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

4

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21 **ABSTRACT**

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

37

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

40

41

42

## 43 1. INTRODUCTION

44 Polycyclic aromatic hydrocarbons (PAH) have generated a great deal of interest over several decades  
45 owing to their known carcinogenic and mutagenic properties (Giger and Blumer, 1974). PAH are  
46 ubiquitous pollutants, present in the atmosphere in the vapour phase and associated with particulate  
47 matter (Harrison et al., 1996), as well as in other environmental media and foodstuffs. PAH congeners  
48 are mainly formed through incomplete combustion or pyrolysis of organic material and many have  
49 mutagenic and carcinogenic properties, leading to many human health concerns (Collins et al., 1998).  
50 Major anthropogenic sources include both stationary sources such as industrial and domestic  
51 combustion, and mobile sources including road traffic. PAH have multiple point and diffuse sources,  
52 and unlike other persistent organic pollutants, cannot be controlled by the introduction of substitute  
53 chemicals (Jang et al., 2013). With the percentage of the population living in urban areas increasing  
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  
58 efficient strategies to reduce pollution of the urban atmosphere by PAH. For example, diagnostic ratios  
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  
61 related sources (Katsoyiannis et al., 2007) and this work has recently been reviewed by Tobiszewski  
62 and Namiesnik (2012). Further studies, however, have highlighted the variable range of emission  
63 factors and compound ratios from given source categories, deeming this method of source  
64 apportionment imprecise (Katsoyiannis et al., 2011). In addition, more recent studies have suggested  
65 that diagnostic ratios are a useful tool for assessing atmospheric reactivity of PAH, rather than source  
66 apportionment, as these ratios are subject to small changes as the distance from the original source

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

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

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

91 **2. EXPERIMENTAL**

92 **2.1 Site Location**

93 Sampling was conducted simultaneously at three locations in Jeddah, the second largest city and most  
94 significant commercial centre in the Kingdom of Saudi Arabia, with a population of *ca.* 3.4 million.

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

105

106 **2.2 Sample Collection**

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

114

### 115 2.3 Sample Analyses

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

124  
125 Samples were analysed for 14 PAH using the methodology described previously (Delgado-Saborit et  
126 al., 2013). Briefly, filter and PUF substrates were spiked with 1000 pg  $\mu\text{L}^{-1}$  deuterated internal  
127 standards for quantification (see Supplementary Material for a list of these compounds). Filters were  
128 immersed in DCM and ultrasonicated for 15 min at 20 °C. The extract was subsequently dried and  
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  $\mu\text{L}$  under a gentle  $\text{N}_2$  flow. PUF substrates were  
131 immersed in 100 mL of DCM and ultrasonicated for 20 min at 20 °C. The sample was then  
132 concentrated to 10 mL using  $\text{N}_2$  and subsequently dried and cleaned as outlined for the filters above.

133 Samples were analysed for PAH compounds using Gas Chromatography (6890, Agilent Technologies)  
134 equipped with a non-polar capillary column (Agilent HP-5MS, 30m, 0.25 mm ID, 0.25  $\mu\text{m}$  film  
135 thickness – 5 % phenylpolysiloxane) in tandem with a Mass Spectrometer (5973N, Agilent  
136 Technologies). The precision of analysis was 8±4% and the accuracy, expressed as the difference  
137 between the measured and true value as a percentage of the true value was 6±4%. The analytical  
138 detection limits varied widely between congeners, and sample detection limits estimated from analysis

139 of blank filters and PUFs all lay well below 1 pg m<sup>-3</sup> for the 24-hour air samples. Further information  
140 regarding the analytical procedure can be found in Delgado-Saborit et al., 2013.

141

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

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

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

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

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

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

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

153 Appropriate uncertainties,  $\partial_{ij}$ , are imperative for PMF analyses, where the user has the freedom to  
154 generate the  $\partial$  matrix based on method detection limits and uncertainties in the measurements.  
155 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).

159 Multiple  $f$  and  $g$  matrices with the same minimum Q value can exist, and thus the least squares  
160 approach can produce multiple solutions depending on the initial starting point (Jang et al., 2013;  
161 Sofowote et al., 2011). In order to estimate a statistically stable solution, factor rotation by changing  
162  $F_{peak}$  values from -1.4 and 0.3 was conducted, as well as utilising the bootstrapping technique, within  
163 EPA PMF v3.0 software, based on arbitrary selection of  $n$  samples from the data. More details on  
164 bootstrapping factor profiles, rotations and other features of PMF can be found elsewhere (Norris et al.,  
165 2008).

166

### 167 **3. RESULTS AND DISCUSSION**

#### 168 **3.1 PAH Concentrations**

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

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

188

189 Table 2 summarises the PAH concentrations measured in Jeddah and some other cities around the  
190 world. The average total suspended particulate (TSP) concentration for sites A, B and C were 435, 396,  
191 232  $\mu\text{g}/\text{m}^3$ , reflecting the large crustal dust component present in particulate matter in the Middle  
192 Eastern area. The measured PAH concentrations, however, are only modestly higher than those  
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  
198  $\text{ng}/\text{m}^3$ , a factor of 17 to 33 times larger than Site A in this study. These high concentrations were  
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,  
201 which may also give rise to the elevated levels reported in their study. In a more recent study, El-  
202 Mubarak et al. (2014) reported  $\text{PM}_{10}$  PAH concentrations in Riyadh, located *ca.* 1000 km north east of

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

211

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

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:

227

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

228

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

234

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

241

## 242 3.2 PMF Modelling

243 A  $52 \times 14$  matrix (sample number  $\times$  14 PAH species) dataset was introduced into the EPA PMF v3.0  
244 software to assess the source contribution to PAH. Total PAH (vapour + particulate) was used to  
245 minimise the influence of partitioning, ageing and photochemical degradation (Kim et al., 2009).  
246 Uncertainties applied to the data corresponded to the calculated limits of detection and recovery  
247 standard deviation of the surrogate standards as outlined in Delgado-Saborit et al. (2013) and as  
248 modified by Jang et al. (2003) to give less weight to the more reactive compounds, which are expected

249 to degrade appreciably between source and receptor. Three source factors were extracted from the PMF  
250 model, illustrated in Figure 3.

251

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

258

259 Factor 2 was attributed to industrial sources, in particular the oil refinery, and accounted for up to 33 %  
260 of the sum of the measured PAH species. This factor was dominated by FLU, PYR and D(ah)A and did  
261 not show a significant difference between weekdays and weekends. The UK National Atmospheric  
262 Emissions Inventory (<http://naei.defra.gov.uk/>) reports relatively large emissions of FLU from refinery  
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  
265 activities and the predominance of B(a)P, PYR and D(ah)A from kerosene uses. Furthermore, in a  
266 recent PMF study of urban air in the UK, it was reported that only a small concentrations of D(ah)A  
267 could be attributed to the net traffic contribution (Jang et al., 2013). This factor was responsible for the  
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

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

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

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  
291 measurements reported for Assuit and Giza (Egypt) and Tehran (Iran) (see Table 2). Concentrations  
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  
294 partitioning of PAH between the particle and vapour phases is broadly similar to that in many other  
295 studies but shows some preferential partitioning into particles especially for low molecular weight  
296 compounds compared to the data from Birmingham (UK). This is attributed to the very much higher

297 concentrations of total suspended particulate matter (TSP) in Jeddah in comparison to Birmingham  
298 with the influence of the higher temperatures in Jeddah being a secondary effect tending towards higher  
299 vapour concentrations.

300  
301 The source apportionment study, which is one of the very few successful published applications of  
302 PMF to PAH datasets, clearly shows three major source contributions. The largest appears to be from  
303 combustion of diesel and fuel oil, the former probably predominantly in road vehicles while there may  
304 be a significant contribution from the Jeddah desalination plant to the latter. The second largest  
305 contribution is from refinery emissions while the third contribution, which shows a strong weekday to  
306 weekend variation, is attributed to gasoline vehicle emissions.

307

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499 **TABLE LEGENDS**

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

504

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

507

508

509 **FIGURE LEGENDS**

510

511 **Figure 1.** Map of Jeddah and locations of sampling sites and major PAH stationary sources.

512

513 **Figure 2.** Average particle-vapour partitioning for PAH measured in Jeddah, SA (this study),  
514 Giza, Egypt (Hassan and Khoder, 2012), Assiut, Egypt (Abdallah et al., 2014),  
515 Birmingham, UK (Alam et al., 2013) and Wanqingsha, China (Huang et al., 2014).  
516 Molecular mass increases from left to right.

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518 **Figure 3.** Source factor profiles of atmospheric PAH obtained from EPA PMF 3.0 model for three  
519 sites in Jeddah, Saudi Arabia. The bars show the chemical profile, and the diamonds  
520 are the variance explained by each factor.

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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.

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 527 Khatab School, Site B – Al Hgag School, Site C – Abhor.  
 528

	Average Concentration (ng/m <sup>3</sup> )											
	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
Σ <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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534 **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	Σ <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

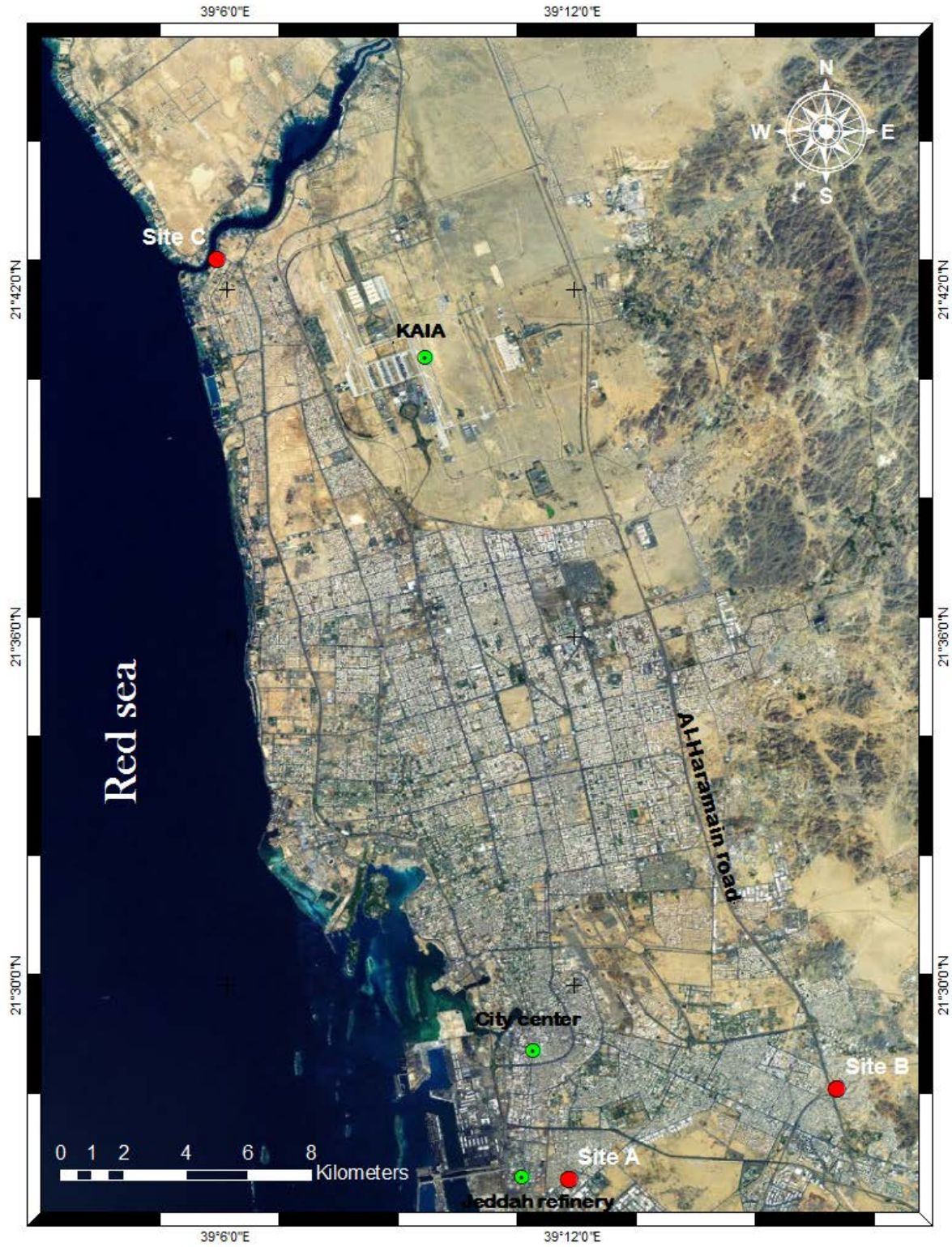
<sup>a</sup> Abdallah et al. (2014); <sup>b</sup> Hassan and Khoder (2012); <sup>c</sup> Halek et al. (2010); <sup>d</sup> Gevao et al. (2006); <sup>e</sup> Huang et al. (2014); <sup>f</sup> Callen et al. (2008) <sup>g</sup> Alam et al. (2013)

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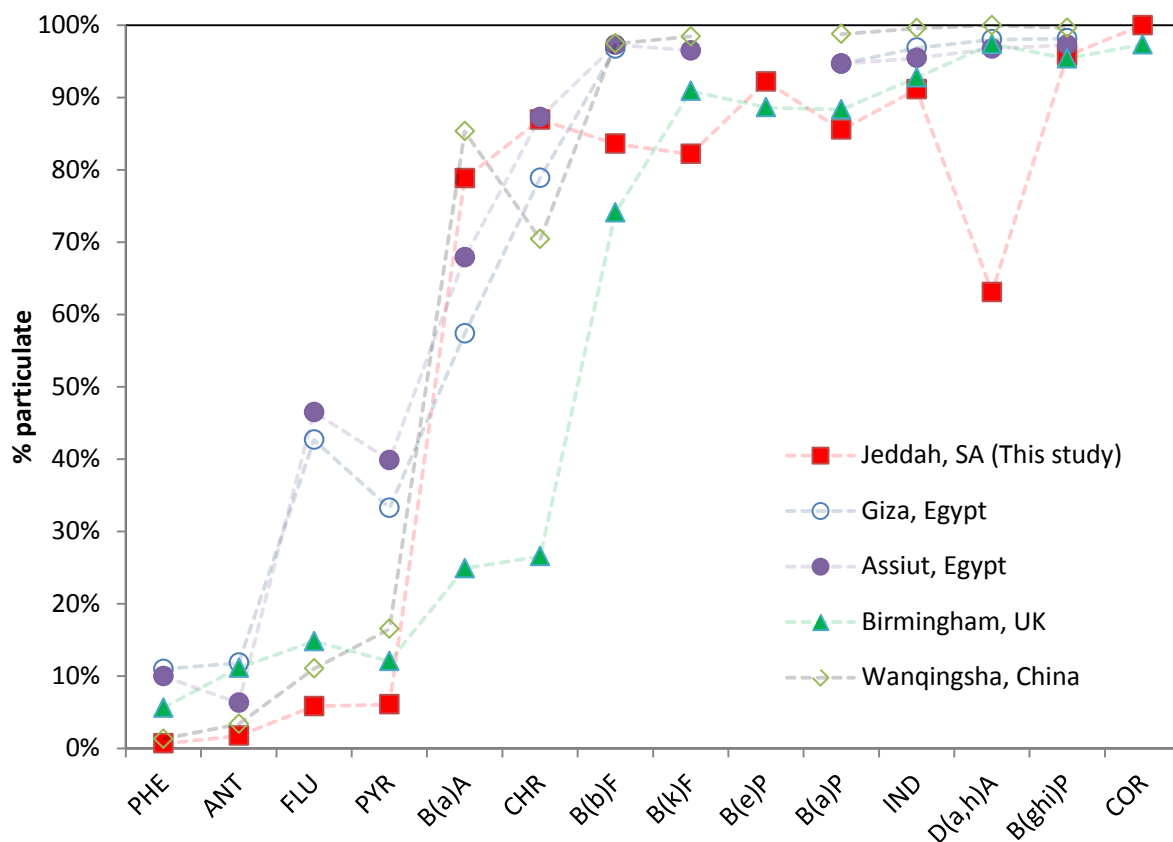


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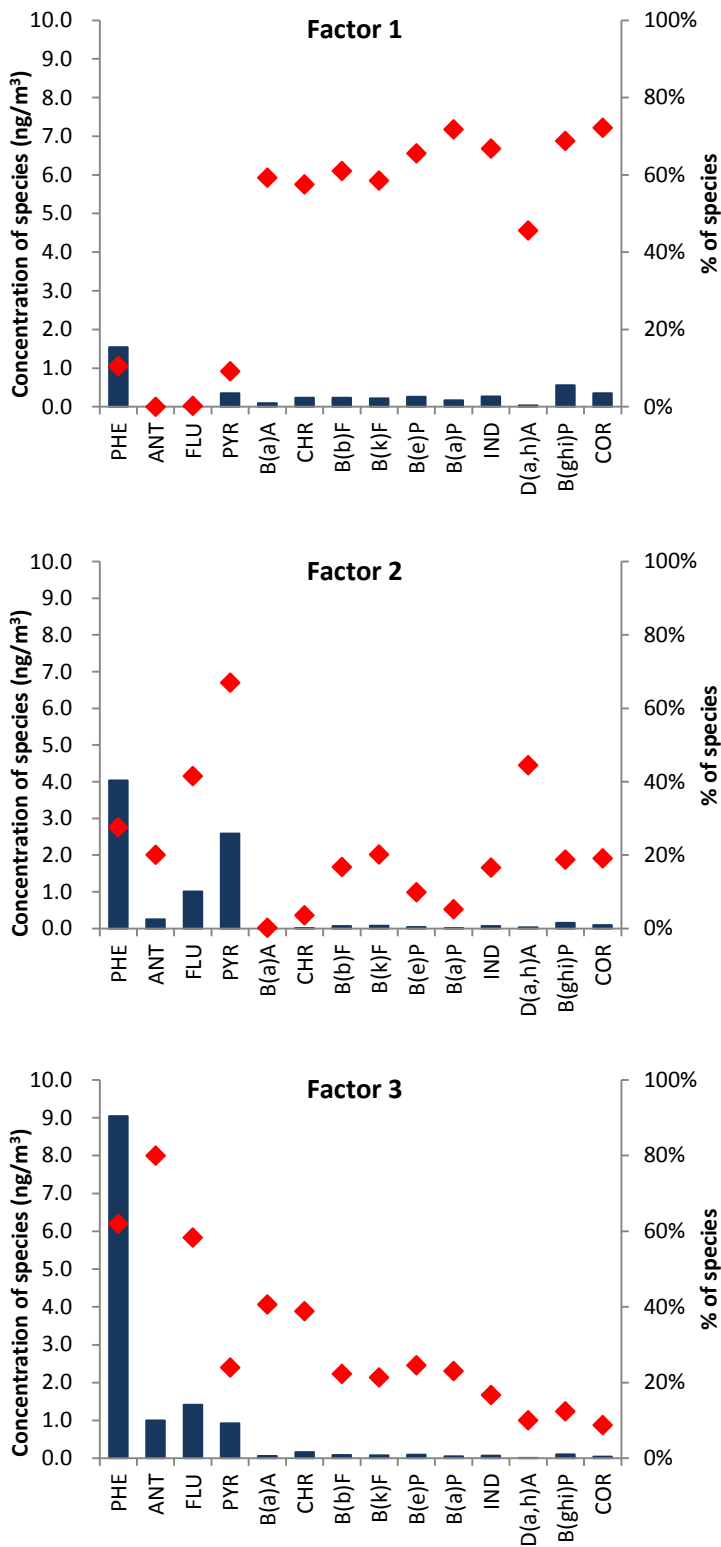
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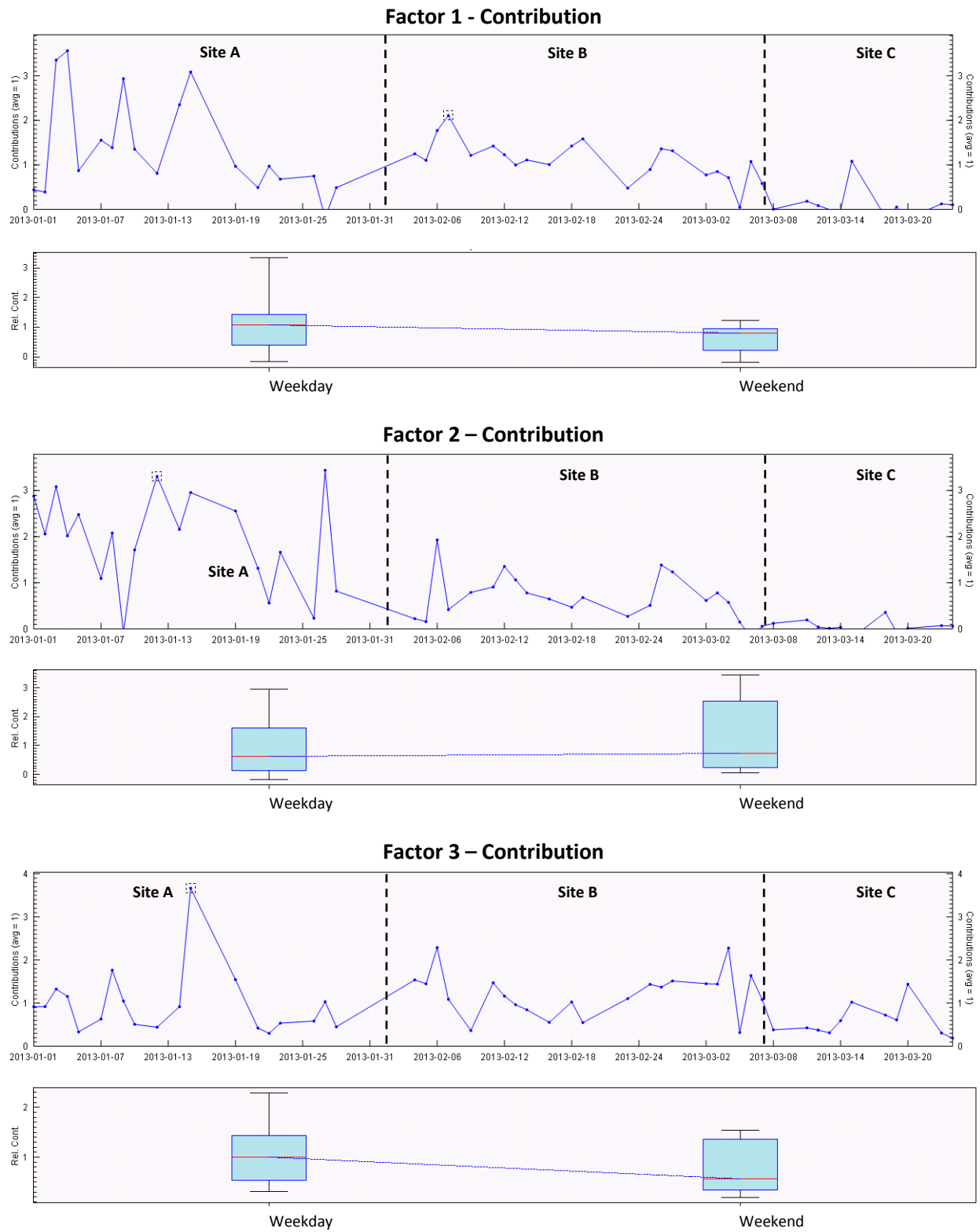
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**Figure 3.** Source factor profiles of atmospheric PAH obtained from EPA PMF 3.0 model for three sites in Jeddah, Saudi Arabia. The bars show the chemical profile, and the diamonds are the variance explained by each factor.



**Figure 4.** Factor contributions to the three sampling sites and the observed variation between weekdays and weekends, obtained from EPA PMF 3.0 model.