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POLYCYCLIC AROMATIC HYDROCARBONS IN AMBIENT AIR OF INDIA: A REVIEW

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ABSTRACT
Polycyclic aromatic hydrocarbons (PAHs) are organic pollutants detected ubiquitously in the environment. Their releasing sources to the environment included combustion processes (fossil fuel, petroleum, coal tar, gas, and wood) and petroleum products. There are several identified PAHs, among them 16 have been included in the list of priority pollutant by various international agencies. Polycyclic aromatic hydrocarbons are known for their ecological and human health effects. Globally, several studies carried out on PAHs in ambient air and their health risks. However, an overview of on PAHs in ambient air is not available for India. After search of various databases, data from published literatures on studies compiled for years between 2007-2021. Based on different climatic conditions in India, the available data was analyzed for the patterns of PAHs in ambient air, possible sources, and cancer risks for humans in India. PAHs with 4 aromatic ring were dominant compounds followed by PAHs with aromatic ring, 6 aromatic ring and 5 aromatic ring PAHs. Various diagnostic tools including composition pattern, molecular ratios of individual PAHs, and correlation coefficient used for identification of possible source. BaP toxicity equivalency (BaPeq) is estimated and presented. Lifetime daily dose (LADD) and subsequent incremental lifetime cancer risk (ILCR) of PAHs through inhalation for humans were estimated and discussed.

Keywords: *Polycyclic Aromatic Hydrocarbons (PAHs), Ambient Air, Possible Source, BaP Equivalency, Risk Assessment, Review*

INTRODUCTION
Polycyclic aromatic hydrocarbons (PAHs) are organic compounds with two or more fused aromatic rings. PAHs are ubiquitous in the environment and commonly detected in air, soil, water and sediment (ATSDR, 1995). They dominantly released during combustion processes (fossil fuel, petroleum, coal tar, gas, and wood) and petroleum products (ATSDR, 1995). Based on volatility of PAHs, they partitioned between the atmospheric particulate matter (PM) and gaseous phase (Chen *et al.*, 2017). It is reported that low molecular weight-PAHs (L-PAHs) and high molecular weight-PAHs (H-PAHs) are dominantly partitioned into gaseous phase and PM, respectively, where gaseous phase content is < 5% of total PAHs (Hassan and Khoder, 2012; Wang *et al.*, 2009).
Among several identified PAHs, 16 have been included in the list of priority pollutant by various agencies (USEPA, 2015; EC, 2001). The priority PAHs are naphthalene (Nap), acenaphthylene (Acy), acenaphthene (Acp), fluorine (Fle), phenanthrene (Phe), anthracene (Ant), fluoranthene (Flt), pyrene (Pyr), benz(a)anthracene (BaA), chrysene (Chr), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), benzo(a)pyrene (BaP), dibenz(a,h)anthracene (DBA), benzo(ghi)perylene (BghiP) and indeno (1,2,3-cd)pyrene (IndP) (USEPA, 2015; ATSDR, 1995). Among priority PAHs, seven PAHs (BaA, Chr, BbF, BkF, BaP, DBA and IndP) are suggested as probable human carcinogens (7C-PAHs) (IARC, 2006, 2010). Through various route (ingestion, inhalation, dermal and dietary), PAHs can enter into the cardiovascular system through trachea, bronchi, bronchioles and alveolar epithelium (Abayalath *et al.*, 2022; Gurbani *et al.*, 2013; Bostrom *et al.*, 2002). In physiological systems, through oxidation-hydroxylation reactions, PAHs form DNA adducts (Perera *et al.*, 2011) and cause to development of mutations in respiratory, digestive, urinary, and reproductive system (Diggs *et al.*,2011; Bosetti *et al.*, 2007; Gaspari *et al.*, 2003). Consequently, several studies carried out on associated with PM bound PAHs and their human health risks in India (Patel *et al.*, 2020; Ray *et al.*, 2019; Hazarika *et al.*,2019; Hazarika & Srivastava 2016; Li *et al.*, 2014; Kaur *et al.*, 2013). However, there is no available review on PAHs in ambient air and their human

health risk. Therefore, this review discussed PAHs in ambient air of India at different locations. Their possible sources and associated risk to humans is also discussed and presented.

MATERIALS AND METHODS

Various databases were searched for the available scientific literature on PAHs in ambient air of India. Within the years 2007-2021, available data from 55 studies on PAHs in ambient air compiled from studies carried out during 1996-2018 at 118 locations in India. Database search was included the studies regardlessof their PM size, and geographical location in India. During this review, exceptionally studies on PM bound PAHs were considered for discussion on profile, possible sources and human health risk of PAHs. Area ofcountry (with population of 1,210,193,422 million) is situated in the Northern Hemisphere, between 8° 4' and 37° 6' latitudes north of the Equator, and 68° 7' and 97° 25' longitudes east (area of 32,87,263 km^2) (India, 2021). Northern sides of India are bounded with the Great Himalayas, Bay of Bengal in east, ArabianSea in west and southern area is bounded by Indian Ocean.

Table 1. Concentrations of PAHs in ambient air of India

PAHs	Min	75th	Mean	Max	SD	CV	SE	%
Concentrations (ng/m^3)								
∑16PAHs	2.31	216	248	1845	266	108	25	100
L-PAHs	0.07	56	58	788	114	197	10.85	30
H-PAH	2.23	160	137	1788	204	148	19.02	70
7C-PAHs	1.92	127	95	773	111	117	10.43	45
BaP Equivalency (BaPeq) (ng/m^3)								
∑PAHs	0.223	27.306	43	1129	13.323	31.28	1.226	100
L-PAHs	0.005	0.218	0.217	3.731	0.849	391	0.088	0.63
H-PAH	0.005	27.142	31.785	1129	12.920	40.65	1.189	91.92
7C-PAHs	0.456	27.250	31.827	1126	12.738	40.02	1.178	92.04

DISTRIBUTION OF PAHS

The concentration of ∑PAHs (sum of sixteen PAHs) in ambient air of India significantly varied between 2.31 to 1845 ng/m^3 (mean 248 ng/m^3), while, 25th and 75th percentile was 53.4 and 216 ng/m^3, respectively. 4-ring PAHs (Flt, Pyr, BaA, Chr) were dominant followed by 3-ring (Acy, Acp, Fle, Phe, Ant), 6-ring (BghiP, DBA, IndP) and 5-ring PAHs (BbF, BkF, BaP) (**Table 1 & Figure 1**). Their contribution to ∑PAHs is accounted for 23%, 24%, 22%, and 17%, respectively.

Elevated PAHs levels have been reported for Agra (27-1845 ng/m^3) (Masih *et al.*, 2012; Dubey *et al.*, 2015; Singla *et al.*, 2012; Lakhani 2012; Rajput & Lakhani 2009, 2010), Kanpur (124-530 ng/m^3) (Pradhi *et al.*, 2021), Lucknow (230-328 ng/m^3) (Pandey *et al.*, 2013), and Modinagar (306 ng/m^3) (Shivani *et al.*, 2018) in state of Uttar Pradesh. ∑PAHs with ranges of 21-288 ng/m^3 reported for Delhi (Chowdhury *et al.*, 2007; Khillare *et al.*, 2008; Singh *et al.*, 2011, 2012; Jyethi *et al.*, 2014; Li *et al.*, 2014; Shivani *et al.*, 2018; Kulshrestha *et al.*, 2019). Roy *et al.*, (2017) reported 11-506 ng/m^3 of PAHs in air for Dhanbad (Jharkhand), while, for Kolkata in West Bengal the reported concentrations are 17-418 (Ray *et al.*, 2017; Saha *et al.*, 2017; Chowdhury *et al.*, 2007; Gupta *et al.*, 2007; Karar & Gupta 2007). Roy *et al.*, (2019) reported 345-447 ng/m^3 for Pune in Maharashtra. In studies, dominant levels of PAHs have been reported in cities of Tamil Nadu state including Chennai (5.29-992 ng/m^3) (Fu *et al.*, 2010), Tiruchirappalli (17-488 ng/m^3) (Mohanraj *et al.*, 2011, Marimuthu *et al.*, 2019) and Coimbatore (143-486 ng/m^3) (Mohanraj *et al.*, 2012).

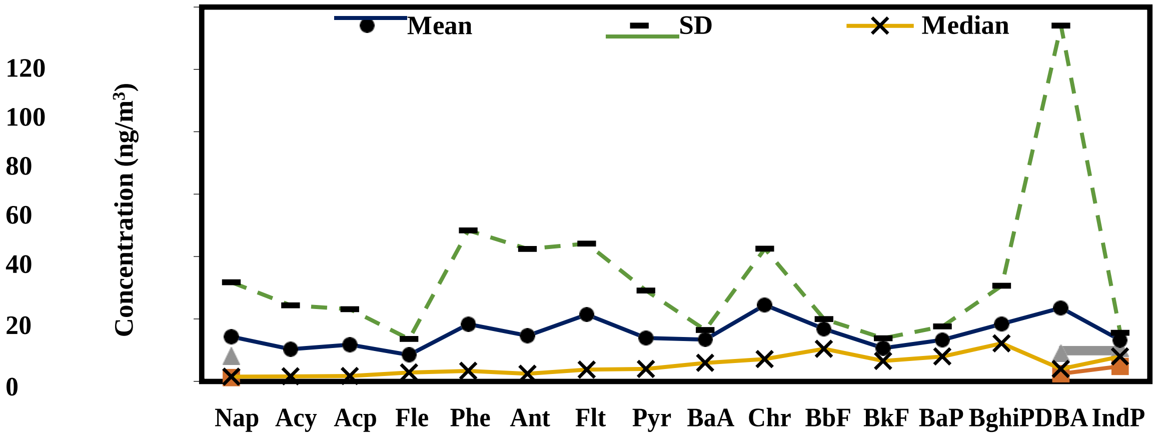

Figure 1. Concentration of individual PAHs in ambient air of India Table. 2. PAHs (ng/m^3) in ambient air at various locations in India

Table 2. PAHs (ng/m^3) in ambient air at various locations in India

Location	State	∑PAHs	Reference
Amritsar	Punjab	96-153	Kaur *et al.*, 2013, 2022
Chandigarh	Chandigarh	25	Garg *et al.*, 2019
Agra	Uttar Pradesh	27-1845	Dubey *et al.*, 2015; Masih *et al.*, 2012; Singla *et al.*, 2012; Lakhani 2012; Rajput & Lakhani 2009, 2010
Kanpur	Uttar Pradesh	124-530	Pradhi *et al.*, 2021
Lucknow	Uttar Pradesh	230-328	Pandey *et al.*, 2013
Allahabad	Uttar Pradesh	78-150	Pradhi *et al.*, 2021
Modinagar	Uttar Pradesh	306	Shivani *et al.*, 2018
Gurgaon	Haryana	113-122	Kulshrestha et al. 2019
Mahindragarh	Haryana	158	Shivani *et al.*, 2018
Jalandhar	Punjab	77-107	Kumar *et al.*, 2014, 2019
Delhi	Delhi	21-288	Kulshrestha *et al.*, 2019; Shivani *et al.*, 2018; Jyethi *et al.*, 2014; Li *et al.*, 2014; Singh *et al.*, 2011, 2012; Khillare *et al.*, 2008; Chowdhury *et al.*, 2007
Dhanbad	Jharkhand	11-506	Roy *et al.*, 2017
Jamshedpur	Jharkhand	37 -109	Kumar *et al.*, 2020a,b
Kolkata	West Bengal	17-418	Ray *et al.*, 2017; Saha *et al.*, 2017; Chowdhury *et al.*, 2007; Gupta *et al.*, 2007; Karar & Gupta 2007
Jharsuguda	Orissa	65-177	Ekka *et al.*, 2021
Mumbai	Maharashtra	17-81	Masih *et al.*, 2019; Abba *et al.*, 2012; Chowdhury *et al.*, 2007
Pune	Maharashtra	345-447	Roy *et al.*, 2019
Raipur	Chhatisgarh	2.31-194	Ramteke *et al.*, 2018; Giri *et al.*, 2013
Mangalore	Karnataka	73-109	Kalaiarasan *et al.*, 2017
Vishakhapatnam	Andhra Pradesh	58	Kulkarni *et al.*, 2014
Coimbatore	Tamil Nadu	143-486	Mohanraj *et al.*, 2012
Chennai	Tamil Nadu	5.29-992	Fu *et al.*, 2010
Tiruchirappalli	Tamil Nadu	17-488	Marimuthu *et al.*, 2019; Mohanraj *et al.*, 2011

Moderate to low levels of PAHs have been reported for other locations in Indian states including Punjab (Kumar *et al.*, 2014, 2019; Kaur *et al.*, 2013, 2022; Garg *et al.*, 2019), Haryana (Kulshrestha *et al.*, 2019; Shivani *et al.*, 2018), Uttar Pradesh (Pradhi *et al.*, 2021), Jharkhand (Kumar *et al.*, 2020a,b), Maharashtra (Masih *et al.*, 2019; Abba *et al.*, 2012; Chowdhury *et al.*, 2007), Karnataka (Kalaiarasan *et al.*, 2017), Chhatisgarh (Giri *et al.*, 2013; Ramteke *et al.*, 2018) and Andhra Pradesh (Kulkarni *et al.*, 2014) (**Table 2**).

Toxic Fraction of PAHs and BaP Equivalent (BaPeq) in Different Zones

The mean concentration of 7C-PAHs is 94.84 ng/m^3 (range, 1.923–773 ng/m^3), and their contribution is approximately 45% to ∑PAHs (**Table 1**). BaP had adequate evidence of carcinogenicity, and has been classified as human carcinogen and used as index of toxicity for PAHs (USEPA, 2017; IARC, 2010). Thus, India has regulatory limit for BaP (1.0 ng/m^3) in ambient air as national ambient air quality standard (NAAQS) (MoEF & CC, 2009). The concentration of BaP in ambient air of India ranged between 0.17-140 ng/m^3 with 25th, 75th and mean values of 3.10 ng/m^3, 17.0 ng/m^3 and 13.35 ng/m^3, respectively. Which are exceeding the NAAQS for BaP (**Figure 1**). BaP toxic equivalence factors (TEF) relative to BaP have been derived (Tsai et al. 2004) and commonly used for estimation of carcinogenic toxicity potential of PAHs as BaP toxicity equivalency (BaPeq). BaPeq was calculated using equation 1 as:

$$BaPeq = C \times TEF \quad [1]$$

Where, C is the individual PAH concentration in ambient air (ng/m^3). The estimated mean value of BaPeq of ∑PAHs is 43 ng/m^3 (75th, 27.306 ng/m^3), and ranged between 0.223 to 1129 ng/m^3 (**Table 1**). H-PAHs with >91% are the main contributors to ∑BaPeq, where 5-ring and 6-ring PAHs were the dominant contributors, and their contributions are accounted for 44% and 51%, respectively to ∑BaPeq (**Table 1, Figure 2**). Among them, BaP and DBA are major contributors with percent contribution of 31% and 54%, respectively to ∑BaPeq. Other significant contributors were BbF (4.1%), BaA (3.2%), and IndP (3.1%). Thus it is observed that H-PAHs including 5-ring and 6-ring PAHs in ambient air are significant for carcinogenic potential.

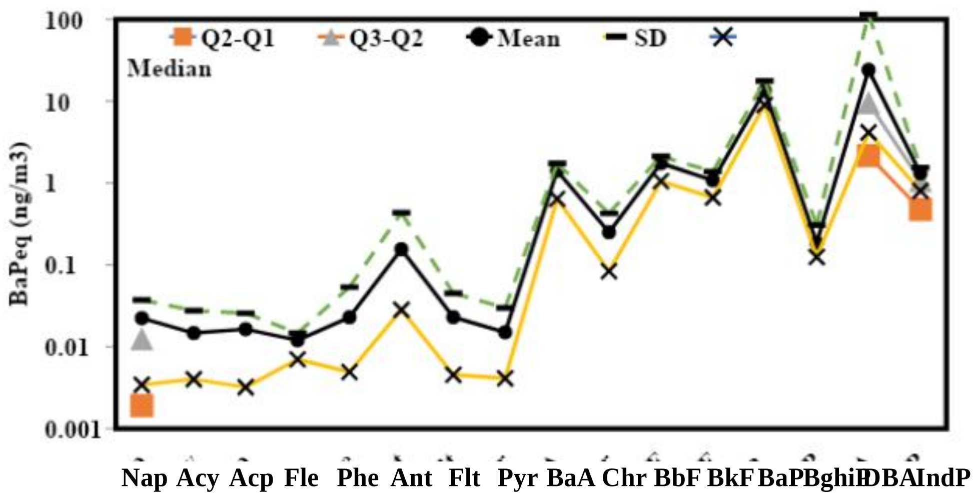

Figure 2. BaPeq of individual PAHs in ambient air of India

SOURCE APPORTIONMENT

There are several available methods for identification of possible source of PAHs, during this review, composition profiles, molecular diagnostic ratios (MDRs) and Pearson's moment correlation were used for identification of possible source PAHs in ambient air of India.

Composition Profiles

Priority 16 PAHs in the atmosphere are classified according to presence of aromatic rings as 2-aromatic rings (Npt), 3- aromatic rings (Any, Ane, Fle, Phe and Ant), 4- aromatic rings (Flt, Pyr, BaA and Chr), 5-aromatic rings (BbF, BkF and BaP) and 6- aromatic rings (BghiP, DBA, and Ind). PAHs also classified according to their molecular weights L-PAHs and H-PAHs and released to the environment from different sources. Petrogenic sources are associated with the dominance of L-PAHs, while higher contents of H-PAHs are indication of pyrogenic sources. It is also reported that L-PAHs can be markers for wood, grass, biomass and industrial oil combustion, however; H-PAHs have been reported for association with coal combustion and vehicular emissions (Wilcke, 2007; Khalili *et al.,* 1995). The dominance of each classified group is used as indicator for their possible source including petrogenic sources (petroleum products) and pyrogenic sources (coal, wood, biomass or oil combustion). Dominance of 4-ring PAHs, followed by 3-ring and 6-ring indicated mixed pyrogenic activates as major sources. The mean concentration of 3-ring 4-ring, 5-ring and 6-ring PAHs is 49.73 ng/m^3, 63.46 ng/m^3, 36.31 ng/m^3 and 45.78 ng/m^3, respectively (**Figure 3**).

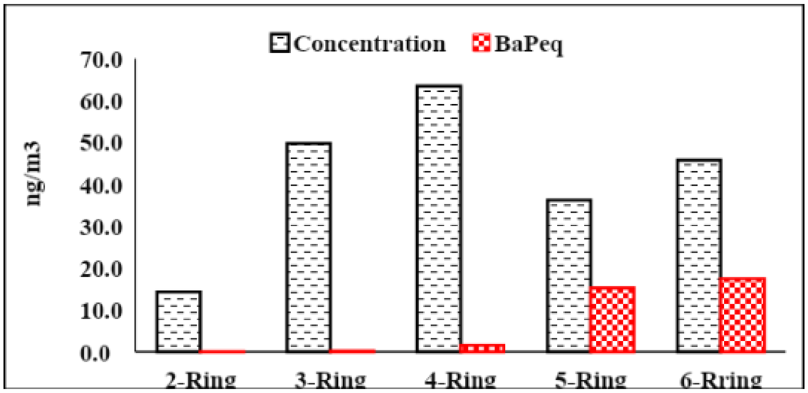

Figure 3. Comparison of Concentration and BaPeq of PAHs with different rings

Emissions of 4-ring and 6-ring PAHs are associated with vehicles, diesel engine, petrol, oil & coal combustion (Elzein *et al.,* 2020; Singh et al. 2012; *Ravindra et al.*, 2008). Emissions of 3-ring PAHs are mostly associated with petrogenic sources including petroleum product, terrestrial plants and biomass (woods, grass) and industrial oil combustion (Elzein *et al.*, 2020; Wilcke 2007; Yunker *et al.*, 2002; Khalili *et al.*, 1995). Similar sources of PAHs to Indian environment have been reported by other authors (Singh *et al.*, 2012). Further, dominance of H-PAHs (70%) over L-PAHs (30%) are also supported pyrogenic sources. L-PAHs with higher volatility and octanol-water partition coefficient (K_{ow}) are partitioned into gaseous phase and moved away from the emission sources (Chen *et al.*, 2017; Hassan and Khoder 2012;). But, H-PAHs had more affinity with air particles, which may cause to remain in close proximity of emission sources (Wang *et al.*, 2009). Furthermore, lower ratio (<1.0) of L-/H-PAHs is indicative of pyrogenic sources (Wilcke 2007). The estimated mean value of 0.71 suggested dominantly pyrogenic sources (**Table 3**).

Molecular Diagnostic Ratio (MDR)

MDR of PAHs are commonly used for identification of possible sources of PAHs emissions. PAHs emissions into the environment have been associated to different sources including petroleum products (petrogenic) and combustion sources (diesel combustion, gasoline, wood combustion, coal combustion, and vehicular emission. MDR of selected PAHs was estimated from available data and used for sources apportionment of PAHs in ambient air of India (**Table 3)**. Estimated value of BaP/(BaP+Chr) (mean, 0.57, range 0.03–1.00) suggested diesel and coal combustion (Khalili *et al.*, 1995). BbF/BkF ratio (range, 0.60-7.50, mean, 1.89) suggested vehicular emissions (Dickhut *et al.*, 2000). BaA/(BaA+Chr) values (range, 0.09-1.00, mean, 0.47) suggested petrogenic sources and vehicular emissions (Yunker *et al.*, 2002). Ratio of IndP/(IndP+BghiP) (range, 0.01-1.00, mean, 0.47) is indicative of petrogenic, petroleum combustion and gasoline (Yunker *et al.*, 2002; Dickhut *et al.*, 2000). Flt/(Flt+Pyr) MDR (range, 0.06-0.95, mean, 0.53) indicated to petroleum, biomass & fossil fuel burning (Yunker *et al.*, 2002; Simcik *et al.*, 1999). Pyr/BaP ratio values are used to distinguish between diesel (>10) and gasoline (<1), which suggested PAHs emissions from diesel and gasoline in India (Ravindra *et al.*, 2008). Values of Fle/(Fle+Pyr) (range 0.02-1.00, mean, 0.43) indicated petrol and diesel emissions (Ravindra *et al.*, 2008). The estimated MDR of BaP/BghiP (range, 0.13-7.65, mean, 1.00) is indicative of vehicular emission and coal combustions (Simcik et al. 1999). The MDR value for Ant/(Ant+Phe) (range, 0.04-1.00, mean, 0.43) suggested petrogenic sources of petroleum products and burning of wood, grass (Ravindra *et al.*, 2008; Yunker *et al.*, 2002) (**Table 3**).

Table 3. MDR of selected PAHs used for possible sources

PAH Ratio	Ratio value	Possible Sources	Reference	This study
L/H-PAHs	<1	Pyrogenic	Wilcke 2007	0.01-20 (0.71)*
	>1	Petrogenic		
BaP/(BaP+Chr)	0.49	Diesel	Khalili *et al.*, 1995	0.03-1.00 (0.57)
	0.73	Gasoline		
BbF/BkF	0.92	Wood burning	Dickchut *et al.*, 2000	0.60-7.50 (1.89)
	1.3	Vehicles		
	3.7	Coal combustion		
BaA/(BaA+Chr)	<0.2	Petrogenic	Yunker *et al.*, 2002	0.09-1.00 (0.47)
	0.35 – 0.53	Vehicles		
IndP/(IndP+BghiP)	<0.22	Petrogenic	Dickhut *et al.*, 2000 Yunker *et al.*, 2002	0.01-1.00 (0.47)
	0.2 - 0.5	Petroleum combustion, gasoline		
	>0.5	Biomass, coal combustion		
Flt/Flt+Pyr	<0.4	Petroleum	Yunker *et al.*, 2002 Simcik *et al.*, 1999	0.06-0.95 (0.53)
	0.4 – 0.5	Biomass, fossil fuel burning		
	>0.5 - <1.0	Coal, diesel engine, gasoline		
Pyr/BaP	10	Diesel	Ravindra *et al.*, 2008	0.02-47 (1.98)
	1	Gasoline		
Fle/(Fle+Pyr)	<0.5	Petrol emissions	Ravindra *et al.*, 2008	0.02-1.00 (0.43)
	>0.5	Diesel emissions		
BaP/BghiP	0.3-0.78	Vehicles	Simcik *et al.*, 1999	0.13-7.65 (1.00)
	0.9-6.6	Coal combustion		
Ant/(Ant+Phe)	<0.1	Petrogenic	Ravindra *et al.*, 2008 Yunker *et al.*, 2002	0.04-1.00 (0.43)
	>0.1	Petroleum, biomass combustion		

**Mean in parenthesis*

Pearson's Moment Correlation Coefficients

Pearson's moment correlation coefficients (p<0.01) were calculated to assess correlation-ship among PAHs (**Table 4 & Figure 4).** A strong correlation was found between L-PAHs and H-PAHs. A very strong correlation between L-PAHs (Nap, Acy, Acp, Fle, Phe and Ant) indicated petrogenic sources and combustion of biomass (crop residue, wood, grass) and industrial emissions (Sampath *et al.*, 2015; Kaur *et al.*, 2013; Singh *et al.*, 2013). Significant correlations among 3-ring and 4-ring PAHs, suggested pyrogenic sources from diesel vehicles and coal & biomass combustions and high temperature combustion processes (Elzein *et al.*, 2020; Singh *et al.*, 2012, 2013; Khalili *et al.*, 1995; Wilcke 2007). A strong correlation between 4-ring and 5-ring PAHs suggested fossil fuel burning. Another significant correlation among 5-ring and 6-ring PAHs suggested mixed pyrogenic activities including heavy duty engine exhaust, vehicles, gasoline, industries, automobile, and coal combustion (Kaur *et al.*, 2013; Khalili *et al.*, 1995; Wilcke 2007; Kavouras *et al.*, 2001). A correlation between Pyr, BaA and Chr is associated with wood and crop residue burning (Singh *et al.*, 2012, 2013). Association of 3-ring, with H-PAHs suggested pyrogenic sources of biomass combustion and high temperature combustion processes such as petrol, gasoline and diesel vehicular emissions (Kalaiarasan *et al.*, 2017; Sampath *et al.*, 2015; Singh *et al.*, 2013; Mohanraj *et al.*, 2011).

Therefore, it is concluded that mixed petrogenic and pyrogenic are the PAHs emission sources to Indian environment. Petrogenic sources includes emissions from surface runoff, automobile workshops and spillage of petroleum products (Singh *et al.*, 2013). However, solid fuels (wood, grass and coal) burning, diesel, industrial and vehicular emissions are the major pyrogenic sources of PAHs in India. Biomass burning is common practice for energy in India (Ekka *et al.*, 2021; Kumar *et al.*, 2020; Ray *et al.*, 2019). Solid fuels (biomass, wood, cow dung) are a major energy requirement for domestic and industrial activities in India (Singh *et al.*, 2013), and have been reported a major contributor of PAHs (WHO, 2000). More than 50% of the total global PAH emissions has been reported from biomass burning (IARC, 2010).

Table 4. Pearson's moment Correlation coefficient matrix for PAHs in ambient air of India

PAHs		Nap	Acy	Acp	Fle	Phe	Ant	Flt	Pyr	BaA	Chr	BbF	BkF	BaP	BghiP	DBA
		2-R	3-R					4-R				5-R				
Acy		0.833*	1.000													
Acp		0.769*	0.911*	1.000												
Fle	3-R	0.779*	0.854*	0.849*	1.000											
Phe		0.789*	0.939*	0.793*	0.772*	1.000										
Ant		0.617*	0.909*	0.881*	0.835*	0.404*	1.000									
Flt		0.640*	0.762*	0.910*	0.825*	0.535*	0.804*	1.000								
Pyr	4-R	0.653*	0.895*	0.849*	0.781*	0.663*	0.583*	0.880*	1.000							
BaA		0.461*	0.534*	0.642*	0.614*	0.244*	0.258*	0.540*	0.419*	1.000						
Chr		0.467*	0.659*	0.593*	0.512*	0.266	0.420*	0.508*	0.543*	0.705*	1.000					
BbF		0.432*	0.534*	0.482*	0.338*	0.121	0.203	0.358*	0.139	0.621*	0.297*	1.000				
BkF	5-R	0.083	0.073	0.385*	0.188	0.032	0.087	0.245*	0.032	0.668*	0.355*	0.848*	1.000			
BaP		0.266	0.220	0.299*	0.148	0.068	0.129	0.258*	0.073	0.581*	0.279*	0.877*	0.874*	1.000		
BghiP		0.020	-0.013	0.409*	0.078	0.079	0.159	0.329*	0.127	0.566*	0.273*	0.820*	0.773*	0.901*	1.000	
DBA	6-R	-0.166	-0.146	0.452*	0.116	0.050	0.115	0.452*	-0.001	0.452*	0.060	0.773*	0.658*	0.874*	0.953*	1.000
IndP		-0.129	-0.137	0.150	-0.041	0.034	0.159	0.235*	0.043	0.458*	0.322*	0.854*	0.777*	0.809*	0.846*	0.766*

Significant correlations at $p<0.01$ are indicated as *

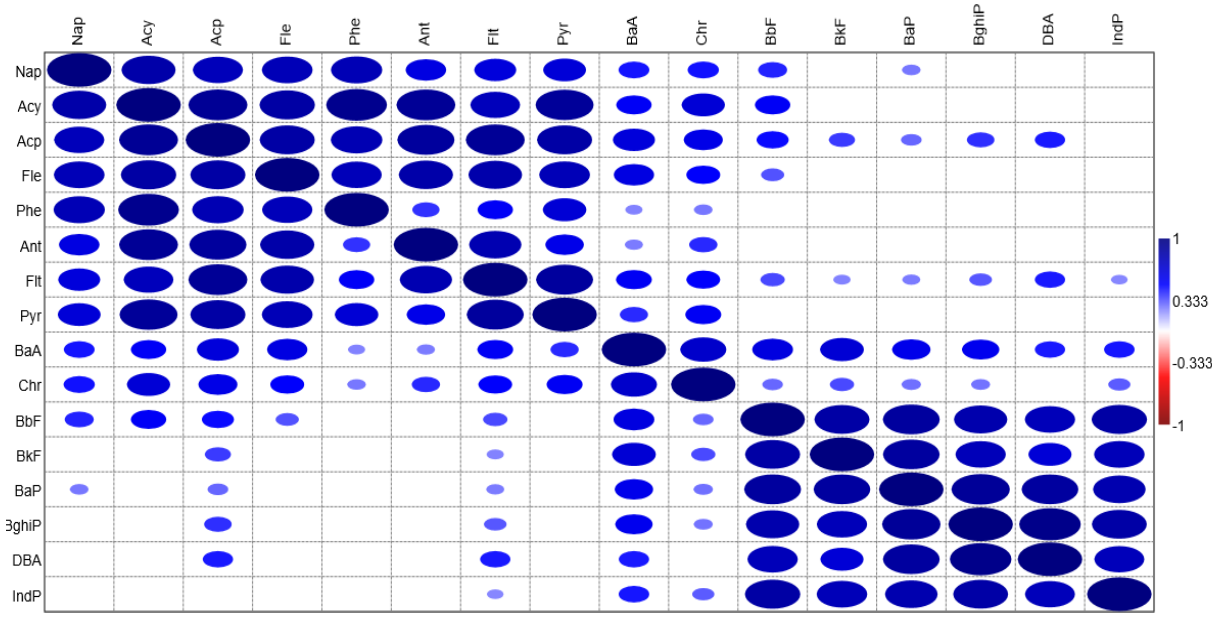

Figure 4. Correlation plot of sixteen PAHs in ambient air

Several authors have reported thermal power plant, vehicles (diesel + gasoline), coal and biomass burning as majorsources of PAH in India (Ekka *et al.*, 2021; Kumar *et al.*, 2020; Gune *et al.*, 2019; Giri *et al.*, 2013; Khillareet *al.*, 2008).

RISK ASSESSMENT

Through various pathways (ingestion, inhalation or dermal contact), humans are exposed to PAHs. During this review, inhalation pathway is considered for exposure, and health impact as cancer risk was estimated. Incremental lifetime cancer risk (ILCR) was estimated by calculating the lifetime average daily dose (LADD) of PAHs. Purposely, LADD and subsequent ILCR was estimated using equation 2 & 3, and input parameters (ATSDR, 2005, Narsinga Rao 2010; USEPA, 2019).

$$\text{LADD (mg/kg/day)} = \frac{\text{C x IR x EF x ED}}{\text{BW x AT}} \text{ x UCF} \qquad [2]$$

$$\text{ILCR} = \text{LADD x CSF} \qquad [3]$$

Where, C is concentration of PAH compound in ng/m^3, IR is inhalation rate in m^3/day (Children, 13.5; Adult, 13), EF is exposure frequency in days (365), ED is exposure duration in years (Children, 12; Adult, 70), BW is body weight in kg (Children, 35; Adult, 65), AT is averaging time in days (Children, 4380; Adult, 25,550), CSF is cancer slope factor for BaP (7.3 mg/kg/day), and UCF is unit conversion factor. Various organizations have categorized the values of ILCR for very low ($\leq 10^{-6}$), low (10^{-6} < - <10^{-4}), moderate (10^{-4} - <10^{-3}), and high (10^{-3} ≤ - <10^{-1}) (USEPA, 2019; NYS DOH, 2007; ATSDR, 2005), and acceptable ILCR of 10^{-6}-10^{-4} has been stipulated by WHO (2000). It is defined that 7.3x10^{-3} per µg BaP/kg/day, or ILCR of 7.3×10^{-3} may be cause by 1 µg BaP kg/day (USEPA, 2017). Estimated average of LADD for adults and children is 6.25x10^{-6} mg/kg/day and 2.39x10^{-6} mg/kg/day, respectively (**Figure 5**). Based on variable characteristic sources of PAHs, ILCR to humans residing in India varied. 75th percentile of LADD of ∑PAHs for adults is 5.37x10^{-6} mg/kg/day, while for children is 2.30x10^{-6} mg/kg/day, respectively. The LADD for adults are comparatively higher than children, but less than recommended value of 1 µg BaP /kg/day (1x10^{-3} mg/kg/day) (USEPA, 2017). Based on LADD, the subsequent average ILCR of ∑PAHs for adults and children is 3.88x10^{-5} and 1.31x10^{-5}, respectively. The 75th percentile of ILCR adults is 3.22x10^{-5}, and for children is 1.09x10^{-5} (**Figure 5**). It is observed that H-

PAHs particulary BaP and DBA with higher TEF are significant for carcinogenic potential. Their contribution to tolal ILCR is accounted for 36% and 62%, respectively. As categorized, estimated ILCR due to ∑PAHs & H-PAHs in India is low (<10^{-4}), and for L-PAHs it is very low (<10^{-6}). Therefore, it is concluded from available data that ILCR to human adults and children due to PAHs in ambient air of India can be categorised as very low to low.

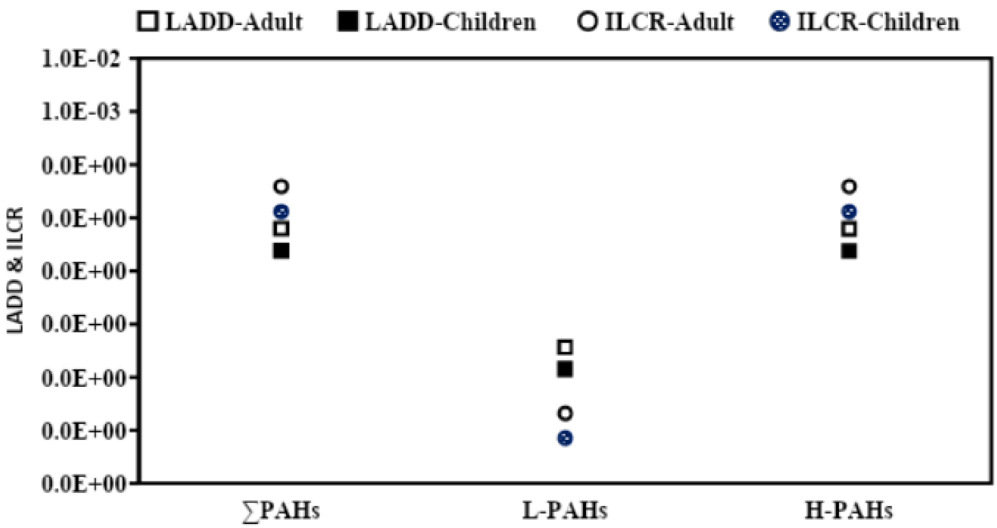

Figure 5. Average LADD and ILCR for human adults and children due to PAHs in ambient air

CONCLUSIONS

Various studies on PAHs in air and their human health risks carried out in India. Globally, several reviewson air PAHs and associated human health risks available, but, no review available for India. Meta-analysisof data on PAHs in ambient air at different location in India retrieved through various databases, shows varied distribution pattern. Dominant PAHs are 4-ring followed by 3-ring PAHs, and BaP was found exceeded the NAAQS. 5-ring and 6-ring PAHs were the dominant contributors to ∑BaPeq and consideredsignificant for carcinogenic potential of PAHs.

Source identification though various tools revealed mixed petrogenic and pyrogenic sources of PAHs emission to Indian environment. Where, petrogenic sources includes emissions from surface runoff, automobile workshops and spillage of petroleum products. However, wood, grass and coal burning, diesel, industrial and vehicular emissions are the major pyrogenic sources.

LADD and subsequent ILCR to humans due to PAHs in air of India were estimated following international guidelines. Although, LADD for adults are comparatively higher than children, but less than recommended limit of 1 µg BaP /kg/day ($1x10^{-3}$ mg/kg/day). The estimated ILCR due to ∑PAHs in India can be categorised very low (<10^{-6}) and low (<10^{-4}) for Indian population. Review warranted the further comprehensive research on PAHs in ambient air in India for planning and control measure strategies need to reduce air pollution.

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