

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

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ABSTRACT

This review paper describes the ambient air PAH concentrations in different developing Asian countries, including China, Afghanistan, India, Malaysia, Turkey, Vietnam, Sri Lanka, Thailand and Cambodia. In this study, more than 75 research papers published in the English literature were reviewed with respect to the seasonal and locational concentrations of PAHs in each of 9 different Asian countries. This study compared, discussed and tabulated the PAH concentrations in developing Asian countries over a one decade (2000-2011) period. The PAH concentrations measured in developing countries highlights the necessity to improve the air quality in those countries. Compared to the developed nations in Asia, developing countries are almost one decade away from implementing environmental policies, such as Euro standards. This review discusses the reasons for the high PAH concentrations in developing nations particularly in China and India. Based on the literature available, some suggestions are made to reduce the concentrations of PAHs in the ambient air of developing nations. The total data obtained from the literature survey is tabulated and presented as supplementary information at the end of the manuscript.

Key words: PAHs, Ambient air, Urban areas, Asia, Developing countries, Bezo(a)pyrene

1. INTRODUCTION

Urban air pollution is a severe problem worldwide but the problem is much more serious in Asian continent. This is highlighted from the data produced by the World Health Organization (WHO). The number of deaths caused by urban air pollution is more severe in Asia: approximately 150-400 people per million (WHO, 2009). Asia is the largest continent in the world

and hosts more than 60% of the world population. In contrast to Western countries, most Asian countries were industrialized during the 1990's. Because of the rapid population growth in Asian countries air pollution has gains more attention and alarming warning bells to the human health. Among the range of urban air pollutants, polycyclic aromatic hydrocarbons (PAHs) have attracted increasing attention from atmospheric scientists because of their carcinogenic, mutagenic and teratogenic properties. PAHs are potent air pollutants that consist of fused aromatic rings with no heteroatoms. Naphthalene is one of the simplest PAHs. PAHs are found in oil, coal and tar deposits, and are produced as byproducts of either fossil fuel or biomass burning (Chen *et al.*, 2012). PAHs are also found in cooked foods. For example, high levels of PAHs have been found in meat cooked at high temperatures, such as grilling or barbecuing, and in smoked fish (Larsson *et al.*, 1983).

The literature survey reveals the seriousness of PAHs pollution in developing countries in Asia. No literature review has discussed the concentrations of PAHs overall in Asian countries. This paper discusses the concentrations of PAHs in almost all Asian countries where data is available.

The United States Environmental Protection Agency (EPA) (ATSDR, 2005) listed 16 PAHs as priority pollutants, based on their availability and adverse effects on human health. Those are naphthalene (Nap), acenaphthylene (Acy), acenaphthene (Acp), fluorene (Flu), phenanthrene (Phe), anthracene (Ant), fluoranthene (Flt), pyrene (Pyr), benz[a]anthracene (BaA), chrysene (Chry), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[a]pyrene (BaP), indeno [1,2,3-c,d] pyrene (IcdP), dibenz[a,h]anthracene (DahA), and benzo[ghi]perylene (BghiP). As mentioned in Part-I, for convenience the Asian countries were divided into two groups based on a recent IMF (International Monetary Fund) report (IMF, 2012). The Asian countries listed in the top 30 are considered developed countries and the remaining countries are regarded as develop-

ing countries. The properties, sources and health implications over PAHs on human health are discussed in detail in Part-I (Lakshmi Narayana *et al.*, 2012). This paper (Part-II), reviews the ambient air concentrations of PAHs in urban areas of developing Asian countries since 2000.

2. AMBIENT AIR CONCENTRATIONS OF PAHS IN DEVELOPING ASIAN COUNTRIES

This section discusses the ambient air PAH concentrations reported since 2000 in developing Asian countries, such as China, Afghanistan, India, Malaysia, Turkey, Vietnam, Sri Lanka, Thailand and Cambodia. Table 1 provides a brief description of the papers reviewed from the developing Asian countries.

2.1 China

Zhou *et al.* (2005) reported the ambient air concentrations of PAHs and their size distribution in urban and suburban sites of Beijing. Particulate samples were collected using a five stage cascade impactor fitted with quartz fiber filters during all seasons of 2003 at one urban site and one suburban site. The PAHs were analyzed by GC/MS. They reported 17 PAHs [benzo [e]pyrene (BeP), along with EPA 16 priority PAHs] in both urban and suburban sites. The sum of the 17 PAH concentrations in suburban and urban sites ranged from 0.84 to 118 ng/m³, and 1.4 to 152 ng/m³. The concentrations of total PAHs measured in urban sites were 1.1-1.6 times higher than those in suburban sites. The concentrations of PAHs was also related to the ambient temperature. They observed that the concentrations of PAHs increased with the decreasing ambient temperature. Regarding the size distribution, 68.4-84.7% of PAHs were adsorbed on particles with an aerodynamic diameter $\leq 2.0 \mu\text{m}$. Based on the diagnostic ratios and normalized distribution studies of PAHs, it was clear that Beijing aerosol particles were derived mainly from fossil fuel combustion.

Liu *et al.* (2007a) examined the exposure of on-duty traffic police to PAHs in Beijing. They reported the exposure levels of PAHs by Beijing traffic police during the summer of 2004. Ambient air samples were collected with personal samples for police with polyurethane foam (PUF) holders. Simultaneously, the samples were also collected from fixed control sites, which were away from traffic. The PAHs were analyzed by GC/MS. The mean exposure concentrations of the total 16 EPA priority PAHs in the gaseous phase and particle phase were 1525 ng/m³ and 148 ng/m³, respectively. On the other hand, the same 16 PAH total con-

centrations in the gaseous and particle phase at the control site was 487 and 43 ng/m³, respectively. The results clearly show that traffic police were exposed 2-2.5 times higher levels of PAHs than urban residents who were away from busy streets with vehicles. Wu *et al.* (2006) reported the ambient air PAH concentrations at an urban site and a rural site of Tianjin city during winter 2003-2004. They measured the EPA 16 priority PAHs in both sites, and observed higher concentrations of PAHs at the urban site than rural site. The sum of 16 priority PAHs at meteorological tower in urban site during their first sampling period was measured as 265, 333 and 239 ng/m³ at 20 m, 40 m, and 60 m height, respectively. They found the sum of the 16 EPA priority PAHs during their second sampling period at same sampling site as 409, 537, 359 ng/m³ at 20 m, 40 m, and 60 m height, respectively. They revealed high concentrations of PAHs at a height of 40 m, which indicate that the emissions from coal combustion boiler chimneys contributed more PAHs in particulate samples. They also examined about the size distribution of different PAHs in the particulate samples. They concluded that a mean fraction of 76.5% and 63.9% of the total PAHs is associated with 0.43-2.1 μm particles at rural and urban sites, respectively.

Tan *et al.* (2006) reported the PAHs associated with PM₁₀ in Guangzhou city from March 2002-June 2003. They observed a strong seasonal trend in the concentrations of PAHs in their sampling site. Based on their studies they concluded that vehicular emissions were the predominant source of airborne PAHs in Guangzhou.

Wu *et al.* (2009) measured the EPA 16 priority PAHs in the particulate phase at inside and outside of South Pu-Tuo (SPT), a traditional Buddhist temple in Xiamen during July-August 2006. The concentrations of 16 priority PAHs was compared with two other sites, i.e., a bus terminal and University campus in Xiamen. The total suspended particles were collected with a medium volume sampler at a flow rate of 100 L/min, from 8.30 a.m.-5.30 p.m. during the sampling days. The samples were analyzed for PAHs with GC/MS. The total 16 PAH concentrations at SPT, bus terminal and University campus ranged from 19.16-119.48 ng/m³, 33.32-123.28 ng/m³, and 8.06-34.37 ng/m³, respectively. The total 16 priority PAH concentrations was comparable at both the temple and bus terminal, but the BaP equivalent concentration at the temple (7.1-26.3 ng/m³) was much higher than at the bus terminal (5.1-6.9 ng/m³). The BaP concentration at the temple was not in the acceptable range compared to the concentration recommended (1 ng/m³) by the State Environmental Protection Administration of China. The main reason for the higher concentration of BaP at temple was the

Table 1. Brief description of the reviewed papers in Developing Asian countries.

S. No.	Country	Site characteristics	Season (s)	No. of samples	Phase/ Particle size	Quality assurance	Analysis	Reference
1	China	Urban	–	–	Particle (TSP)	–	GC/MS	Duan <i>et al.</i> , 2005
		Urban, Sub-urban	Winter, Autumn	–	Particle (TSP)	–	GC/MS	Wu <i>et al.</i> , 2005
		Residential and Commercial	–	29	Particle (TSP & PM _{2.5})	SRM 1649a	GC/MS	Deng <i>et al.</i> , 2006
		Industrial, Residential, traffic	All	51	Vapor (PUF) Particle (TSP)	–	GC/MS	Li <i>et al.</i> , 2006
		Near High way	All	57-64	Particle (TSP)	SRM 1649a	HPLC/FLD	Okuda <i>et al.</i> , 2006
		Residential	All	–	Particle (TSP)	–	GC/MS	Duan <i>et al.</i> , 2007
		Road side	Summer	4-11	Particle (PM ₁₀ & PM ₁₀₀)	–	GC/MS	Hu <i>et al.</i> , 2007
		Residential and Traffic	–	10	Particle (Airborne particulates)	–	GC/MS	Liu <i>et al.</i> , 2007b
		University campus	Winter	10	Vapor (PUF) Particle (TSP)	–	GC/MS	Liu <i>et al.</i> , 2007c
		–	–	–	Particle (PM ₁₀ & PM _{2.5})	–	GC/MS	Wang <i>et al.</i> , 2007
		Urban	–	48	Vapor (PUF) Particle (TSP)	–	GC/MS	Ma <i>et al.</i> , 2010
		University campus	All	94	Particle (TSP)	SRM 1649a	HPLC/FLD	Okuda <i>et al.</i> , 2010
		Commercial	All	5	Particle (PM ₁₀)	–	GC/MS	Shi <i>et al.</i> , 2010
University campus	All	40	Vapor (PUF) Particle (TSP)	–	GC/MS	Ma <i>et al.</i> , 2011		
2	Afghanistan	Military campus	Autumn	14	Particle (PM _{2.5})	SRM 1649b	GC/MS	Wingfors <i>et al.</i> , 2011
3	India	Institution	Rainy season	13	Vapor (PUF) Particle (TSP)	–	HPLC/UV	Sahu <i>et al.</i> , 2004
		Residential, Industrial	All	53	Particle (PM ₁₀)	–	GC/FID	Karar and Gupta, 2006
		University campus	Winter, Summer	14-16	Particle (PM ₁₀ & PM _{2.5})	–	GC/MS	Singh <i>et al.</i> , 2011
4	Malaysia	University campus	–	19	Particle (PM ₁₀)	–	GC/MS	Omar <i>et al.</i> , 2006
5	Turkey	Institutional and Residential	–	20	Vapor (PUF & XAD-2) Particle (TSP)	–	GC/MS	Tasdemir and Esen, 2007
		Industrial	Summer, Winter	14	Vapor (PUF & XAD-2) Particle (TSP)	–	GC/MS	Bozlaker <i>et al.</i> , 2008
		Suburban, Urban	–	63	Vapor (PUF) Particle (TSP)	–	GC/MS	Demircioglu <i>et al.</i> , 2011
		Urban, Rural	–	135	Vapor (PUF) Particle (TSP)	SRM 1649a	HPLC/UV and FLD	Hanedar <i>et al.</i> , 2011
6	Vietnam	Residential and traffic	–	46-60	Particle (TSP)	–	HPLC	Hien <i>et al.</i> , 2007b
7	Sri Lanka	Urban	–	–	Particle (PM ₁₀)	–	HPLC/UV	Wickramasinghe <i>et al.</i> , 2011
8	Thailand	Urban	Summer	89	Particle (TSP)	–	HPLC/UV	Ruchirawat <i>et al.</i> , 2002
		Urban road side	–	–	Particle (TSP)	–	HPLC/UV	Ruchirawat <i>et al.</i> , 2005
		Urban down town and University campus	–	–	Particle (TSP)	–	HPLC/FLD	Tekasakul <i>et al.</i> , 2008
9	Cambodia	River side, Mountain area and Urban	–	23	Particle (TSP)	–	HPLC/FLD	Furuuchi <i>et al.</i> , 2007

burning of incense. In the same city, at a busy traffic site, Wu *et al.* (2010) measured the PAH concentrations to understand the day-night variations in their concentrations. The concentrations of PAHs were measured at the specified traffic site during October-December, 2008 using a high volume sampler with a flow rate of 1130 L/min. The day time samples were collected from 8.00 am-7.00 pm, and the night samples were collected from 8.00 pm-7.00 am in the next day. The sum of the measured 19 PAH [BeP, perylene (Pery) and coronene (Cor) are additional to the EPA priority 16 PAHs] concentrations during night time in the colder sampling period was significantly different from that at day time during the same period. This may be due to thermal inversion following low temperatures and high atmospheric pressures in the colder period.

Liu *et al.* (2007b) reported the atmospheric concentrations of PAHs in north China during winter (November 2005-February 2006). They found that the concentrations of PAHs was higher in northern China than in other developed countries and southern Chinese cities. They predicted that the major reason and source for the high concentrations of PAHs was biomass and domestic coal combustion in their study area. Wu *et al.* (2007) reported the characterization of PAHs bound to the total suspended particulate matter at rural and urban sites of Tianjin during the winter season (15 November 2003-15 March 2004). They concluded coal combustion to be the major source for PAHs in both rural and urban sites of Tianjin during winter. Another important issue was that the high molecular weight PAHs comprised approximately 90% in the total concentrations. Tao *et al.* (2007) reported the vertical distribution of PAHs in the atmospheric boundary layer of Beijing in the winter season of 2006. They studied the altitudinal distributions of PAHs in the atmospheric boundary layer of Beijing in winter at different heights ranging from 8 m to 320 m. Wang *et al.* (2011) reported the gas and particle phase PAHs concentrations at a background site (Xiaolongmen), two rural village sites (Gubeikou and Donghe) and at an urban site (Beijing) in the north China plain during September 2007-August 2008. Duan *et al.* (2005) reported a difference in the size distribution of PAHs between urban and rural sites of Guangzhou city during October-December 2003. Duan *et al.* (2007) reported the concentrations of PAHs in four seasons during August 2003-April 2004 at the same site. They measured 13 PAHs (except Nap, Ace, and Acp in EPA 16 priority PAHs) at the specified sites.

Wu *et al.* (2005) analyzed the distribution of particle phase PAHs in Tianjin during winter and autumn seasons. They found higher concentrations of PAHs in winter than in autumn at their study sites. In their

study, they found a very high range of BaP concentrations (12.92-218.98 ng/m³) at an industrial site.

Deng *et al.* (2006) measured the atmospheric concentrations of PAHs associated with PM_{2.5} and the total suspended particulate matter at an electronic waste recycling site in Guiyu (southeast China) during August-September 2004. Li *et al.* (2006) reported the vapor and particle phase concentrations of PAHs at Guangzhou during April 2001-March 2002. Based on seasonal variation studies, they found higher concentrations of PAHs during winter than summer. The reasons for high PAHs concentrations in winter were attributed to enhanced vehicle exhaust at low temperature and accumulation of pollutants in decreased boundary layer, slower wind speed, and long term dryness conditions. Okuda *et al.* (2006) reported the particle phase PAHs at Tsinghua University campus (located to near highway) during September 2003-April 2005. They examined the change in the concentrations of PAHs in the heating and non-heating seasons. They found very high amounts of PAHs in the heating season compared to the non-heating season. They predicted the reason for high concentrations of atmospheric PAHs during winter due to coal combustion for residential heating.

Hu *et al.* (2007) reported the exposure of traffic police to PAHs in Tianjin city during summer (July-August) in 2005. Liu *et al.* (2007c) reported the concentrations of particulate PAHs at a residential and traffic sites of Beijing during December 2004-August 2005. In their study, they found high concentrations of PAHs in the month of December. Liu *et al.* (2007d) reported the inhalation exposure of traffic police officers to PAHs during the winter of 2005. They compared the concentrations of PAHs exposure to the police with a background site away from busy streets and traffic. Wang *et al.* (2007) examined the concentrations of PAHs associated with PM₁₀ and PM_{2.5} in Xiamen city during December 2004.

Ma *et al.* (2010) reported the atmospheric concentrations of PAHs at an urban site of Harbin city, northeast China during the heating and non-heating seasons (August 2008-July 2009). They carried out a comprehensive study of the seasonal variations and sources of PAHs at their study site. Okuda *et al.* (2010) measured the PAHs concentrations at Xi'an city during October 2005-October 2007 using automated column chromatography followed by HPLC/fluorescence detection. Shi *et al.* (2010) characterized the PM₁₀ bound PAHs concentrations in urban city of Tianjin during April 2008-January 2009. Ma *et al.* (2011) reported the atmospheric concentration, sources and gas-particle partitioning of PAHs in Beijing after the 29th Olympic games (September 2008-July 2009).

2.2 Afghanistan

Wingfors *et al.* (2011) analyzed the PAHs in two military camps in Afghanistan cities, namely Kabul and Mazar-e-Sharif (MeS). Kabul and MeS is the largest and fourth largest cities in Afghanistan, respectively. In Kabul and MeS, samples were collected from 19 October-2 November 2009 and 20 October-3 November 2009, respectively. They measured the concentrations of PAHs associated with PM_{2.5}, which was collected using impact sampling heads (connected to electric pumps) with a flow rate of 10L/min. They analyzed the PAHs by GC/MS. The authors also collected air samples in Ume city of Sweden from 14 April-18 April 2010. The PAH concentrations in two cities of Afghanistan and Ume city of Sweden were compared. The accuracy and reproducibility of the method was checked with SRM 1649b (Urban dust, NIST, MD, USA). They measured the concentrations of 15 PAHs, but of these, 13 PAHs were listed in EPA priority PAHs. The measured priority PAHs were Ant, BaA, BbF, BkF, BghiP, BaP, Chry, DahA, Flt, IcdP, Phe, Pyr and BeP. Their results clearly showed high concentrations of BaP in ambient air of Kabul and MeS cities. In particular, in Kabul, the concentration of BaP was much higher (15-50 ng/m³) than in the other cities. The concentrations of measured PAHs in Ume city of Sweden was much lower than in Afghanistan cities. Based on these studies, authors predicted poorer air quality in urban locations of Afghanistan than in Western countries. According to them, traffic and the combustion of coal and biomass were the main sources of the high levels of particulate-bound organic compounds (including PAHs) in ambient air.

2.3 India

Sharma *et al.* (2007) measured the concentrations of various PAHs in the total suspended particulate matter (TSPM) in New Delhi, the capital city of India, during 2002 to 2003. They selected 12 PAHs for their study, namely Ant, BaP, BaA, BbF, BkF, BghiP, Chry, DahA, Flt, IcdP, Phe and Pyr. They determined the above mentioned PAHs in ambient air at Jawaharlal Nehru University campus, New Delhi. Air borne particles were collected on glass-fiber filter paper (8'' × 10'') over a 24 h period during the sampling period. The total year was classified into four seasons, winter (December, January, and February), summer (March, April, May), monsoon (June, July, August) and post monsoon (September, October, November). The authors analyzed the PAHs according to the USEPA, Method TO-13A (USEPA, 1999). The annual mean concentrations of total PAHs (twelve) were found to be 668 ± 399 and 672 ± 388 ng/m³ in the years 2002 and 2003, respectively. These results show that the concentrations of

PAHs was higher in the winter months than in the summer and monsoon months. The authors attributed the reason for the higher concentrations of PAHs in winter to the increased emissions from the higher consumption of fossil fuels for heating purposes, larger traffic volumes and less dispersion due to meteorological conditions. At the same location of New Delhi, Shankar (1990) reported the total (eight) PAH concentrations in ambient air (406 ng/m³). Sharma *et al.* (2007) reported the sum of the same eight PAH concentrations to be 434 and 413 ng/m³ in 2002 and 2003, respectively. The increase in PAHs levels might be due to an increase in vehicular traffic in New Delhi (3.4 million registered vehicles). Their results suggested diesel and gasoline vehicles to be the main sources of PAHs in all seasons.

Mumbai is the largest metropolitan city in India with a population of more than 19 millions and surrounded by thousands of small and medium scale industries including petrochemical, fertilizers and power plants. Kulkarni and Venkataraman (2000) measured the atmospheric particulate PAH concentrations at two locations [Regional telecommunications training centre at Saki Naka (SN), and Indian Institute of Technology (IIT), Bombay] during the winter of 1996 (November and December). They measured the ambient concentrations of seven PAHs, such as Pyr, Flt, BaA+Chry, BbF, BaP, BkF and IcdP, at the above two locations. The particulate ambient air samples were collected on glass fiber filters using an eight-stage Andersen impactor. The samples were analyzed for PAHs by HPLC with a UV absorption detector. The total PAH concentrations (seven compounds) at Saki Naka and IIT were 38.8 and 24.5 ng m⁻³, respectively. The measured ambient PAH concentrations showed that Pyr and BaA+Chry are abundant at both sites. The high Pyr concentration in the ambient samples in Mumbai were attributed to cooking fuel combustion. Based on previous studies (Harrison *et al.*, 1996; Venkataraman and Friedlander, 1994; Rogge *et al.*, 1993a, b) and their current study, they predicted the sources for the individual PAHs in ambient air. The sources for individual PAHs in ambient air an urban atmosphere is as follows: Phe, Flt and Pyr (coal combustion); Ant, Phe, and BaP (coke production); Pyr, Phe and Flt (incineration); BaP and Flt (wood combustion); Flt, Pyr and Chry (industrial oil burning); BghiP, IcdP and Cor (petrol powered vehicles); Flt and Pyr with higher ratios of BbF and BkF (diesel powered vehicles).

Prajapati *et al.* (2008) reported the bio monitoring ability of *Ficus benghalensis* leaves to seasonal variations in PAH concentrations. They selected Varanasi city, which is one of the oldest cities in the world. In this city, they collected the leaves of *Ficus benghalensis*.

sis from six different sites during August 2005, January 2006 and May 2006, and found the highest leaf PAH concentrations in January 2006 (1240-3358 ng/g) followed by May 2006 (775-1210 ng/g) and August 2005 (630-965 ng/g). The result revealed the maximum PAH concentrations in leaves of *Ficus benghalensis* in winter (January 2006) season.

Ravindra *et al.* (2006) assessed the PAH concentrations in ambient air in Delhi before and after implementing Compressed Natural Gas (CNG) as a fuel to public transport instead of gasoline and diesel. In Delhi, CNG was used in public transport from 2001. The authors measured the ambient air PAH concentrations adsorbed on PM₁₀ from January to March 2003. They observed higher concentrations of PAHs in winter than in the other seasons. They measured the concentrations of ten PAHs (Flt, Pyr, BaA, Chry, BbF, BkF, BaP, DahA, BghiP and IcdP) in ambient air at two sites of Delhi, Bahadur Shah Zafar (BSZ) road and Siri Fort (SF). The PM₁₀ samples were collected using an APM-460 RDS (Envirotech, Delhi) respirable dust sampler. The flow rate was maintained at 800-1200 L/min. During the sampling period, the total average of ten PAH concentrations for the BSZ and SF sites were 11.5 ng/m³ and 4.52 ng/m³, respectively. They concluded that the PAH levels were lower in the ambient air of Delhi after the implementation of CNG to the public transport from a comparison of the above PAH concentrations with the previous data available.

Khillare *et al.* (2008) reported a comparative assessment of the concentrations of PAHs in Delhi before and after the implementation of compressed natural gas (CNG). In Delhi, the government implemented a new policy i.e., replacement of fuel gases with CNG in all public transport vehicles to reduce the level of particulate matter in the ambient atmosphere in 2002. The authors reported the concentrations of PAHs associated with PM₁₀ in Delhi at all seasons in 1998 and 2004, before and after implementation of the CNG policy. The concentrations of total PAHs was reduced by up to 51-74% compare to the pre-CNG data. They measured the ambient air concentrations of PAHs at three different sites in Delhi. Before implementing the CNG policy, the BaP concentrations at three different sites ranged from 0.95-29.82 ng/m³, whereas it was 0.53-7.24 ng/m³ after implementing the CNG policy, showing a sharp decrease.

Karar and Gupta (2006) reported the seasonal variations and chemical characterization of ambient PM₁₀ at residential and industrial sites of an urban region of Kolkata during November 2003-November 2004. They measured the concentrations of Flt, Pyr, BaA, BbF and BaP at the specified sites. The major PAH com-

pound at their monitoring sites was BbF, which was 30 ng/m³ and 20 ng/m³ at residential and industrial sites, respectively. Regarding the seasonal variations in the concentrations of PAHs, they found higher levels in winter than in summer due to temperature inversion, leading to an accumulation of pollutants over the city. Sahu *et al.* (2004) reported precipitation scavenging of PAHs in Mumbai. They collected rain water and air samples simultaneously during thirteen rain events between the last week of May and the end of June 2001. Based on their studies, they concluded that the gas phase scavenging ratio increased with increasing molecular weight of PAH. The particle phase scavenging ratio values were higher for the volatile PAHs than the less volatile PAHs.

Recently, Mohanraj *et al.* (2011a, b) reported the concentrations of particulate PAHs in two major southern Indian cities, i.e. Chennai and Tiruchirappalli. Singh *et al.* (2011) examined the concentrations of EPA 16 priority PAHs associated with both PM₁₀ and PM_{2.5} in the eastern part of Delhi during winter and summer period of 2007-2008. In their studies, they revealed higher concentrations of PAHs in winter than in summer. The low molecular weight PAHs (2-3 ring) contributed a lower fraction in the total PAHs, and a higher fraction in the high molecular weight PAHs ranging from 80.1% to 95.2%. The reason for this might be the combustion of petroleum fuels. They observed high concentration of IcdP in both PM₁₀ and PM_{2.5} in winter but BkF was found at higher concentrations in summer.

2.4 Malaysia

Omar *et al.* (2006) reported the concentrations and profiles of PM₁₀-bound PAHs in the ambient air of Kuala Lumpur, the capital city of Malaysia. The authors also compared the results with earlier results (Abas *et al.*, 2004; Omar *et al.*, 2002) obtained in the same city. They collected the ambient air samples at University of Malaya (UM), Kuala Lumpur during 22 March-12 December 2001. A high volume air sampler fitted with annealed glass fiber filters was used for ambient air sampling. The PAHs bound to PM₁₀ was analyzed by GC/MS. Quality control was maintained by comparing the retention times with those of external standards. Abas *et al.* (2004) reported the concentrations of PAHs in Kuala Lumpur during haze episodes (during forest fires), but Omar *et al.* (2002) reported the concentrations of PAHs in street level particulate matter (PM) and soil of the same city.

The main PM₁₀ bound PAHs observed in the ambient air at UM were BaP, BbF, BeP, BghiP, BkF, Chry, Cor, IcdP, and Pyr. The UM PAH concentrations were lower than those reported earlier in the same city dur-

ing the clear (street level PM and soil) and haze conditions. During clear and haze conditions, they observed high concentrations of BbF and BkF, which was related to biomass burning. On the other hand, at UM they observed high concentrations of BghiP than other PAHs, which was mostly associated with vehicular emissions. Based on their results obtained at UM, they concluded the main source of particulate PAHs at this site to be vehicular emissions. At UM site, they found only 3% medium molecular weight PAHs (4 ringed PAHs) and did not find low molecular weight (2- and 3-ring PAHs) PAHs. This might be due to sample ageing and exposure to solar radiation. At this site they found 97% high molecular weight PAHs (5-, 6-, 7-ring PAHs).

They discussed the health risk assessment of PAHs based on BaP equivalent concentration at three conditions (UM, Haze, Street PM). The potential health risk of the haze smoke particles was 4 times higher than that of street level particles, which was 2 times higher than that of ambient particles.

2.5 Turkey

Gaga *et al.* (2011) reported the gas-particle partitioning of PAHs in an urban traffic site in Eskisehir, Turkey. The city has a population of 570,000 and is surrounded by many small-sized industries that use natural gas as fuel. They suggested that the main sources for PAHs in this city were residential heating fuels and traffic. Forty-one ambient air samples were collected in winter (January-March 2006) and fifty five samples were collected in summer (July-Sep 2006) with a flow rate of 225 L/min using a PUF sampler. The sampling duration was 24 h. With the exception of Nap, the remaining 15 PAHs in the EPA priority PAHs list were found and analyzed by GC/MS. Based on their results, they concluded that on average, 66% and 69% of the total concentrations of PAHs was found in the gas-phase in the heating and non-heating period samples, respectively. At the same time, the PAH concentrations in the heating season was seven to eight times higher than the concentrations in the non heating season. Meteorological parameters, such as wind speed and wind direction had a larger influence on the measured PAH concentrations.

Esen *et al.* (2008) reported the atmospheric concentrations of PAHs in residential areas of Bursa (a major city with a population around 1.2 millions). The atmospheric PAH concentrations were measured in Bursa between August 2004 and April 2005. The total sampling period divided into heating and non-heating seasons. Twenty air samples were collected in the sampling period with a flow rate of 160 L/min using a high volume sampler. The sampling duration was 26 h. The

particles were collected on glass fiber filters, and vapor samples were collected on PUF and XAD-2. The PAH concentrations were analyzed by GC/MS. In the non heating and heating seasons the total concentrations (gas+particle) of 14 PAHs (except Nap and acenaphthylene in EPA priority 16 PAH list) ranged from 28.6-324.0 ng/m³ (mean 152.5 ng/m³), and 288.5-1672.0 ng/m³ (mean 1249.4 ng/m³), respectively. The total PAH concentrations in the heating season were almost ten times higher than those in the non-heating season. They suggested that the reason for the high concentration of PAHs in the heating season than non-heating season was the burning of large amounts of coal and wood for heating and the greater emissions from traffic due to cold ignition. This was further confirmed by their diagnostic ratios and factor analysis studies. In the same city, Bursa, Esen *et al.* (2006) measured the atmospheric concentrations of 15 PAHs (except Nap in EPA 16 priority PAHs list) between July 2004 and May 2005. Twenty five ambient air samples were collected in the sampling period (except rainy days) with a flow rate of 170 L/min using a high volume sampler. The particles were collected on glass fiber filters and vapor samples were collected on XAD-2 and PUF, and analyzed by GC/MS. The measured average concentrations of PAHs for summer, fall, winter and spring were 55 ± 40, 187 ± 202, 645 ± 588 and 148 ± 132 ng/m³, respectively. Based on their gas/particle partitioning studies they found that 76% of the total (gas+particle) PAH concentrations were in the vapor phase. They attributed the large variations in the concentrations of PAHs to residential heating, vaporization, industrial activities and meteorological conditions.

Tasdemir and Esen (2007) reported the atmospheric concentrations, temporal changes and gas/particle partitioning at a traffic site of Bursa city during August 2004-May 2005. They measured and compared the EPA 16 priority PAHs concentrations in Bursa and to the other major cities in the world like Chicago, London, and Tainan. In their study, they reported high concentration of BaP than in the other cities they compared. Bozlaker *et al.* (2008) reported the atmospheric concentrations, dry deposition and air-soil exchange of PAHs in an industrial site of Izmir city during August 2004 and March-April 2005. They found that the specific site has lower concentrations of PAHs than the other major cities, they compared. In the same city of Izmir, Demircioglu *et al.* (2011) reported the particle phase dry deposition and air-soil exchange of PAHs during May 2003-May 2004. Hanedar *et al.* (2011) examined the concentrations and sources of PAHs at three different sites in Istanbul during September 2006-December 2007. In their study, they found that the

vehicle emissions to be the major sources of PAHs in their specified sites.

2.6 Vietnam

Hien *et al.* (2007a) reported particle-phase PAHs and their variability causes in the ambient air in Ho Chi Minh City, Vietnam and in Osaka, Japan during 2005-06. Hien *et al.* (2007b) examined the distribution characteristics of PAHs according to particle size in urban aerosols at the road side in Ho Chi Minh city, Vietnam. In their study, they concentrated on the PAH concentrations, particle size distribution and seasonal variations at a road side in the Ho Chi Minh City. The samples were collected during the dry season (January-February 2005) and rainy season (July 2005) using a low pressure cascade impactor. The particles were separated into nine fractions. The first fraction contained the particles $>9 \mu\text{m}$ in size, whereas the last fraction contained the particles $<0.4 \mu\text{m}$ in size. In this study, they found ten PAHs in the ambient air of the selected site. They were Flt, Pyr, triphenylene, BaA, Chry, BbF, BkF, BaP, BghiP and IcdP. The separation and identification of these PAHs were performed using a HPLC fluorescence detector. The sum of the above-mentioned PAHs in ambient air of Ho Chi Minh City were 44.1 and 67.0 ng/m^3 in the dry and rainy seasons, respectively. They observed high PAH concentrations during the rainy season. Regarding the relationship between the size distribution of the particulate matter and PAH concentrations, almost 80% of the total PAHs were in fine particles $<2.1 \mu\text{m}$ in size. The variation of the PAH concentrations in the two seasons may be affected by the wind direction and wind speed but not temperature because the mean temperature did not show considerable variations during the sampling periods.

2.7 Sri Lanka

Kandy is the one of the most popular tourist spots in Sri Lanka. This is a world heritage city and rapidly urbanizing area in Sri Lanka. The city population has grown to $>150,000$. In addition, the city attracts approximately 100,000 tourists per day. The estimated 24 h traffic flow entering and leaving the city was 106,000, which indicates high levels of vehicular emissions over a limited land area ($\sim 4 \text{ Km}^2$) of the city main core. Wickramasinghe *et al.* (2011) reported the concentrations of EPA 16 priority PAHs bound to PM_{10} in ambient air of Kandy city, Sri Lanka. The sampling of PM_{10} -bound PAHs was performed for eight hours (from 9 A.M.) with a high volume sampler (Envirotech-APM 460) from July 2008-March 2009. The particulate matter fraction of ambient air was collected on glass micro fibre filters. The sampling

and analysis of PAHs was performed according to a modification of the procedure developed by Wickramasinghe and Karunaratne (2008) based on the US EPA Compendium method TO-13A (US EPA, 1999). The PAHs were analyzed by HPLC. They reported the 8 h average concentrations of the total PAHs bound to PM_{10} . The urban area was divided into Urban Heavy Traffic (U/HT) ($>15,000$ vehicles d^{-1}) and Urban Light Traffic (U/LT) (2,000-15,000 vehicles d^{-1}). In the U/HT area of Kandy city, the total 16 PAH concentrations ranged from 191.05-1246.12 ng/m^3 (mean = 695.94 ng/m^3), whereas the mean concentrations were 105.55 ng/m^3 in U/LT. In their studies, they determined the average concentration of BaP during the sampling period at the U/HT and U/LT areas to be $\sim 50 \text{ ng}/\text{m}^3$ and $\sim 40 \text{ ng}/\text{m}^3$, respectively.

2.8 Thailand

Ruchirawat *et al.* (2002) examined the exposure of Bangkok Royal Thai police to genotoxic compounds with an analysis of PAHs associated with the particles in ambient air. Ambient air particulates were collected on glass fiber filters (37 mm) using personal samplers (battery operated) with a flow rate of 2 L/min, which is the breathing zone of police officers. The extraction and analysis of PAHs were performed using a modified US EPA TO-13 method. They analyzed the PAH concentrations with HPLC-UV and fluorescence detectors. In this study the authors mainly concentrated mainly on eight carcinogenic PAHs, namely BaA, Chry, BbF, BkF, BaP, DahA, BghiP and IcdP. The traffic police officers were divided into two groups: high exposure group (working in traffic) and low exposure group (working in an office). The sum of the eight PAHs that the police officers in traffic and in the office were exposed to was 72.79 ng/m^3 and 6.88 ng/m^3 , respectively. They concluded that the police officers working in traffic are exposed 20 times higher total PAHs levels than officers working in an office. They found BghiP to be the major PAH that traffic police are exposed to. The same authors performed a similar study (Ruchirawat *et al.*, 2005) on street vendors, monks and nuns, grilled-meat vendors and school children in Bangkok. They measured the ambient air PAH concentrations at five different sites (on the road, road side, temple, school area and class room) in Bangkok city. They found that the total PAHs in these sites ranged from 7.10-83.04 ng/m^3 . Based on their exposure study they concluded that the grilled-meat vendors were highly exposed to PAHs compared to the others. Tekasakul *et al.* (2008) analyzed the atmospheric PAH concentrations and size distribution in the city, Hat Yai, southern Thailand. The atmospheric PAH concentrations in Hat Yai city was influenced mainly by rubber

sheet production, wind direction and precipitation. Hat Yai city is mostly surrounded by rubber industries. Air samples were collected with a high volume sampler at the downtown area of Hat Yai and Prince of Songkla University (PSU) in the year 2005. Downtown of Hat Yai city is a heavy traffic area but the PSU campus has low traffic. Both sites are surrounded by many rubber smoking cooperatives. The size distribution of particulates was also carried out with 8-stage cascade impactors. The flow rate of ambient air sampling was maintained at 500 L/min for 24 h. Based on their studies, they suggested that the PAH concentrations in both sites were directly proportional to the rubber production in the surrounding industries. They compared the ambient PAH concentrations in those sites with the rubber production in the nearby industries. Along with rubber production the concentrations of PAHs in the two sites was affected significantly by the wind direction and precipitation.

Boonyatumanond *et al.* (2007) measured the PAH concentrations in ambient air of Bangkok city (different sites) during November 2003-January 2004. They collected ambient air samples using a high volume sampler at a flow rate of 1000 L/min for 24 h. They measured both the particulate and vapor phase PAHs in different sites of Bangkok. The analysis of PAHs was carried out using GC/MS. The mean total PAH concentrations at the measured urban sites were 19.1 and 111 ng/m³ in the particulate and vapor phase, respectively. The PAHs found in the study sites were Phe, Ant, 1-methylphenanthrene, 2-methylphenanthrene, 3-methylphenanthrene, 9-methylphenanthrene, Flt, Pyr, BaA, Chry, BbF, benzo[j]fluoranthene (BjF), BkF, BeP, BaP, Pery, IcdP, BghiP and Cor.

2.9 Cambodia

Furuuchi *et al.* (2007) examined the characteristics of ambient particle-bound PAHs in the Angkor monument area of Cambodia. They selected four sites in and around Angkor wat monument and Siem Reap (lake). Using a high volume sampler, TSPM (Total Suspended Particulate Matter) was collected at the specified sites during May 2005-November 2006. All samples collected in these sites were transported to Japan and analyzed for 15 PAHs (except Acy, in the EPA priority PAHs) by HPLC with a fluorescence detector. The PAH concentrations in the city site were always greater than in the other sites. During the rainy season (southwest monsoon) the PAH concentrations at Angkor Wat was similar to the concentrations at the city site, whereas they were similar to the rural areas during north or northeast monsoon. This suggests that PAHs are transported from the city to the monument area in the rainy season. They also studied the seasonal

variations in the PAH concentrations at the specified sites. The sum of the mass fraction of 4-6 ring PAHs were compared with other Asian cities, such as Kanazawa, Japan, Phnom Penh city, Cambodia and Bangkok, Thailand. The PAH concentrations were higher in their studied sites than in the other cities they compared.

3. DISCUSSION

Measuring the PAHs in ambient air is a hot topic around the world because clean air is very important to public health, which also plays a crucial role in the economic growth of a country. Developed countries in the world have already implemented environmental policies to reduce the air pollution, but less work has been done in this area by developing countries. For example, the European Union (EU) adopted catalyst-forcing standards for new gasoline-fuelled cars in the early 1990s (commonly considered as the Euro 1 standards), and gradually tightened them in several steps by implementing Euro 2 in 1996, Euro 3 in 2000, Euro 4 in 2005 and Euro 5 in 2008. Valerio *et al.* (2009) reported that with the implementation of the Euro standards, the reduction in air pollution estimated for the complete substitution of non-catalytic gasoline vehicles was 89% for BaP, 85% for the total PAHs. Rhys-Tyler *et al.* (2011) have reported the significant decrease in hydrocarbon emissions from petrol cars in London with the introduction of each successive Euro emissions standard from Euro 1 onwards. The implementation of new vehicle emissions standards will be facilitated if governments announce a schedule for tightening the requirements well in advance. The majority of Asian countries have adopted the Euro 1 standards to regulate new car and truck emissions but only a few countries have implemented the subsequent Euro 2, 3, 4 and 5 standards (http://www.adb.org/documents/guidelines/vehicle_emissions/im_ch03.pdf). Many Asian countries (Sri Lanka, Vietnam, Malaysia, Thailand, India, and China) are far behind the European new vehicle standards and fuel requirements by approximately a decade. On the other hand, in recent years, developing countries also implemented some policies to reduce the concentration of air pollutants. For example in New Delhi (India), CNG (Compressed Natural Gas) was implemented for public transport vehicles in 2001. Ravindra *et al.* (2006) reported a decrease in the concentrations of PAHs in ambient air of New Delhi after the implementing the above policy. Similarly, the Indian government implemented Euro 4 emission norms in New Delhi from April, 2010 (The Times of India, March 26, 2010).

Nevertheless, these norms have not been extended to other major cities in India. In Beijing, China, the Euro 4 emission norms were also implemented from 2008. This type of tightening of environmental policies in developing countries will reduce air pollution particularly PAHs. For this, social awareness is also important because these policies will not succeed without the participation of the public. Another major concern regarding air pollution is the urbanization of Asian countries. Most Asian cities, such as Delhi, Mumbai (India), Shanghai, Beijing (China), Istanbul (Turkey), are undergoing rapid urbanization (Der Duh *et al.*, 2008), which is expected to causes more air pollution if the regulatory policies are not effective.

The concentrations of PAHs throughout the year may not be the same: it is mostly seasonal dependent. The most important factor affecting the concentrations of PAHs in ambient air is temperature. Most researchers reported the high concentrations of PAHs in the winter season of the year irrespective of the nation in Asia (Singh *et al.*, 2011; Ma *et al.*, 2010; Okuda *et al.*, 2010; Duan *et al.*, 2007; Okuda *et al.*, 2006; Wu *et al.*, 2005; Guo *et al.*, 2003). The reasons for the high concentrations of PAHs during winter than the other seasons may be the low temperature, slower photolysis and radical degradation rates. Residential solid fuel combustion including straw, firewood and coal dominated the pattern of the overall seasonal variation with a peak in winter (Zhang and Tao, 2008). The low temperature in winter produced favorable conditions for the condensation or sorption of PAHs on suspended particles in air. On the other hand, gas phase PAHs are influenced mainly by condensation or sorption (Sklorz *et al.*, 2007). Therefore, the concentrations of PAHs in ambient air depends on meteorological factors, such as temperature, wind direction and wind speed.

Another important issue regarding PAHs is the ambient air concentration of Nap. Many researchers did not measure the Nap concentration along with the other PAHs despite being toxic (Preuss *et al.*, 2003). The California EPA (California EPA, 1997) has considered Nap to be a hazardous compound and given its unit risk value. Napthalene in ambient air exists in both vapor and particle phases, but most of it is in the vapor phase. The sampling medium (filter or PUF or XAD) plays an important role in the measuring the concentration of Nap. The concentration of Nap measured by XAD will be higher than that measured with PUF at the same site. Furthermore, it will be higher when measured with adsorption tubes than with XAD. Determination of Nap concentration in ambient air is always a challenging task to researchers. To avoid this difficulty, most researchers measured the PAH concentrations in the particulate phase only and ignored the

measurement of Nap (Esen *et al.*, 2006; Guo *et al.*, 2003). Although they measured both vapor and particulate phase PAHs they found small amounts of Nap (Ma *et al.*, 2011; Ma *et al.*, 2010; Li *et al.*, 2006). This may be due to the gaps in the knowledge of measurement techniques. This literature survey revealed considerable uncertainty in the determination of the concentration of Nap. The researchers did not provide accurate measurements of the ambient air concentration of Nap. Therefore, in future, researchers should concentrate on accurate determination of the Nap con-

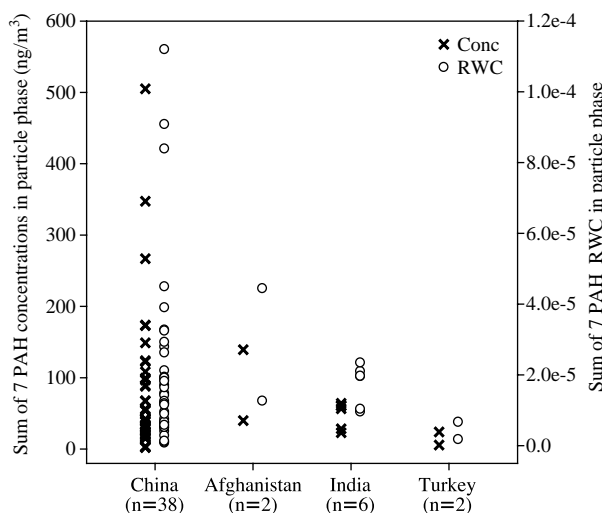


Fig. 1. Sum of 7 PAH concentrations and RWC in developing Asian countries (The 7 PAHs are: BaA, Chry, BbF, BkF, BaP, IcdP and DahA).

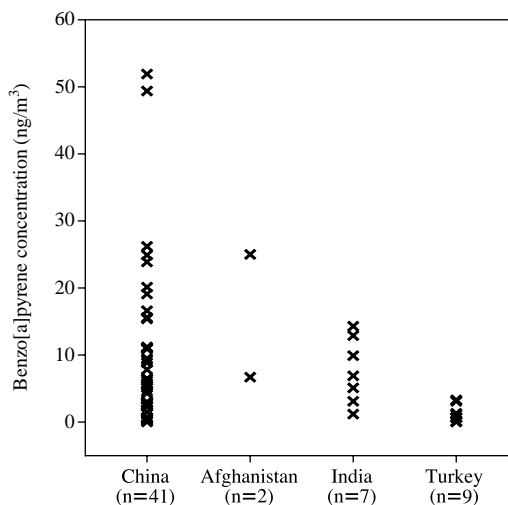
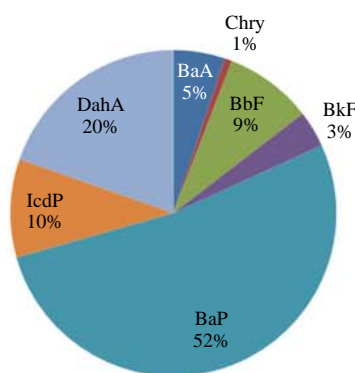
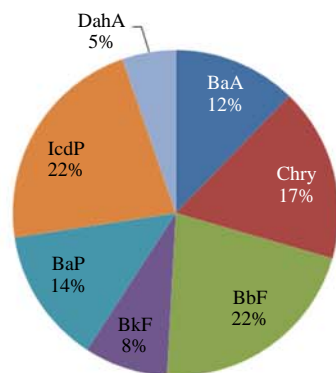


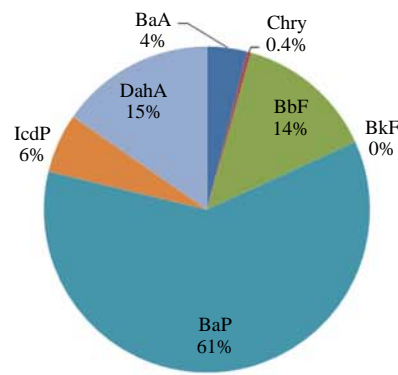
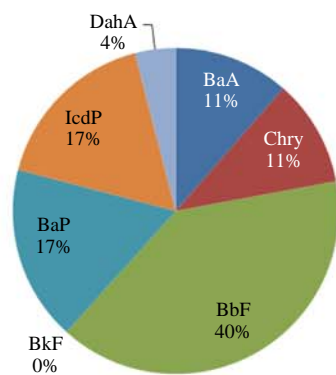
Fig. 2. Benzo(a)pyrene concentration in developing Asian countries.

(a) The portion of PAH concentrations

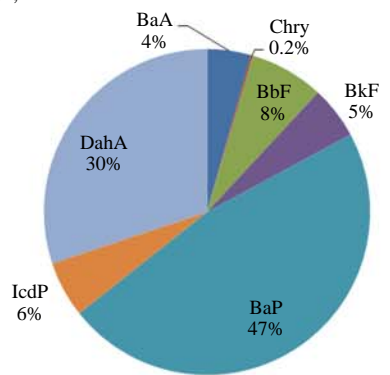
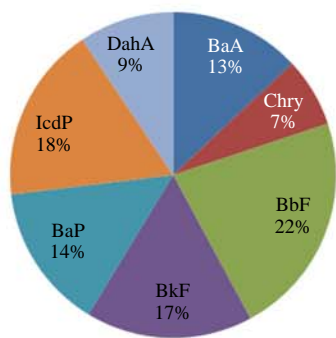
(b) The portion of PAH RWC



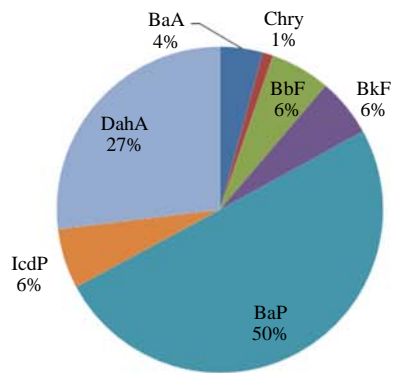
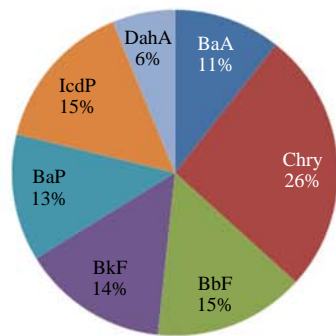
(I) China, n=38



(II) Afghanistan, n=2



(III) India, n=6



(IV) Turkey, n=2

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).

centration in ambient air.

Regarding the reliability of the data produced by the researchers, it is important that the data be compared with Standard Reference Materials like SRM 1649a or SRM 1649b. In this literature survey, however, only few authors were aware of this (Hanedar *et al.*, 2011; Wingfors *et al.*, 2011; Okuda *et al.*, 2010; Deng *et al.*, 2006; Okuda *et al.*, 2006). Most researchers did not use such standard materials, which creates some uncertainty in their data. If standard reference materials are unavailable, an interlab comparison of the results may also provide a good estimation of the uncertainty of the data measured.

In EPA 16 priority PAHs list, eight (BaP, DahA, Nap, BaA, BbF, BkF, Chry and IcdP) were placed in the IARC carcinogen list. On the other hand, the Nap concentrations are uncertain. Therefore, the present study, calculated the sum of the concentrations and sum of the Risk Weighted Concentrations (RWC) of the seven PAHs in particle phase (except Nap in the above eight PAHs) is 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 that PAH in $(\mu\text{g}/\text{m}^3)^{-1}$. The unit risk value of each PAH was taken from the California EPA (California EPA, 1997). The RWC better predicts the accurate toxicity or risk associated with the PAHs in ambient air than the sum of their concentrations.

In EPA 16 priority PAHs, BaP was considered the top most priority PAH in ambient air because it is the only PAH listed as a group 1 carcinogen by the IARC. A plot was made of the countries and the mean concentration of BaP reported in those countries during the review period (Fig. 2). In developing Asian countries, Chinese researchers reported high BaP concentrations (up to $51.9 \text{ ng}/\text{m}^3$) in ambient air. The reason for the high BaP concentrations in developing countries, such as, China and India, may be the use of solid fuels (WHO, Household energy database, http://www.who.int/indoorair/health_impacts/he_database/en/; India: Household energy, indoor air pollution and health, World Bank, 2002) for cooking and heating purposes, as well as vehicular exhaust. Overall, in developing Asian countries, the order of BaP concentration reported was as follows China > Afghanistan > India > Turkey. As mentioned earlier, among the 16 priority PAHs, seven PAHs are considered carcinogenic. A pie chart of the concentration portion of each PAH of a total of seven PAH concentrations was prepared (Fig. 3). Among the seven carcinogenic PAHs, the BaP concentration portion in developing countries was in the range of 13-17%. This appears small but the RWC portion of BaP among the seven PAHs was 47-61%. In con-

trast, the portion of BbF, BkF and Chry among the seven PAHs was approximately 50% but the RWC of these PAHs in the seven PAHs was slightly below 14%. Based on this pie chart, the concentration of BaP and DahA are much more important than the others with respect to their risk to humans.

In conclusion, measurements of the concentrations of PAHs in ambient air have been treated as a local issue by every country. Accordingly, some of the authors published their research results in local journals and in local languages. This literature survey being only from English journals is a limitation to this study.

4. SUMMARY

In this present study, we discussed the concentrations of polycyclic aromatic hydrocarbons (PAHs) in different developing Asian countries reported by several authors during 2000-2011. We strongly believe that the information provided in this paper will be useful to the researchers who are working in this issue. In EPA 16 priority PAHs, BaP was considered the top most priority PAH in ambient air because it is the only PAH listed as a group 1 carcinogen by the IARC. The reported concentration of BaP during review period in the developing Asian countries was follows the order China > Afghanistan > India > Turkey. The reason for the high BaP concentrations in developing countries, such as, China and India, may be the use of solid fuels. In overall 16 EPA priority PAHs, determination of the concentration of BaP and DahA were much more important than the others with respect to their risk to humans. Based on this review, we suggest to the developing countries the strict implementation of environmental policies such as Euro standards and reduce the usage of solid fuels, to decrease the concentrations of PAHs in ambient air because most of the developing countries are still extensively using solid fuels for cooking and heating purposes (World Health Organization, Household energy database, http://www.who.int/indoorair/health_impacts/he_database/en/) which leads to the higher concentrations of PAHs in the atmosphere.

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SUPPLEMENTARY INFORMATION

Table 1. Ambient air concentrations (ng m⁻³) of PAHs in developing countries (China, Afghanistan, India, Malaysia, Turkey and Vietnam).

Reference	Wu <i>et al.</i> (2005)													
Country	China													
Location	Xingken	Wushan (WS)-1	WS-2	WS-3	Liwan (LW)-1	LW-2	LW-3							
Site characteristics	Rural	Urban Residential and traffic	Urban	Urban	Urban Residential and traffic	Urban	Urban	Urban	Sub Urban**					
Sampling period	20 Oct-26 Oct-2003	30 Oct-2 Nov-2003	2 Nov-5 Nov-2003	5 Nov-8 Nov-2003	25 Nov-28 Nov-2003	28 Nov-2 Dec-2003	2 Dec-6 Dec-2003	28 Nov-2 Dec-2003	28 Nov-2 Dec-2003	28 Nov-2 Dec-2003	Sep-Oct	Dec-Feb	Sep-Oct	Sep-Oct
Season/s											Winter	Autumn	Winter	Autumn
No. of samples														
Sampling device	Low vol. sampler Micro orifice uniform deposit impactor (MOUDI)													
Sampling media	QFF													
Flow rate, duration	30 L/min, 48 h	30 L/min, 24 h			30 L/min, 24 h									
Phase	Particle													
Particle size	TSP													
Extraction	Ultrasonic													
Solvent	DCM													
Analysis	GC/MS													
Quality assurance	-													
Nap	-	-	-	-	-	-	-	-	-	-	0.07-2.21	1.21-17.4	0.10-1.34	0.96-21.53
Ace	-	-	-	-	-	-	-	-	-	-	3.93-7.99	0.01-0.07	4.77-5.34	0.02-0.07
Acp	-	-	-	-	-	-	-	-	-	-	0.00-4.43	0.00-0.07	0.00-3.54	0.00-0.04
Flu	1.46	1.38	1.32	1.59	1.89	2.50	5.15	1.13	1.13	0.05-0.18	3.54-6.46	0.05-0.18	4.54-4.80	0.05-0.23
Phe	0.98	0.55	0.46	0.73	0.49	0.60	1.13	0.06	0.13	0.33-0.80	6.94-257.54	0.33-0.80	7.42-123.21	0.21-0.62
Ant	0.10	0.08	0.06	0.07	0.05	0.06	0.06	0.05	0.05	0.01-0.02	5.78-42.45	0.01-0.02	6.43-12.32	0.01-0.29
Flt											3.92-46.01	0.59-1.62	3.98-23.42	0.59-1.18
Pyr	1.55	1.52	1.49	1.79	1.88	2.61	5.88	0.94	0.94	1.88	3.56-37.87	0.04-1.01	3.60-19.02	0.44-0.88
BaA	0.86	1.74	1.32	1.87	0.94	2.67	9.55	3.43	3.43	0.94	14.61-252.73	0.00-1.37	5.19-172.36	0.26-0.38
Chry	3.60	6.39	4.51	7.11	3.43	7.52	26.4	4.29 [†]	4.29 [†]	4.29 [†]	27.19-452.74	0.49-3.65	11.66-329.81	0.88-1.14
BbF								13.58 [†]	13.58 [†]	13.58 [†]	14.28-252.73	0.70-6.18	5.24-185.93	0.88-1.53
BkF	5.10 [†]	10.36 [†]	8.79 [†]	8.79 [†]	4.29 [†]	6.43 [†]	24.03 [†]	2.80	2.80	2.80	6.28-164.39	0.00-5.66	5.64-125.68	0.90-1.82
BaP	2.60	6.37	6.13	11.04	2.80	5.11	19.10	4.45	4.45	4.45	12.92-218.98	1.22-6.80	4.32-168.63	1.55-2.83
IcdP	6.61	12.48	13.58	16.13	4.45	6.49	15.56	1.62	1.62	1.62	9.90-182.09	0.01-6.90	3.05-129.08	0.99-1.76
DahA	1.72	4.03	3.88	4.48	1.15	1.62	4.87	5.22	5.22	5.22	5.65-157.92	0.01-1.35	15.69-103.71	0.15-0.25
BghiP	7.32	14.32	15.77	17.82	5.22	7.83	17.05	17.05	17.05	17.05	16.87-316.99	0.04-1.26	2.64-223.13	0.61-1.31

*The range of PAHs concentrations at ten urban sites in Tianjin; **The range of PAHs concentrations at three sub-urban sites in Tianjin; †Concentration of benzo(b+k)fluoranthene

Table 1. Continued.

Reference	Deng <i>et al.</i> (2006)	Li <i>et al.</i> (2006)	Okuda <i>et al.</i> (2006)	Duan <i>et al.</i> (2007)
Country	China	China	China	China
Location	Guiyu, South east China	Guangzhou	Beijing	Guangzhou (Wushan)
Site characteristics	Residential and commercial	Luhu park (Industrial, residential, traffic)	Tsinghua University (Near high way)	Residential, highways
Sampling period	Aug-Sep 2004	Apr 2001-Mar 2002	Sep 2003-Apr 2005	Aug-Sep 2003
Season/s	–	All	All	Summer
No. of samples	29	51	57-64	–
Sampling device	High vol. sampler	High vol. sampler	High vol. sampler	Low vol. sampler MOUDI
Sampling media	QFF	PUF	QFF	QFF
Flow rate, duration	1000-1200* L/min, 24h	232* L/min, 24h	800 L/min, 24h	30 L/min, NA [#]
Phase	Particle	Vapor	Particle	Particle
Particle size	TSP	PM _{2.5}	TSP	TSP
Extraction	Soxhlet	Soxhlet	ASE	Ultrasonic
Solvent	Acetone:Hexane (1:1)	DCM	DCM, n-hexane	DCM
Analysis	GC/MS	GC/MS	HPLC/FLD	GC/MS
Quality assurance	SRM 1649a	–	SRM 1649a	–
Nap	4.29	2.1	–	–
Ace	0.05	3.9	–	–
Acp	–	0.8	–	–
Flu	0.16	22.0	–	0.41
Phe	4.30	196.0	6.2	1.32-1.59
Ant	1.00	29.8	1.1	0.46-0.73
Flt	4.54	2.80	28.1	0.06-0.08
Pyr	10.2	6.81	20.5	–
BaA	5.03	2.82	36.7	1.49-1.79
Chry	11.40	8.54	15.5	1.32-1.87
BbF	32.00 [†]	0.8	21.5	4.51-7.11
BkF	–	NA	25.0	8.79-13.58 [†]
BaP	15.40	NA	6.7	–
IcdP	30.10	NA	10.9	1.17
DahA	2.77	NA	13.3	6.13-11.04
BghiP	27.90	NA	8.5	12.48-16.13
			–	3.88-4.48
			11.9	14.32-17.82
			18.3	3.64
			4.4	–

*Converted the flow rate from cubic meter per minute to liter per minute; [#]Not Available (sampling duration); [†]Concentration of benzo(b+k)fluoranthene

Table 1. Continued.

Reference	Duan <i>et al.</i> (2007)	Hu <i>et al.</i> (2007)	Liu <i>et al.</i> (2007b)
Country	China	China	China
Location	Guangzhou (Wushan)	Tianjin	Beijing
Site characteristics	Residential, highways	Road intersection (traffic)	Road sides (traffic) Campus
Sampling period	Jan-Apr 2004 Apr 2004	Jul-Aug 2005	Mar 2005 Apr 2005 May 2005 Aug 2005
Season/s	Winter Spring	Summer	Summer
No. of samples	–	10	10 10 10 10
Sampling device	Low vol. sampler MOUDI	Personal Environmental Monitors Low vol. sampler	High vol. sampler
Sampling media	QFF	QFF	QFF
Flow rate, duration	30 L/min, NA	10 L/min, 6h	700 L/min, 24 h
Phase	Particle	Particle	Particle
Particle size	TSP	PM ₁₀	Airborne particulates
Extraction	Ultrasonic	Ultrasonic	Ultrasonic
Solvent	DCM	DCM	Benzene : Ethanol (3 : 1 v/v)
Analysis	GC/MS	GC/MS	GC/MS
Quality assurance	–	–	–
Nap	–	–	23.29 225.63 16.54 1.64 1.55
Ace	–	–	2.31 1.71 0.61 0.50 0.47
Acp	–	–	0.46 0.52 ND ND ND
Flu	1.34-3.41	19.5	2.28 2.20 0.70 0.62 0.57
Phe	0.37-0.85	145.8	24.03 7.78 2.57 1.39 1.25
Ant	0.04-0.08	56.0	6.69 2.23 0.94 0.74 0.69
Flt	–	84.9	60.88 13.34 5.03 2.04 1.84
Pyr	1.37-3.49	47.3	52.57 12.01 4.51 1.77 1.61
BaA	1.24-5.06	35.4	37.05 10.18 6.39 2.25 1.86
Chry	4.21-15.80	53.9	31.14 9.03 6.26 2.10 1.47
BbF	4.8-20.73 [†]	34.4	37.19 11.77 9.00 4.56 4.26
BkF	–	34.8	19.56 6.25 5.49 2.57 2.28
BaP	2.69-11.50	26.2	23.88 7.84 5.55 2.82 2.30
IcdP	4.37-19.20	307.0	20.26 8.13 6.69 3.72 3.57
DahA	1.01-4.43	13.3	4.70 2.94 2.67 2.30 2.24
BghiP	4.06-18.81	7.3	15.86 6.58 5.03 2.80 2.57

[†] Concentration of benzo(b+k)fluoranthene

Table 1. Continued.

Reference	Liu <i>et al.</i> (2007c)			Wang <i>et al.</i> (2007)**			Ma <i>et al.</i> (2010)			
Country	China			China			China			
Location	Beijing, Haidian	PU*-1	PU-2	Xiamen	PU-1	PU-2	Harbin, Northeast china	Urban		
Site characteristics	Police	Away from busy streets	Police					Aug 2008- July 2009		
Sampling period	Jan 2005			Dec 2004	Dec 2004		Heating (mid Oct 2008- Mid Apr 2009)			
Season/s	Winter						48			
No. of samples	10	10	10	10	10	10	High vol. sampler			
Sampling device	Low vol. sampler			PM ₁₀ sampler	PM _{2.5} sampler		PUF			
Sampling media	PUF		QFF	GFF	GFF		800 [†] L/min, 24h			
Flow rate, duration	1.2 L/min, 12h			100 L/min, 23h	5 L/min, 23h		Vapor			
Phase	Vapor		Particle	Particle	Particle		Particle			
Particle size	–			PM ₁₀	PM _{2.5}		–			
Extraction	Soxhlet			Ultrasonic	Ultrasonic		Soxhlet			
Solvent	n-hexane : Cyclohexane (1 : 1)			DCM	DCM		Acetone : Hexane (1 : 1)			
Analysis	GC/MS			GC/MS	GC/MS		GC/MS			
Quality assurance	–			–	–		–			
Nap	3820.00	1430.00	2000.00	59.40	58.70	76.80	0.01	0.04	37.70	0.8
Ace	183.00	112.00	186.00	7.03	9.10	10.90	0.00	0.00	11.20	1.4
Acp	41.90	24.80	33.90	3.30	2.35	3.44	0.13	0.00	2.40	0.1
Flu	82.50	105.00	142.00	18.00	12.80	15.70	0.91	0.14	9.00	1.5
Phe	78.30	110.00	161.00	109.00	62.40	78.20	5.01	1.31	17.70	14.8
Ant	18.20	18.00	20.10	21.00	14.80	21.80	0.23	0.08	1.40	2.1
Flt	42.30	6.62	10.90	105.00	98.80	113.00	0.45	0.30	2.10	17.3
Pyr	40.70	5.75	8.26	110.00	98.80	118.00	1.26	1.19	1.20	13.2
BaA	2.14	0.05	0.08	38.70	23.30	30.80	0.25	0.90	0.03	5.8
Chry	4.16	1.11	0.77	56.20	38.50	48.70	0.64	0.00	0.04	6.6
BbF	0.79	ND	ND	52.50	24.80	33.20	0.20	0.29	0.01	5.1
BkF	0.71	ND	0.16	43.20	26.60	33.50	0.24	0.32	0.01	4.0
BaP	0.68	ND	ND	51.90	9.49	24.90	0.42	0.55	0.01	4.6
IcdP	0.13	ND	ND	16.60	1.22	1.99	0.44	0.58	0.01	3.6
DahA	ND	ND	ND	7.86	ND	ND	0.02	0.02	0.01	3.8
BghiP	ND	ND	ND	48.70	16.50	20.30	0.40	0.67	0.01	3.8

*Peking University, **Calculated mean concentration of PAHs at four different sites; † Converted the flow rate from cubic meter per minute to liter per minute

Table 1. Continued.

Reference	Ma <i>et al.</i> (2010)	Okuda <i>et al.</i> (2010)	Shi <i>et al.</i> (2010)*	Ma <i>et al.</i> (2011)
Country	China	China	China	China
Location	Harbin, Northeast china	Xi'an	Tianjin	Beijing
Site characteristics	Urban	University campus near residential and traffic	Commercial	Beijing Forestry University (5 km to Olympic stadium)
Sampling period	Aug 2008-July 2009	Oct 2005-Oct 2007	Apr 2008-Jan 2009	Sep 2008-July 2009 (after 28 th Olympic games)
Season/s	Non heating (mid Apr 2009-Oct 2009)	All	Spring	All
No. of samples	48	94	5	40
Sampling device	High vol. sampler	Low vol. sampler	Med vol. sampler	High vol. sampler
Sampling media	PUF	Cellulose nitrate membranes	QFF	PUF plugs
Flow rate, duration	800 [†] L/min, 24 h	5 L/min, 24 h	100 L/min, 24 h	800 [†] L/min, 24 h
Phase	Vapor	Particle	Particle	Vapor
Particle size	-	TSP	PM ₁₀	Particle
Extraction	Soxhlet	Modified Soxhlet	Ultrasonic	Soxhlet
Solvent	Acetone : Hexane (1 : 1)	DCM	DCM	Acetone : Hexane (1 : 1)
Analysis	GC/MS	HPLC/FLD	GC/MS	GC/MS
Quality assurance	-	SRM 1649a	-	-
Nap	1.90	-	0.35	4.2
Ace	1.20	-	0.02	11.2
Acp	0.70	-	0.02	2.5
Flu	3.90	-	0.29	23.7
Phe	12.10	19.4	2.25	43.1
Ant	0.80	1.5	2.78	7.3
Flt	3.10	44.9	3.18	15.2
Pyr	1.90	26.1	2.44	9.9
BaA	0.10	9.2	5.75	0.4
Chry	0.20	19.3	3.06	0.8
BbF	0.01	25.9	5.76	0.1
BkF	0.01	7.2	3.34	0.1
BaP	<0.02	11.2	2.37	0.1
IcdP	0.01	16.4	2.74	ND
DahA	<0.02	-	0.39	ND
BghiP	<0.02	15.5	1.61	ND
			4.26	7.7

*Calculated mean of PAHs concentrations at five different sites in each season; † Converted the flow rate from cubic meter per minute to liter per minute

Table 1. Continued.

Reference	Wingfors <i>et al.</i> (2011)*	Sahu <i>et al.</i> (2004)	Karar and Gupta (2006)	Sing <i>et al.</i> (2011)
Country	Afghanistan	India	India	India
Location	Kabul Mazar-e-sharif	Mumbai	Kolkatta	New Delhi
Site characteristics	Military camps Military camps	BARC, Mumbai	Residential Industrial	GGSIIP University campus, traffic site
Sampling period	Oct-Nov 2009 Oct-Nov 2009	May-June 2001	Nov 2003-Nov 2004	2007-2008 2007-2008 2008
Season/s	Autumn	Rainy season	All	Winter Winter Summer Summer
No. of samples	14 14	13	53	16 16 14 14
Sampling device	Impact sampling heads Low vol. sampler	High vol. sampler	Respirable dust sampler High vol. sampler	APM 460 Respirable dust sampler APM 550 Fine particulate dust sampler APM 460 APM 460
Sampling media	PTFE	GFF, PUF	QFF	GFF GFF GFF
Flow rate, duration	10 L/min, 24 h	1100** L/min, 24 h	800-1400** L/min, 24 h	1200 [†] L/min, 24 h 16.6 L/min, 24 h 1200 [†] L/min, 24 h 16.6 L/min, 24 h
Phase	Particle	Ambient air	Particle	Particle Particle Particle Particle
Particle size	PM _{2.5}		PM ₁₀	PM ₁₀ PM _{2.5} PM ₁₀ PM _{2.5}
Extraction	Ultrasonic	Soxhlet	Ultrasonic	Ultrasonic Ultrasonic Ultrasonic
Solvent	DCM	Hexane	Cyclohexane	DCM DCM DCM DCM
Analysis	GC/MS	HPLC/UV (254 nm)	GC-FID	GC/MS GC/MS GC/MS GC/MS
Quality assurance	SRM 1649b	-	-	- - - -
Nap	-	-	-	1.4 2.1 0.2 1.8
Ace	-	-	-	0.6 2.2 0.3 1.3
Acp	-	-	-	1.1 0.6 0.6 0.4
Flu	-	-	-	0.4 1.2 0.2 0.8
Phe	1.70-12.00	2.6	-	0.8 1.2 0.5 1.0
Ant	0.39-2.90	1.6	-	2.4 2.4 0.8 1.6
Flt	5.10-35.00	2.9	22.7	1.7 3.8 0.6 2.7
Pyr	5.40-33.00	1.8	18.2	4.1 2.1 2.5 1.5
BaA	10.00-41.00	-	22.9	3.2 3.6 2.1 1.8
Chry	11.00-34.00	-	-	4.4 3.7 2.2 2.8
BbF	32.00-93.00 [#]	-	23.7	8.8 11.8 4.4 5.4
BkF	-	1.3	-	9.6 13.6 3.9 6.9
BaP	15.00-50.00	1.2	14.3	6.9 9.9 3.1 5.1
IcdP	13.00-46.00	-	-	13.8 18.7 3.6 4.2
DahA	3.10-11.00	-	-	9.8 2.8 3.7 2.1
BghiP	14.00-58.00	-	-	12.5 15.5 4.4 6.4

*Concentrations of PAHs in Geo mean values; **Converted the flow rate from cubic meter per minute to liter per minute; [†] Corrected flow rate (by communicating the corresponding author);[#]Concentration of benzo(b+k)fluoranthene

Table 1. Continued.

Reference	Omar <i>et al.</i> (2006)	Tasdemir and Esen (2007)	Bozlaker <i>et al.</i> (2008)	Demircioglu <i>et al.</i> (2011)
Country	Malaysia	Turkey	Turkey	Turkey
Location	Kuala Lumpur	Butal, Bursa	Izmir	Izmir
Site characteristics	University of Malaya (min traffic)	Institutional and residential	Industrial region	Sub-urban (Residential)
Sampling period	Mar-Dec 2001	Aug 2004-May 2005	2-17 Aug 2004	May 2003-May 2004
Season/s	-	-	Summer	Winter
No. of samples	19	20	14	14
Sampling device	High vol. sampler	High vol. sampler	High vol. sampler	High vol. sampler
Sampling media	GFF	GFF, PUF, XAD-2	QFF, XAD-2 and PUF	PUF
Flow rate, duration	1150* L/min, 24 h	161 ± 42* L/min, 24 ± 7.3 h	180 ± 15* L/min, 24 h	270* L/min, 11 h
Phase	Particle	Vapor and Particle	Vapor and Particle	Vapor
Particle size	PM ₁₀			Particle
Extraction	Ultrasonic	Soxhlet	Soxhlet	Soxhlet
Solvent	DCM	DCM : Ether (1 : 4 v/v)	DCM : Ether (1 : 4)	DCM : Ether (1 : 4 v/v)
Analysis	GC/MS	GC/MS	GC/MS	GC/MS
Quality assurance	-	-	-	SS
Nap	-	216.7	-	-
Ace	-	2.5	-	-
Acp	-	12.5	1.6	-
Flu	-	22.6	4.1	4.10
Phe	-	76.2	13.4	11.70
Ant	-	7.0	0.5	0.50
Flt	-	47.8	2.9	3.70
Pyr	0.04	31.1	2.0	2.40
BaA	-	4.7	0.1	0.10
Chry	0.07	10.6	0.7	0.40
BbF	0.25	5.8	0.3	0.05
BkF	0.38	4.7	0.2	0.02
BaP	0.16	3.3	0.1	0.02
IcdP	0.47	3.9	0.1	0.01
DahA	-	1.3	0.1	0.02
BghiP	0.76	5.6	0.2	0.03

*Calculated flow rate from the volume of the sample

Table 1. Continued.

Reference	Demircioglu <i>et al.</i> (2011)	Hanedar <i>et al.</i> (2011)	Hien <i>et al.</i> (2007)
Country	Turkey	Turkey	Vietnam
Location	Izmir	Istanbul	Ho Chi Minh
Site characteristics	Urban (heavy traffic)	Urban-1 (European part of the city) Heavy traffic	Vietnam National University (VNU) (Residential and traffic)
Sampling period	May 2003-May 2004	Sep 2006- Dec 2007	Jan 2005- Mar 2006
Season/s		–	Jan 2005-Feb 2006
No. of samples	63	135	60
Sampling device	High vol. sampler	PUF sampler	High vol. sampler
Sampling media	PUF QFF	GFF, PUF	QFF
Flow rate, duration	210* L/min, 11 h	210* L/min, 24 h	1000 L/min, 22 h
Phase	Vapor	Vapor and Particle	Particle
Particle size		TSP	TSP
Extraction	Soxhlet	Soxhlet	Ultrasonic
Solvent	DCM: Ether (1 : 4 v/v)	n-hexane: Ether (9 : 1 v/v)	Benzene: Ethanol (3 : 1 v/v)
Analysis	GC/MS	HPLC-UV and FLD	HPLC
Quality assurance		1649a	–
Nap	–	34.7	–
Acc	–	13.7	–
Acp	–	2.1	–
Flu	12.50	4.2	–
Phe	40.80	20.2	–
Ant	5.60	5.2	–
Flt	27.30	7.0	0.25
Pyr	20.20	4.7	0.25
BaA	0.60	1.4	0.21
Chry	1.60	1.7	0.27
BbF	0.03	1.2	0.88
BkF	0.02	3.4	0.34
BaP	<0.01	3.1	0.60
IcdP	<0.01	3.4	1.20
DahA	<0.01	0.8	1.30
BghiP	<0.01	0.5	–
		1.7	2.00
		22.9	–
		8.3	–
		1.7	–
		2.6	–
		16.8	–
		7.9	–
		7.9	0.24
		5.1	0.27
		1.7	0.27
		2.5	0.37
		1.4	1.09
		0.5	0.44
		1.3	0.72
		1.3	1.30
		0.7	–
		1.9	2.10

*Calculated flow rate from volume of the sample