 PAH concentrations and RWC in developed Asian countries (The 7 PAHs are: BaA, Chry, BbF, BkF, BaP, IcdP and DahA; n=number of papers).



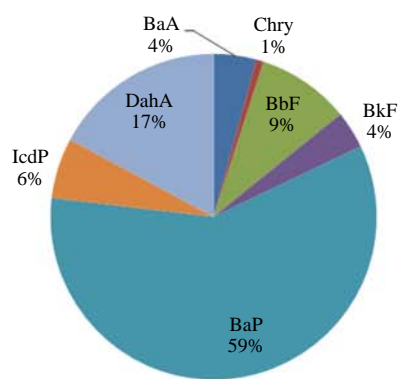
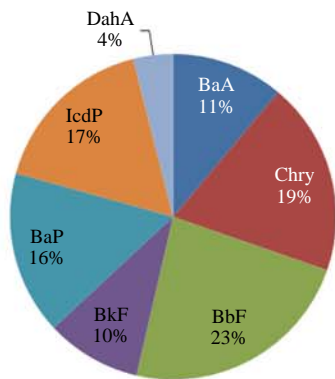
**Fig. 2.** Benzo(a)pyrene concentration in developed Asian countries.

tration (seven PAHs) than in Taiwan. Therefore, the RWC predicts the accurate toxicity or risk associated with PAHs in ambient air than the sum of their concentrations.

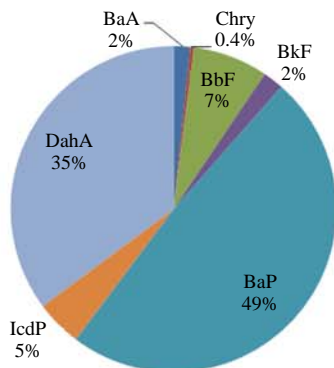
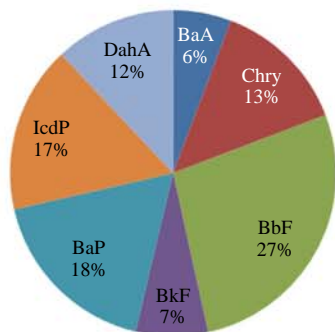
In EPA 16 priority PAHs, BaP is considered the top most priority PAH in ambient air because it is only the PAH listed as a group 1 carcinogen by the IARC. A plot of the mean concentration of BaP reported in developed Asian countries during the review period was prepared (Fig. 2). In developed Asian countries, Lin *et al.* reported the highest concentration of BaP in

(a) The portion of PAH concentrations

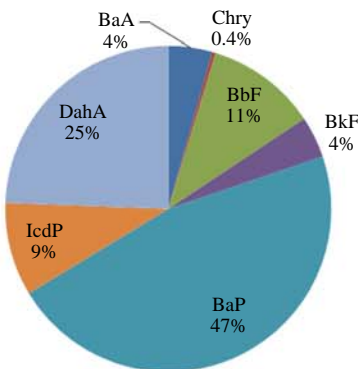
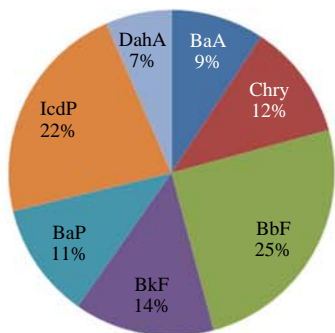
(b) The portion of PAH RWC



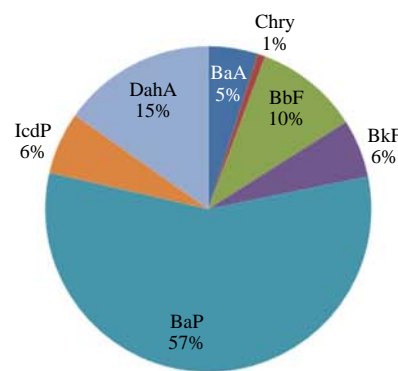
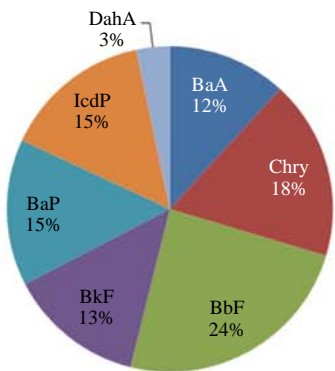
Japan, n=13



Hong Kong, n=8



Taiwan, n=11



Korea, n=19

**Fig. 3.** (a) The portion of each PAH concentration in total 7 PAH concentrations, (b) The portion of RWC of each PAH in total 7 PAHs RWC (The 7 PAHs are: BaA, Chry, BbF, BkF, BaP, IcdP and DahA).

Taiwan ( $10.3 \text{ ng/m}^3$ ) (Lin *et al.*, 2002). The major source of the PAHs in this site was the burning of different types of incense inside the temple. Overall, in developed Asian countries, the reported order of the BaP concentration is as follows: Taiwan > Hong Kong > South Korea > Japan. One of the factors influencing the concentrations of PAHs is the economic condition of the country. The concentrations of PAHs in Western countries was reported as lower than in developed Asian countries, which have a lower concentrations of PAHs than developing Asian countries (Lakshmi Narayana *et al.*, 2012). This indicates the relationship between the economic status of a country and the ambient concentrations of PAHs. With better economic conditions of the country, the people can use the pure fuel which reduces the air pollution particularly the concentrations of PAHs in ambient air. By improving the financial status of the country, the government can also afford the money for research in air monitoring which gives an overview for the implementation of environmental policies like euro standards. In our opinion, funding for the research in air pollution is one of the investments made by the government because it reduces the public medical expenses. Without knowing the quality of air, it is highly impossible to implement any policies for reducing the air pollutants, such as PAHs. So, the monitoring of air pollutants, such as PAHs is always an important task which makes a big impact on public health.

Comparing the concentrations of PAHs reported in different countries is difficult because they are dependent on a range of meteorological conditions, such as the wind direction, wind speed and temperature. In this paper, an attempt was made to compare the concentrations of PAHs and their risk to humans. As mentioned earlier, among the 16 priority PAHs, seven PAHs (Nap is omitted due to uncertainty in its measurement), are considered to be carcinogenic. A pie chart on the concentration portion of each PAH, in total seven PAH concentrations, was prepared (Fig. 3). Among the seven carcinogenic PAHs, the BaP concentration portion in developed Asian countries was in the range of 15-18%. This appears to be a small portion but the RWC portion of BaP among the seven PAHs was 47-59%. In contrast, the portion of BbF, BkF and Chry among the seven PAHs was approximately 50% but the RWC of the seven PAHs was less than 17%. Based on this pie chart, the concentration of BaP and DahA were much more important than the other PAHs with respect to their risk to humans. Identifying the sources of the PAHs, such as BaP and DahA, is very important. If the sources of these PAHs determined, it will be easy to control their concentration in ambient air. Benzo[a]pyrene, mostly enters the ambient air by the

emissions from automobiles (particularly from diesel engines), and the combustion of organic materials, such as cigarette smoke and charbroiled food. The sources of DahA include the natural phenomena, such as forest fires and anthropogenic activities, such as cigarette smoke and automobile exhaust (<http://www.nature.nps.gov/hazardssafety/toxic/dibenzah.pdf>).

The concentrations of PAHs in ambient air in developed Asian countries was lower than that of developing Asian countries, such as China and India. In Asia, developed countries are aware of air pollution and implemented the Euro standards to motor vehicles to reduce vehicular emissions ([http://www.adb.org/documents/guidelines/vehicle\\_emissions/im\\_ch03.pdf](http://www.adb.org/documents/guidelines/vehicle_emissions/im_ch03.pdf)). The implementation of environmental policies, such as euro standards, has shown good results in achieving quality air in developed Asian countries. The reported PAHs concentrations during the review period (2000-2011) in developed Asian countries was lower than in developing Asian countries but higher than in Western countries. This highlights the importance of monitoring the PAHs concentrations in ambient air in developed Asian countries.

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(Received 7 May 2012, revised 11 July 2012, accepted 11 July 2012)

## SUPPLEMENTARY INFORMATION

**Table 1.** Ambient air concentrations ( $\text{ng m}^{-3}$ ) of PAHs in developed countries (Japan, Hong Kong, Taiwan, and South Korea).

Reference	Wada <i>et al.</i> (2001)	Ohura <i>et al.</i> (2004c)*	Tang <i>et al.</i> (2005)**
Country	Japan	Japan	Japan
Location	Nagasaki	Fuji	Kanazawa
Site characteristics	Street sides (heavy traffic)	Industrial	Commercial
Sampling period	July 1997-June 1998	Aug 1999	1999
Season/s	All	Summer	Summer
No. of samples	136	—	14
Sampling device	High vol. sampler	Low vol. sampler	High vol. sampler
Sampling media	Silica fiber paper	GFF <sup>#</sup> and XAD-2	QFF <sup>†</sup>
Flow rate, duration	1200 L/min, 9 h	1.0 L/min, 24 h	1000 L/min, 24 h
Phase	Particle	Vapor and Particle	Particle
Particle size	> 0.3 $\mu\text{m}$	—	Airborne particles
Extraction	—	Ultrasonic	Ultrasonic
Solvent	Hexane	DCM (Particle) <sup>***</sup> , DCM and hexane	Benzene/ethanol (3:1 v/v)
Analysis	HPLC/FLD <sup>****</sup>	HPLC/FLD	HPLC/FLD
Quality assurance	—	—	—
Nap	6.62	213.00	174.29
Ace	—	345.00	213.44
Acp	0.02	2.87	3.54
Flu	0.16	5.76	5.56
Phe	1.58	26.27	17.25
Ant	0.09	0.42	0.31
Flt	0.83	4.57	1.85
Pyr	0.23	3.00	1.51
BaA	0.50	0.12	0.04
Chry	1.75	0.41	0.11
BbF	1.30	0.52	0.13
BkF	0.56	0.17	0.05
BaP	0.71	0.18	0.07
IcdP	0.72	0.18	0.10
DahA	0.25	0.04	0.01
BghiP	2.92	0.29	0.12
			0.53
			0.36
			0.42
			0.36
			0.23
			0.41
			0.48
			0.20
			0.28
			0.30
			—
			0.55

\*Concentrations of PAHs in Geo mean values; \*\*Concentrations of PAHs converted from  $\text{p.mol.m}^{-3}$  to  $\text{ng.m}^{-3}$ ; <sup>†</sup> Quartz Fiber Filter; <sup>\*\*\*</sup>DCM: Dichloromethane; <sup>\*\*\*\*</sup>High Performance Liquid Chromatography/Fluorescence Detector; <sup>#</sup>Glass Fiber Filter

Table 1. Continued.

Reference	Tang <i>et al.</i> (2005)*	Tamamura <i>et al.</i> (2007)	Hien <i>et al.</i> (2007a)
Country	Japan	Japan	Japan
Location	Sapporo	Kitakyushu	Osaka
Site characteristics	Commercial	Industrial	Osaka Prefecture University (Residential)
Sampling period	1997	1997	Apr 2005- May 2006
Season/s	Summer Winter	Summer Winter	-
No. of samples	20	20	97
Sampling device	High vol. sampler		High vol. sampler
Sampling media	QFF		QFF
Flow rate, duration	1000 L/min, 24h	1000 L/min, 24h	1000 L/min, 24h
Phase	Particle		Particle
Particle size	Airborne particulates		TSP**
Extraction	Ultrasonic		Ultrasonic
Solvent	Benzene/ethanol (3:1 v/v)		Benzene/ethanol (3:1 v/v)
Analysis	HPLC/FLD		HPLC/FLD
Quality assurance			-
Nap	-	-	-
Ace	-	-	-
Acp	-	-	-
Flu	-	-	-
Phe	-	-	0.08
Ant	-	-	-
Flt	0.40	0.26	-
Pyr	0.55	0.38	0.45
BaA	0.27	0.21	0.38
Chry	0.39	0.32	0.19
BbF	0.43	0.50	0.30
BkF	0.18	0.20	0.41
BaP	0.35	0.35	0.17
IcdP	0.39	0.41	0.25
DahA	-	-	0.28
BghiP	0.66	-	-
		0.02	0.29

\*Concentrations of PAHs converted from p.mol.m<sup>-3</sup> to ng.m<sup>-3</sup>, \*\*Total Suspended Particulate matter



Table 1. Continued.

Reference	Tham <i>et al.</i> (2008)	Lee <i>et al.</i> (2001)	Guo <i>et al.</i> (2003)
Country	Japan	Hong Kong	Hong Kong
Location	Hiroshima	Hung Hom, Kowloon	Hung Hom
Site characteristics	Hiroshima University campus	Polytechnic University (Heavy traffic)	Polytechnic University (Heavy traffic)
Sampling period	Jan 2006-Jan 2007	Apr 1999-Apr 2000	Nov 2000-Mar 2001
Season/s	All	All	Summer Winter
No. of samples	21	33	15 16
Sampling device	High vol. sampler	Med. vol. sampler	High vol. sampler
Sampling media	GFF	Teflon impregnated GFF, PUF*, XAD-4	QFF
Flow rate, duration	1000 L/min, 24 h	180 L/min, 24 h	1130-1410** L/min, 24 h
Phase	Particle	Vapour+Particle	Particle
Particle size	PM <sub>10</sub>	TSP	PM <sub>2.5</sub> PM <sub>10</sub>
Extraction	Ultrasonic	Soxhlet	Ultrasonic
Solvent	DCM	PUF (10% ether in Hexane), GFF, XAD-4 (DCM)	DCM
Analysis	GC/MS***	GC/MS	GC/MS
Quality assurance	-	-	-
Nap	-	993.14	ND <sup>#</sup>
Ace	0.006	4.84	0.01
AcP	0.001	6.73	0.01
Flu	0.005	17.53	0.03
Phe	0.027	30.88	0.36
Ant	0.035	3.31	0.29
Flt	0.090	8.14	0.53
Pyr	0.170	7.53	0.30
BaA	0.190	0.60	0.36
ChrY	0.260	1.38	0.55
BbF	-	0.78	0.53
BkF	-	-	0.53
BaP	0.520	0.49	0.67
IcdP	0.450	0.66	0.58
DahA	-	0.19	0.07
BghiP	0.140	0.88	0.10
			ND
			0.01
			0.01
			0.02
			0.03
			0.28
			0.55
			0.01
			5.94
			6.43
			1.10
			3.47
			12.12
			0.36
			3.24
			4.70
			4.71
			2.88
			ND
			0.01
			0.01
			0.02
			0.25
			0.55
			0.01
			5.47
			6.35
			0.16
			0.34
			16.85
			0.41
			0.27
			0.19
			2.65
			7.38
			7.99
			4.47
			ND
			0.01
			0.01
			0.02
			0.26
			0.15
			0.47
			0.24
			0.21
			0.41
			10.31
			0.50
			0.56
			0.94
			0.71
			0.10
			0.17
			ND
			0.01
			0.01
			0.02
			0.33
			0.80
			0.01
			6.97
			7.78
			1.08
			3.54
			10.31
			0.27
			1.91
			3.14
			6.35
			2.07

\*Poly Urethane Foam; \*\*Converted the flow rate from cubic meter per minute to liter per minute; \*\*\*Gas Chromatography/Mass detector; <sup>#</sup>ND: Not Detected

Table 1. Continued.

Reference	Lin <i>et al.</i> (2002)*	Chiang <i>et al.</i> (2003)	Fang <i>et al.</i> (2004b)											
Country	Taiwan	Taiwan	Taiwan											
Location	Tainan	Taipei	Taichung											
Site characteristics	Taiwanese temple - inside	Near river, road side traffic	Taichung Industrial Park (Industrial area)											
Sampling period	Mar 1996	Mar 1996	1990	1991	1992	1993	1994	1995	1996	1997	1998	Aug 2002-Jul 2003		
Season/s	-	-	All	-	-	-	-	-	-	-	-	All		
No. of samples	6	6	20	22	23	14	11	10	13	10	8	23		
Sampling device	High vol. sampler	High vol. sampler	High vol. sampler	-	-	-	-	-	-	-	-	PUF sampler, Med vol. sampler		
Sampling media	GFF, PUF and XAD-2	GFF	GFF	-	-	-	-	-	-	-	-	PUF, XAD-16 QFF		
Flow rate, duration	NA**, 8 h	NA, 24 h	1400 L/min, 24h	-	-	-	-	-	-	-	-	NA, 48h		
Phase	Vapor+Particle	Particle	Particle	-	-	-	-	-	-	-	-	Vapor		
Particle size	-	TSP	TSP	-	-	-	-	-	-	-	-	Particle		
Extraction	Soxhlet	Soxhlet	Soxhlet	-	-	-	-	-	-	-	-	Soxhlet		
Solvent	DCM/n-hexane (50:50 v/v)	DCM	DCM	-	-	-	-	-	-	-	-	DCM/n-hexane (1:1 v/v)		
Analysis	GC/MS	GC/MS	GC/MS	-	-	-	-	-	-	-	-	GC/MS		
Quality assurance	-	-	-	-	-	-	-	-	-	-	-	SRM-1597		
Nap	1224.3	160.3	-	-	-	-	-	-	-	-	-	336.7	183.0	1.0
Ace	3186.3	8.4	-	-	-	-	-	-	-	-	-	112.7	75.4	2.6
Acp	294.9	9.6	-	-	-	-	-	-	-	-	-	123.1	41.1	0.9
Flu	29.9	3.5	-	-	-	-	-	-	-	-	-	133.8	69.4	2.1
Phe	132.3	4.5	0.67	0.17	0.30	0.39	0.77	1.43	0.15	0.06	0.09	141.4	4.2	59.7
Ant	24.1	0.4	-	-	-	-	-	-	-	-	-	179.4	5.3	61.4
Flt	200.6	1.7	1.18	0.16	0.17	0.41	1.06	0.34	0.33	0.16	0.21	83.2	3.4	41.3
Pyr	22.7	0.9	1.29	0.39	0.92	0.42	0.94	0.35	0.68	0.22	0.25	119.5	5.2	34.6
BaA	19.8	1.4	0.45	0.07	0.11	0.12	0.28	0.12	0.11	0.16	0.42	16.1	0.8	15.4
Chry	14.5	0.5	-	-	-	-	-	-	-	-	-	35.6	1.7	13.8
BbF	9.1	0.9	1.38	0.55	0.59	0.53	0.93	0.31	0.60	0.43	0.32	7.3	1.8	3.9
BkF	4.7	0.7	-	-	-	-	-	-	-	-	-	10.9	1.7	4.0
BaP	102.1	10.3	0.28	0.37	0.30	0.14	0.45	0.22	0.26	0.24	0.11	8.7	0.9	4.6
IcdP	2.4	0.3	0.05	0.21	0.65	0.67	0.83	0.46	0.84	0.95	0.17	3.3	1.9	3.9
DahA	22.8	2.4	ND	0.02	0.08	0.10	0.10	0.01	0.08	0.20	0.02	3.7	1.9	1.1
BghiP	90.5	3.7	0.90	0.65	1.50	1.34	1.57	1.14	1.72	2.03	0.38	3.0	3.5	2.7

\*Concentrations of PAHs in Geo mean values; \*\*NA: Not Available

Table 1. Continued.

Reference	Son <i>et al.</i> (2000)	Park <i>et al.</i> (2001)	Park <i>et al.</i> (2002)
Country	South Korea	South Korea	South Korea
Location	Suwon	Seoul	Seoul
Site characteristics	Traffic+Industrial	Residential	Urban
Sampling period	Feb-Jun 1996	Mar-Apr 2000	Oct 1998-Dec 1999
Season/s	Winter+Spring	Spring	All
No. of samples	115	5	8
Sampling device	High vol. sampler	High vol. sampler	PUF sampler
Sampling media	QFF	QFF	QFF
Flow rate (L/min)	1130* L/min, 24 h	650* L/min, 24 h	NA, 24 h
Phase	Particle	Particle	Particle
Particle size	PM <sub>10</sub>	TSP (non yellow sand)	PM <sub>10</sub> (yellow sand)
Extraction	Ultrasonic	ASE (accelerated solvent extraction)	Ultrasonic
Solvent	DCM	diethyl ether/hexane (1:9)	DCM
Analysis	GC/FID	GC/MS	GC/MS
Quality assurance	-	-	SRM 1649
Nap	-	0.19-0.57	0.23-0.68
Ace	-	ND-ND	ND-0.13
Acp	-	ND-0.14	ND-0.09
Flu	0.34	ND-0.27	0.08-0.26
Phe	-	0.69-1.47	0.68-2.01
Ant	-	0.79-1.73	1.13-2.38
Flt	-	0.51-1.51	1.09-2.53
Pyr	0.73	0.67-1.84	2.27
BaA	0.36	0.53-1.39	2.25
ChrY	0.50	0.76-2.05	1.82
BbF	0.67	0.69-1.74	2.78
BkF	-	0.55-1.73	4.89
BaP	1.04	0.31-1.21	2.55
IcdP	-	0.33-0.75	3.59
DahA	-	ND-0.18	0.55
BghiP	-	0.24-0.86	3.21
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
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			0.67-2.48
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			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
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			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
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			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
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			0.73-2.46
			0.59-2.08
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			0.49-0.92
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			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
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			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
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			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02
			0.67-2.48
			0.31-1.20
			0.76-2.36
			0.73-2.46
			0.59-2.08
			1.41-1.92
			0.49-0.92
			0.31-1.22
			0.09-0.44
			0.22-1.66
			0.20-0.65
			0.26-0.73
			0.71-1.95
			0.83-1.85
			0.67-2.02

Table 1. Continued.

Reference	Choi and Baek (2003)	Lee et al. (2003)
Country	South Korea	South Korea
Location	Daegu	Chongju
Site characteristics	Residential Commercial Industrial Suburban	Residential
Sampling period	Sep 1993-Nov 1994	Jan-Feb, Jul-Aug 2002
Season/s	All	Winter Summer
No. of samples	84 84 84 84	15 15 14 14
Sampling device	High vol. sampler	URG sampler
Sampling media	QFF	QFF, PUF
Flow rate (L/min)	1120* L/min, 24h	10 L/min, 24h
Phase	Particle	Particle Vapor Particle Vapor
Particle size	PM <sub>10</sub>	PM <sub>2.5</sub> PM <sub>2.5</sub>
Extraction	Soxhlet	Soxhlet
Solvent	DCM	DCM
Analysis	HPLC/UV-FLD	GC/MS
Quality assurance	SRM 11649	-
Nap	-	-
Ace	-	0.02
Acp	-	-
Flu	-	-
Phe	0.87	0.48
Ant	0.11	-
Flt	1.46	1.35
Pyr	1.50	1.27
BaA	0.80	0.63
Chry	1.76	0.98
BbF	1.59	0.99
BkF	0.62	-
BaP	1.22	-
IcdP	1.59	0.57
DahA	0.21	0.33
BghiP	1.47	0.06
		1.00
		3.65
		0.02
		0.48
		1.35
		1.27
		0.63
		0.98
		0.99
		-
		0.57
		0.33
		0.06
		1.00
		3.65
		0.02
		0.40
		0.25
		ND
		ND
		ND
		0.06
		-
		ND
		ND
		0.01
		0.01
		ND
		ND
		0.04
		0.17
		-
		-
		-
		1.98
		-
		0.05
		0.35
		ND
		ND
		ND
		0.02
		0.02
		0.03
		0.05
		0.06
		-
		0.02
		0.01
		0.01
		0.01
		0.04

\*Converted flow rate from cubic meter per minute to liter per minute



Table 1. Continued.

Reference	He and balasubramanian (2009)									
Country	Singapore									
Location	South east Asia									
Site characteristics	National University of Singapore (industrial and traffic)									
Sampling period	November and December 2006									
Season/s	Spring	Summer	Autumn	Winter	All	Autumn	Autumn	Autumn	Autumn	Autumn
No. of samples	15	15	28	28	86	31				
Sampling device	High vol. sampler									
Sampling media	QFF and PUF									
Flow rate (L/min)	250 L/min, 24h									
Phase	Vapor and Particle									
Particle size	PM <sub>10</sub>									
Extraction	Ultrasonic									
Solvent	Hexane : Benzene : Isopropanol (2 : 2 : 1)									
Analysis	GC/MS									
Quality assurance	SRM1649a									
Nap	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ace	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Acp	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Flu	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Phe	0.96	0.14	0.99	3.46	1.39	7.20	0.86			
Ant	0.08	0.02	0.23	0.40	0.22	2.00	0.19			
Flt	1.44	0.20	0.16	5.23	2.14	5.60	1.29			
Pyr	1.17	0.22	1.43	4.16	1.77	7.30	1.11			
BaA	0.75	0.27	1.19	2.51	1.21	0.50	0.87			
Chry	0.74	0.18	1.15	2.45	1.16	0.90	0.83			
BbF	1.28	0.45	2.41	4.05	2.12	1.20	1.82			
BkF	0.99	0.32	1.88	3.04	1.62	0.20	1.57			
BaP	0.83	0.25	1.76	2.54	1.41	0.50	1.28			
IcdP	1.05	0.30	1.53	2.69	1.43	0.80	1.01			
DahA	0.28	0.07	0.32	0.68	0.34	0.07	0.23			
BghiP	0.81	0.28	1.33	2.15	1.18	1.00	0.75			