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# Receptor modelling study of polycyclic aromatic hydrocarbons in Jeddah, Saudi Arabia

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2 3	Receptor Modelling Study of Polycyclic Aromatic Hydrocarbons in Jeddah, Saudi Arabia
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# 21 ABSTRACT

Measurements of 14 polycyclic aromatic hydrocarbons (PAH) have been made in Jeddah, Saudi 22 Arabia, with a view to establishing the concentrations in this major city, and quantifying the 23 contributions of major sources. Particulate and vapour forms have been sampled and analysed 24 separately. The concentrations are compared to measurements from other sites in the Middle Eastern 25 region and are towards the lower end of the range, being far lower than concentrations reported from 26 Riyadh (Saudia Arabia), Assiut (Egypt) and Tehran (Iran) but broadly similar to those measured in 27 Damascus (Syria) and higher than those measured in Kuwait. The partitioning between vapour and 28 particle phases is similar to that in data from Egypt and China, but with many compounds showing a 29 higher particle-associated percentage than in Birmingham (UK) possibly reflecting a higher 30 concentration of airborne particulate matter in the former countries. Concentrations in Jeddah were 31 32 significantly higher at a site close to the oil refinery and a site close to a major ring road than at a suburban site to the north of the city. Application of Positive Matrix Factorisation to the pooled data 33 elicited three factors accounting respectively for 17%, 33% and 50% of the measured sum of PAH and 34 35 these are interpreted as arising from gasoline vehicles, industrial sources, particularly the oil refinery, and to diesel/fuel oil combustion. 36

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38 Keywords: Polycyclic aromatic hydrocarbons; PAH; Positive Matrix Factorisation; PMF; Source
 39 apportionment

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# 43 1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAH) have generated a great deal of interest over several decades 44 owing to their known carcinogenic and mutagenic properties (Giger and Blumer, 1974). PAH are 45 46 ubiquitous pollutants, present in the atmosphere in the vapour phase and associated with particulate matter (Harrison et al., 1996), as well as in other environmental media and foodstuffs. PAH congeners 47 are mainly formed through incomplete combustion or pyrolysis of organic material and many have 48 mutagenic and carcinogenic properties, leading to many human health concerns (Collins et al., 1998). 49 Major anthropogenic sources include both stationary sources such as industrial and domestic 50 combustion, and mobile sources including road traffic. PAH have multiple point and diffuse sources, 51 and unlike other persistent organic pollutants, cannot be controlled by the introduction of substitute 52 chemicals (Jang et al., 2013). With the percentage of the population living in urban areas increasing 53 54 and liable to exposure to elevated concentrations of PAH, it is important to understand and assess the 55 occurrence and sources of PAH.

56

57 Numerous studies have assessed different methods of source apportionment, in an attempt to devise efficient strategies to reduce pollution of the urban atmosphere by PAH. For example, diagnostic ratios 58 59 have been utilised to identify pyrogenic or petrogenic sources (Zhang et al., 2005), diesel or gasoline 60 sources (El-Mubarak et al., 2014), fuel or combustion (De La Torre-Rouche et al., 2009) and traffic related sources (Katsoyiannis et al., 2007) and this work has recently been reviewed by Tobiszewski 61 and Namiesnik (2012). Further studies, however, have highlighted the variable range of emission 62 63 factors and compound ratios from given source categories, deeming this method of source apportionment imprecise (Katsoyiannis et al., 2011). In addition, more recent studies have suggested 64 that diagnostic ratios are a useful tool for assessing atmospheric reactivity of PAH, rather than source 65 apportionment, as these ratios are subject to small changes as the distance from the original source 66

increases (Alam et al., 2013; Alam et al., 2014; Keyte et al., 2013; Katsoyiannis and Breivik, 2014). 67 Principal component analysis (PCA) has also been utilised as a source apportionment method which 68 separates chemical constituents of the atmosphere according to their source using a statistical factor 69 70 analysis method (Hopke et al., 2006; Mari et al., 2010). However, PCA is subject to drawbacks including the issue of negative solutions. This has been subsquently overcome by using positive matrix 71 factorisation (PMF) as the preferred technique of source apportionment of atmospheric constituents 72 (Jang et al., 2013; Dvorska et al., 2012). The other commonly used source apportionment method, the 73 74 Chemical Mass Balance model, requires locally generated PAH source profiles which were not 75 available.

A vast number of measurements of airborne concentrations of PAH have been reported from various 76 geographical locations, including UK, Europe, USA and China. However, very little information has 77 been reported from the Middle East. The environmental concerns of Saudi Arabia, in particular, are 78 79 increasing with increasing developmental activity (Magram et al., 2009). Jeddah, the second largest city and most significant commercial centre in Saudi Arabia, has experienced a rapid and diverse 80 growth over the last thirty years and has been accompanied by environmental degradation. Air quality 81 has progressively deteriorated and the number of vehicles has increased to more than 1.4 million (Saudi 82 Network, 2008). The city's major stationary PAH sources include a desalination plant, a power 83 generation plant and an oil refinery. The oil refinery was originally built in a non residential area, but 84 with urbanisation, is now in the middle of a highly populated area (Al-Jahdal and Bisher, 2008). 85

In this study, we report the airborne concentration of 14 PAH compounds in both vapour and particulate phases in Jeddah, Saudi Arabia. Three sampling locations were chosen according to their proximity to the Jeddah oil refinery and data were collected simultaneously. Positive matrix factorisation is utilised to separate the chemical constituents according to their congener profile and the results are discussed in terms of likely source categories.

# 91 **2. EXPERIMENTAL**

#### 92 2.1 Site Location

Sampling was conducted simultaneously at three locations in Jeddah, the second largest city and most 93 significant commercial centre in the Kingdom of Saudi Arabia, with a population of ca. 3.4 million. 94 The sampling sites are shown in Figure 1. The locations where chosen according to their distance from 95 the Jeddah oil refinery. Site A was a primary school situated in a highly populated economically 96 disadvantaged residential area, located in the Ghulail district, south of the city and ca. 700 m east of the 97 Jeddah oil refinery. Site B was a primary school, located in the Al-Muntazahat district, East of Jeddah, 98 ca. 150 m adjacent to the heavily trafficked Al-Haramain ring road. Site C was an urban background 99 site located in the Al-Murjan district, situated on the Red Sea Creek (Sharm Obhur), and is subjected to 100 anthropogenic emissions from some moderately busy roads (nearest road ca. 300 m away) and 101 102 surrounding activities from a few local residents. The samplers at all sites were located at a height of ca. 9 m above street level. This was to ensure that contaminated road dust was not sampled, and to 103 104 ensure that samplers were not interfered with.

105

# 106 **2.2** Sample Collection

Daily (24 h) samples were collected simultaneously at the three sampling locations between 23 February 2013 and 23 April 2013, using a polyurethane foam high volume air sampler (TE-PUF, Tisch Environmental, Inc). The sampler typically draws volumes of air in the range of 240 – 300 m<sup>3</sup> over a 24 h period, through a quartz microfibre filter (TE-QMA4 10.16 cm) substrate, to collect compounds in the particulate phase, followed by an absorbent polyurethane foam (PUF) substrate, to collect compounds present in the gaseous phase. Temperatures during the study ranged between 26 and 30 °C for all three sites.

# 115 **2.3** Sample Analyses

Prior to sampling, the filters were preheated at 400 °C for 48 h in a box furnace, wrapped in clean 116 preheated foil, placed in a cardboard box and sealed in an airtight metallic container. The PUF 117 118 substrates were pre-cleaned prior to their use in the field by immersing in 100 mL of dichloromethane (DCM) and ultrasonicating at 20 °C for 30 min. The solvent was then drained and the PUF substrates 119 were left to dry in a sealed metal container under a stream of nitrogen. The clean and dry PUF 120 substrates were subsequently sealed in airtight plastic bags and stored in the freezer. Once exposed, the 121 122 filter and PUF substrates were wrapped separately with clean preheated foil, enclosed in airtight plastic bags and stored at approximately -18 °C. 123

124

Samples were analysed for 14 PAH using the methodology described previously (Delgado-Saborit et 125 al., 2013). Briefly, filter and PUF substrates were spiked with 1000 pg  $\mu L^{-1}$  deuterated internal 126 127 standards for quantification (see Supplementary Material for a list of these compounds). Filters were immersed in DCM and ultrasonicated for 15 min at 20 °C. The extract was subsequently dried and 128 129 cleaned using a chromatography column filled with 0.5 g of anhydrous sodium sulphate (puriss grade 130 for HPLC). The extract was further concentrated to 50 µL under a gentle N<sub>2</sub> flow. PUF substrates were immersed in 100 mL of DCM and ultrasonicated for 20 min at 20 °C. The sample was then 131 concentrated to 10 mL using N<sub>2</sub> and subsequently dried and cleaned as outlined for the filters above. 132

Samples were analysed for PAH compounds using Gas Chromatography (6890, Agilent Technologies) equipped with a non-polar capillary column (Agilent HP-5MS, 30m, 0.25 mm ID, 0.25  $\mu$ m film thickness – 5 % phenylpolysiloxane) in tandem with a Mass Spectrometer (5973N, Agilent Technologies). The precision of analysis was 8±4% and the accuracy, expressed as the difference between the measured and true value as a percentage of the true value was 6±4%. The analytical detection limits varied widely between congeners, and sample detection limits estimated from analysis of blank filters and PUFs all lay well below 1 pg m<sup>-3</sup> for the 24-hour air samples. Further information
regarding the analytical procedure can be found in Delgado-Saborit et al., 2013.

141

# 142 **2.4 Positive Matrix Factorisation (PMF)**

PMF is a multivariate receptor model that is used to identify a number of factors (*p*), the species profile (*f*) of each source and the amount of mass (*g*) contributed by each factor to each individual sample, and is defined as follows:

$$x_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij}$$

where  $x_{ij}$  is the  $j_{th}$  measured species concentration in the  $i_{th}$  sample,  $g_{ik}$  is the is the factor contribution of *k* source to  $i_{th}$  sample,  $f_{kj}$  is the fraction of *j* species in the *k* source, and  $e_{ij}$  is the residuals matrix. PMF is described in detail elsewhere (Paatero and Tapper, 1994; Paatero, 1997). Briefly, it is weighted least square fit, to search for a proper residual matrix by minimising the object function, Q(E), as follows (Hopke, 2001):

$$Q(E) = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\frac{E_{ij}}{\partial_{ij}}\right)^{2}$$

where  $\partial_{ij}$  is the estimated uncertainty associated with the determination of  $x_{ij}$  and  $E_{ij}$  is the scaled residual defined as:

$$E_{ij} = x_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}$$

Appropriate uncertainties,  $\partial_{ij}$ , are imperative for PMF analyses, where the user has the freedom to generate the  $\partial$  matrix based on method detection limits and uncertainties in the measurements. Information regarding method detection limits and uncertainties in the chemical measurements, which

156	were applied to these data, are described elsewhere (Delgado-Saborit et al., 2013). The robust mode is
157	the default mode with EPA PMF v3.0, which reduces the effect of very large variables by treating them
158	as outliers so that they do not affect the model fitting process and results (Sofowote et al., 2011).

Multiple f and g matrices with the same minimum Q value can exist, and thus the least squares approach can produce multiple solutions depending on the initial starting point (Jang et al., 2013; Sofowote et al., 2011). In order to estimate a statistically stable solution, factor rotation by changing Fpeak values from -1.4 and 0.3 was conducted, as well as utilising the bootstrapping technique, within EPA PMF v3.0 software, based on arbitrary selection of n samples from the data. More details on bootstrapping factor profiles, rotations and other features of PMF can be found elsewhere (Norris et al., 2008).

166

# 167 3. **RESULTS AND DISCUSSION**

# 168 **3.1 PAH Concentrations**

The average total (vapour and particulate) concentration of PAH measured at the three sampling sites 169 between 23 February and 23 April 2012-2013 are shown in Table 1. Concentrations measured at sites A 170 and B were statistically larger (t test, p < 0.01) than those measured at site C, where average total 171 concentrations for all PAH measured at site C were between 50 and 90 % lower (see Table 1). Total 172 concentrations measured at site A were significantly larger (t test, p < 0.05) to those at site B, with the 173 174 exception of ANT and B(a)A, where no significant difference was observed. This demonstrates the importance of oil refinery and traffic related emissions of PAH. Lower molecular weight (LMW) PAH 175 compounds (Da <202) were predominantly in the vapour phase, where the most abundant PAH 176 177 measured at the three sites were PHE, FLU and PYR, in agreement with previous measurements from Western Europe, the Middle East and China (Albinet et al., 2007; Gevao et al., 2006; Ma et al., 2011). 178

The concentrations of vapour phase LMW PAH were largest at site A followed by B and C, with the 179 exception of ANT, which was frequently (~53 %) larger at site B. Higher molecular weight (HMW) 180 PAH compounds (Da >228) were predominantly in the particulate phase, with B(ghi)P and COR being 181 the most abundant at sites A and B, and B(ghi)P and CHR being the two most abundant PAH at site C. 182 This suggests that sites A and B may be associated with high levels of vehicular emissions, as B(ghi)P 183 and COR are often used as vehicular emission tracers (Greenberg et al., 1981; Harkov et al., 1984). 184 Furthermore, although HMW PAH in the particulate phase (B(b)F to COR) were statistically different 185 between all sites, LMW PAH in the particulate phase (PHE to CHR) were remarkably similar for sites 186 A and B (within 10%). 187

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Table 2 summarises the PAH concentrations measured in Jeddah and some other cities around the 189 190 world. The average total suspended particulate (TSP) concentration for sites A, B and C were 435, 396, 232  $\mu$ g/m<sup>3</sup>, reflecting the large crustal dust component present in particulate matter in the Middle 191 Eastern area. The measured PAH concentrations, however, are only modestly higher than those 192 193 measured in urban areas of the United Kingdom (Delgado-Saborit et al., 2013; Alam et al., 2013), and 194 significantly lower than those previously measured in different areas of Saudi Arabia (El-Mubarak et 195 al., 2014; Habeebullah, 2013). Habeebullah (2013) conducted a risk assessment of PAH in Makkah, 196 located ca. 85 km east of Jeddah, during an influx of approximately 2.8 million pilgrims to the city, in 197 November 2010. They reported total particulate PAH concentrations in the range of 103.5 to 195.2  $ng/m^3$ , a factor of 17 to 33 times larger than Site A in this study. These high concentrations were 198 199 attributed to various residential activity and traffic emissions. Makkah City, however, has been subject 200 to extensive building construction since 2009, particularly in the vicinity of two of their sampling sites, which may also give rise to the elevated levels reported in their study. In a more recent study, El-201 202 Mubarak et al. (2014) reported PM<sub>10</sub> PAH concentrations in Riyadh, located *ca*. 1000 km north east of

Jeddah, in December 2010. The authors reported extremely high concentrations of individual PAH 203 congeners of up to 1003 ng/m<sup>3</sup>, with an average concentration of B(a)P of 400 ng/m<sup>3</sup>, three orders of 204 magnitude larger than this study (0.39  $ng/m^3$  for site A). Furthermore, Abdallah et al. (2014) 205 206 investigated gaseous and particulate PAH concentrations across 9 sampling locations in Assiut, Egypt and reported total mean concentrations of B(a)P of up to 108.2 ng/m<sup>3</sup> in high population density areas. 207 The large concentrations measured were attributed to vehicular exhaust emissions which was also 208 highlighted by Hasan and Khoder (2012) who reported total mean concentrations for B(a)P and 209 B(ghi)P of 159.55 and 219.32  $ng/m^3$ , respectively; at a traffic related site in Giza, Egypt. 210

211

Concentrations reported from Middle Eastern countries other than Egypt and other parts of Saudi 212 Arabia are also relatively higher than those reported in this study. Total mean concentrations of PHE, 213 B(a)P and B(ghi)P in Tehran, Iran were 278.19, 18.71 and 34.38 ng/m<sup>3</sup> where the major emission 214 sources are thought to be traffic-related (Halek at el., 2010). In Damascus, Syria, the concentration of 215 particulate B(a)P and B(ghi)P was ~ 4.5 and 5.2  $ng/m^3$ , respectively (Dimashki et al., 1996). However, 216 PAH concentrations reported from Kuwait were lower than those in this study (Gevao et al., 2006), 217 where average airborne concentrations were in the range of 2.63  $ng/m^3$  (for PHE) and 0.07  $ng/m^3$  (for 218 D(ah)A). The authors also reported that approximately 70 to 90 % of the total PAH concentration 219 220 consisted of PHE, FLU and PYR, and a substantial increase in the contribution of HMW PAH to the total PAH was observed at sites closer to the oil lakes of Kuwait. 221

222

223 The influences upon the partitioning of PAH between the vapour and condensed phases need to be
224 considered as PAH are known to cycle actively between the particle and vapour phases. There have
225 been various theoretical treatments of these processes reviewed in Keyte et al. (2013), the simplest
226 being due to Yamasaki et al. (1982), which can be expressed as:

$$\log[A(TSP)F^{-1}] = -mT^{-1} + c$$

228

in which *A* is the gas-phase concentration, *TSP* is total suspended particulate matter, *F* is the particulate (filter) concentration, *T* is the sampling temperature (K), and *m* and *c* are compound-dependent empirical constants. From this, it may be seen that an increase in temperature will be associated with a relative increase in vapour (A/F increases), and an increase in *TSP* leads to a reduction in vapour (A/Fdecreases).

234

Figure 2 shows the percentage particulate PAH in various locations. The data from Jeddah are very similar to those from Egypt (Giza and Asiut) and China (Wanqingsha), but for the lower molecular weight compounds have a higher particulate component than in the data from Birmingham (UK). This seems likely to be reflective of the higher TSP loading in Jeddah causing greater partitioning into the particle phase, outweighing the effect of temperature in increasing the vapour phase component, as TSP concentrations in Birmingham are generally < 30  $\mu$ g m<sup>-3</sup> (unpublished data).

241

## 242 **3.2 PMF Modelling**

A 52 × 14 matrix (sample number × 14 PAH species) dataset was introduced into the EPA PMF v3.0 software to assess the source contribution to PAH. Total PAH (vapour + particulate) was used to minimise the influence of partitioning, ageing and photochemical degradation (Kim et al., 2009). Uncertainties applied to the data corresponded to the calculated limits of detection and recovery standard deviation of the surrogate standards as outlined in Delgado-Saborit et al. (2013) and as modified by Jang et al. (2003) to give less weight to the more reactive compounds, which are expected to degrade appreciably between source and receptor. Three source factors were extracted from the PMF
model, illustrated in Figure 3.

251

Factor 1 accounted for 17 % of the sum of the measured PAH species and was attributed to traffic emissions, in particular gasoline powered vehicles. The profile (see Figure 3) includes conventional traffic biomarkers including B(a)P, B(ghi)P and COR (Greenberg et al., 1981; Harkov et al., 1984; Mastral et al., 2003; Ning et al., 2007). A strong temporal profile was also observed in this factor with average concentration levels during weekdays being significantly larger for the sum of PAH ( $\Sigma$ PAH) and B(a)P than at weekends (Figure 4).

258

Factor 2 was attributed to industrial sources, in particular the oil refinery, and accounted for up to 33 % 259 260 of the sum of the measured PAH species. This factor was dominated by FLU, PYR and D(ah)A and did not show a significant difference between weekdays and weekends. The UK National Atmospheric 261 Emissions Inventory (http://naei.defra.gov.uk/) reports relatively large emissions of FLU from refinery 262 263 combustion between 2002 and 2006, in agreement with Factor 2 from this study. Kulkarni and 264 Venkataraman, (2000) reported the significance of FLU and PYR emissions from oil combustion activities and the predominance of B(a)P, PYR and D(ah)A from kerosene uses. Furthermore, in a 265 266 recent PMF study of urban air in the UK, it was reported that only a small concentrations of D(ah)A could be attributed to the net traffic contribution (Jang et al., 2013). This factor was responsible for the 267 268 largest contribution at site A, which is located *ca*. 700 m from Jeddah's oil refinery. Site specific plots 269 and weekday-weekend variation are shown in Figure 4.

270

Factor 3 accounted for 50 % of the sum of the measured PAH species and was dominated by LMW
PAH compounds (PHE, ANT, FLU, B(a)A and CHR). A strong temporal profile was also observed in

this factor with average concentration levels during weekdays being significantly larger for  $\Sigma$ PAH and 273 B(a)P than at weekends (Figure 4). This factor was responsible for PAH concentrations in the order, 274 site B > site A > site C. The predominance of PHE along with FLU, CHR and PYR have been 275 276 previously reported as diesel exhaust markers and thus been associated with diesel traffic emissions (Riddle et al., 2008; Zielinska et al., 2004). However, enhanced levels of LMW PAH species have also 277 been attributed to oil combustion (Lee et al., 2004). In comparison to a previously reported diesel 278 combustion derived source profile from the UK NAEI (Jang et al., 2013), factor 3 has a larger 279 contribution of ANT, B(a)A and CHR, which may be explained by the use of different compositions of 280 diesel fuels between the UK and Saudi Arabia. Alternatively, the enhanced levels of LMW PAH 281 observed in factor 3 may be due to both oil combustion, originating from Jeddah's desalination plant, 282 and diesel traffic emissions, with a possible contribution from shipping, which burns predominantly 283 284 heavy fuel oils. This would affect predominantly site 1 which is close to the port. The desalination plant is situated central to all three sites (see Figure 1) and the prevailing north westerly winds means 285 that the emissions from the plant may affect mainly the sites A and B. 286

287

# 288 4. CONCLUSION

289 The concentrations of PAH measured in Jeddah are overall surprisingly similar to those in Birmingham 290 (UK) and Wanqingsha (China), while being higher than those reported for Kuwait, but far below the measurements reported for Assuit and Giza (Egypt) and Tehran (Iran) (see Table 2). Concentrations 291 292 decline from site A close to the oil refinery to site B which was close to the ring road, which are both 293 significantly higher than those at site C which was in a suburban area in the north of the city. The partitioning of PAH between the particle and vapour phases is broadly similar to that in many other 294 studies but shows some preferential partitioning into particles especially for low molecular weight 295 296 compounds compared to the data from Birmingham (UK). This is attributed to the very much higher concentrations of total suspended particulate matter (TSP) in Jeddah in comparsion to Birmingham
with the influence of the higher temperatures in Jeddah being a secondary effect tending towards higher
vapour concentations.

300

The source apportionment study, which is one of the very few successful published applications of PMF to PAH datasets, clearly shows three major source contributions. The largest appears to be from combustion of diesel and fuel oil, the former probably predominantly in road vehicles while there may be a significant contribution from the Jeddah desalination plant to the latter. The second largest contribution is from refinery emissions while the third contribution, which shows a strong weekday to weekend variation, is attributed to gasoline vehicle emissions.

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# 499 TABLE LEGENDS

Table 1. Average concentrations of PAH in ambient air (vapour and particulate phases) measured at the three sampling sites. Site A – Zaid Ibn Al-Khatab School, Site B – Al Hgag School, Site C – Abhor.

- **Table 2.**Average total (vapour and particulate) concentrations of PAH in ambient air measured at<br/>various cities around the world.

# 508509 FIGURE LEGENDS

- **Figure 1.** Map of Jeddah and locations of sampling sites and major PAH stationary sources.
- Figure 2. Average particle-vapour partitioning for PAH measured in Jeddah, SA (this study),
  Giza, Egypt (Hassan and Khoder, 2012), Assiut, Egypt (Abdallah et al., 2014),
  Birmingham, UK (Alam et al., 2013) and Wanqingsha, China (Huang et al., 2014).
  Molecular mass increases from left to right.
- Figure 3. Source factor profiles of atmospheric PAH obtained from EPA PMF 3.0 model for three sites in Jeddah, Saudi Arabia. <u>The bars show the chemical profile, and the diamonds are the variance explained by each factor.</u>
- 522 Figure 4. Factor contributions to the three sampling sites and the observed variation between
  523 weekdays and weekends, obtained from EPA PMF 3.0 model.

Table 1. Average concentrations of PAH in ambient air (vapour and particulate phases) measured at the three sampling sites. Site A - Zaid Ibn Al-Khatab School, Site B – Al Hgag School, Site C – Abhor. 

		Vapour			Particulate			TOTAL		% Particulate			
	Site A Site B Site C		Site A Site B Site C		Site A Site B		Site C	Site A	Site B	Site C			
PHE	21.00	16.70	8.60	0.15	0.13	0.05	21.15	16.83	8.65	0.69	0.78	0.53	
ANT	1.40	1.60	0.70	0.03	0.03	0.01	1.43	1.63	0.71	2.43	1.66	1.13	
FLU	3.30	2.50	1.05	0.17	0.19	0.06	3.47	2.69	1.11	5.00	7.09	5.36	
PYR	6.00	3.90	0.75	0.23	0.26	0.07	6.23	4.15	0.82	3.73	6.15	8.34	
B(a)A	0.05	0.04	0.02	0.19	0.20	0.05	0.23	0.24	0.06	80.22	84.95	71.31	
CHR	0.13	0.05	0.02	0.52	0.56	0.15	0.65	0.61	0.17	79.78	91.34	89.74	
B(b)F	0.09	0.07	0.02	0.48	0.40	0.10	0.57	0.47	0.12	83.86	85.02	81.94	
B(k)F	0.10	0.06	0.02	0.49	0.36	0.09	0.60	0.42	0.11	82.56	85.85	78.16	
B(e)P	0.02	0.02	0.02	0.59	0.47	0.11	0.60	0.50	0.13	97.12	95.30	84.22	
B(a)P	0.04	0.03	0.02	0.35	0.27	0.07	0.39	0.30	0.09	89.44	89.79	77.45	
IND	0.06	0.02	0.01	0.57	0.44	0.09	0.63	0.47	0.11	91.10	94.85	87.43	
D(ah)A	0.07	0.03	BDL	0.08	0.05	0.02	0.15	0.09	0.02	52.48	60.21	100.00	
B(ghi)P	0.05	0.03	0.01	1.22	0.99	0.16	1.27	1.03	0.17	95.77	96.83	94.78	
COR	BDL	BDL	BDL	0.79	0.61	0.09	0.79	0.61	0.09	100.00	100.00	100.00	
∑ <sub>14</sub> PAH	32.31	25.06	11.24	5.85	4.97	1.10	38.17	30.03	12.34	15.33	16.53	8.92	

BDL – below detection limit

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**Table 2.** Average total (vapour and particulate) concentrations of PAH in ambient air measured at various cities around the world.

		Average total (vapour + particulate) concentrations (ng/m <sup>3</sup> )														
		PHE	ANT	FLU	PYR	B(a)A	CHR	B(b)F	B(k)F	B(e)P	B(a)P	IND	D(ah)A	B(ghi)P	COR	∑ <sub>14</sub> PAH
This study	Site A	21.15	1.43	3.47	6.23	0.23	0.65	0.57	0.60	0.60	0.39	0.63	0.15	1.27	0.79	38.17
	Site B	16.83	1.63	2.69	4.15	0.24	0.61	0.47	0.42	0.50	0.30	0.47	0.09	1.03	0.61	30.03
	Site C	8.65	0.71	1.11	0.82	0.06	0.17	0.12	0.11	0.13	0.09	0.11	0.02	0.17	0.09	12.35
Assuit, Egypt <sup>a</sup>		100.39	57.12	79.62	70.04	65.01	78.18	90.26	48.40	-	49.39	32.26	45.86	63.39	-	779.91
Giza, Egypt <sup>b</sup>		257.18	187.27	216.79	188.09	175.99	211.56	229.88	-	-	159.55	123.08	174.97	246.32	-	2,170.68
Tehran, Iran <sup>c</sup>		278.19	155.04	802.78	61.09	30.79	29.41	41.61	27.68	-	18.71	32.28	28.93	34.38	-	1,540.89
Kuwait <sup>d</sup>		2.63	0.24	1.18	1.12	0.35	0.30	0.10	0.09	-	0.25	0.09	0.07	0.15	-	6.57
Wanqingsha, China <sup>e</sup>		40.00	1.54	14.60	9.81	1.09	3.21	3.15	1.29	-	1.65	2.33	0.37	2.67	-	81.71
Zaragoza, Spain <sup>f</sup>		2.30	0.46	1.10	1.10	0.33	0.41	0.47	0.13	0.28	0.29	1.	10	1.00	1.50	10.47
Birmingham, UK <sup>g</sup>		20.65	1.61	9.02	10.26	1.15	2.88	0.73	0.53	0.25	0.18	0.22	0.18	0.21	0.15	48.01

<sup>a</sup> Abdallah et al. (2014); <sup>b</sup> Hassan and Khoder (2012); <sup>c</sup> Halek et al. (2010); <sup>d</sup> Gevao et al. (2006); <sup>e</sup> Huang et al. (2014); <sup>f</sup> Callen et al. (2008) <sup>g</sup> Alam et al. (2013)











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Figure 2. Average particle-vapour partitioning for PAH measured in Jeddah, SA (this study), Giza, Egypt
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