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

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ABSTRACT

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

Keywords: Polycyclic aromatic hydrocarbons; PAH; Positive Matrix Factorisation; PMF; Source apportionment
1. **INTRODUCTION**

Polycyclic aromatic hydrocarbons (PAH) have generated a great deal of interest over several decades owing to their known carcinogenic and mutagenic properties (Giger and Blumer, 1974). PAH are 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 are mainly formed through incomplete combustion or pyrolysis of organic material and many have mutagenic and carcinogenic properties, leading to many human health concerns (Collins et al., 1998). Major anthropogenic sources include both stationary sources such as industrial and domestic combustion, and mobile sources including road traffic. PAH have multiple point and diffuse sources, and unlike other persistent organic pollutants, cannot be controlled by the introduction of substitute chemicals (Jang et al., 2013). With the percentage of the population living in urban areas increasing and liable to exposure to elevated concentrations of PAH, it is important to understand and assess the occurrence and sources of PAH.

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 have been utilised to identify pyrogenic or petrogenic sources (Zhang et al., 2005), diesel or gasoline 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 and Namiesnik (2012). Further studies, however, have highlighted the variable range of emission 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 that diagnostic ratios are a useful tool for assessing atmospheric reactivity of PAH, rather than source apportionment, as these ratios are subject to small changes as the distance from the original source...
Principal component analysis (PCA) has also been utilised as a source apportionment method which separates chemical constituents of the atmosphere according to their source using a statistical factor 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 subsequently overcome by using positive matrix factorisation (PMF) as the preferred technique of source apportionment of atmospheric constituents (Jang et al., 2013; Dvorska et al., 2012). The other commonly used source apportionment method, the Chemical Mass Balance model, requires locally generated PAH source profiles which were not available.

A vast number of measurements of airborne concentrations of PAH have been reported from various geographical locations, including UK, Europe, USA and China. However, very little information has been reported from the Middle East. The environmental concerns of Saudi Arabia, in particular, are 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 growth over the last thirty years and has been accompanied by environmental degradation. Air quality has progressively deteriorated and the number of vehicles has increased to more than 1.4 million (Saudi Network, 2008). The city’s major stationary PAH sources include a desalination plant, a power generation plant and an oil refinery. The oil refinery was originally built in a non residential area, but with urbanisation, is now in the middle of a highly populated area (Al-Jahdal and Bisher, 2008).

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.
2. EXPERIMENTAL

2.1 Site Location

Sampling was conducted simultaneously at three locations in Jeddah, the second largest city and most significant commercial centre in the Kingdom of Saudi Arabia, with a population of ca. 3.4 million. The sampling sites are shown in Figure 1. The locations were chosen according to their distance from the Jeddah oil refinery. Site A was a primary school situated in a highly populated economically disadvantaged residential area, located in the Ghulail district, south of the city and ca. 700 m east of the Jeddah oil refinery. Site B was a primary school, located in the Al-Muntazahat district, East of Jeddah, ca. 150 m adjacent to the heavily trafficked Al-Haramain ring road. Site C was an urban background site located in the Al-Murjan district, situated on the Red Sea Creek (Sharm Obhur), and is subjected to anthropogenic emissions from some moderately busy roads (nearest road ca. 300 m away) and 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 ensure that samplers were not interfered with.

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 m³ 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.
2.3 Sample Analyses

Prior to sampling, the filters were preheated at 400 °C for 48 h in a box furnace, wrapped in clean preheated foil, placed in a cardboard box and sealed in an airtight metallic container. The PUF 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 were left to dry in a sealed metal container under a stream of nitrogen. The clean and dry PUF substrates were subsequently sealed in airtight plastic bags and stored in the freezer. Once exposed, the filter and PUF substrates were wrapped separately with clean preheated foil, enclosed in airtight plastic bags and stored at approximately -18 °C.

Samples were analysed for 14 PAH using the methodology described previously (Delgado-Saborit et al., 2013). Briefly, filter and PUF substrates were spiked with 1000 pg µL⁻¹ deuterated internal 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 cleaned using a chromatography column filled with 0.5 g of anhydrous sodium sulphate (puriss grade for HPLC). The extract was further concentrated to 50 µL under a gentle N₂ flow. PUF substrates were immersed in 100 mL of DCM and ultrasonicated for 20 min at 20 °C. The sample was then concentrated to 10 mL using N₂ and subsequently dried and cleaned as outlined for the filters above.

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 µm 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\(^{-3}\) for the 24-hour air samples. Further information regarding the analytical procedure can be found in Delgado-Saborit et al., 2013.

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 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
were applied to these data, are described elsewhere (Delgado-Saborit et al., 2013). The robust mode is the default mode with EPA PMF v3.0, which reduces the effect of very large variables by treating them 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).

3. RESULTS AND DISCUSSION

3.1 PAH Concentrations

The average total (vapour and particulate) concentration of PAH measured at the three sampling sites between 23 February and 23 April 2012-2013 are shown in Table 1. Concentrations measured at sites A and B were statistically larger ($t$ test, $p<0.01$) than those measured at site C, where average total concentrations for all PAH measured at site C were between 50 and 90 % lower (see Table 1). Total concentrations measured at site A were significantly larger ($t$ test, $p<0.05$) to those at site B, with the 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 compounds (Da <202) were predominantly in the vapour phase, where the most abundant PAH 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).
The concentrations of vapour phase LMW PAH were largest at site A followed by B and C, with the exception of ANT, which was frequently (~53 %) larger at site B. Higher molecular weight (HMW) PAH compounds (Da >228) were predominantly in the particulate phase, with B(ghi)P and COR being the most abundant at sites A and B, and B(ghi)P and CHR being the two most abundant PAH at site C. This suggests that sites A and B may be associated with high levels of vehicular emissions, as B(ghi)P and COR are often used as vehicular emission tracers (Greenberg et al., 1981; Harkov et al., 1984). Furthermore, although HMW PAH in the particulate phase (B(b)F to COR) were statistically different between all sites, LMW PAH in the particulate phase (PHE to CHR) were remarkably similar for sites A and B (within 10 %).

Table 2 summarises the PAH concentrations measured in Jeddah and some other cities around the world. The average total suspended particulate (TSP) concentration for sites A, B and C were 435, 396, 232 µg/m³, reflecting the large crustal dust component present in particulate matter in the Middle Eastern area. The measured PAH concentrations, however, are only modestly higher than those measured in urban areas of the United Kingdom (Delgado-Saborit et al., 2013; Alam et al., 2013), and significantly lower than those previously measured in different areas of Saudi Arabia (El-Mubarak et al., 2014; Habeebullah, 2013). Habeebullah (2013) conducted a risk assessment of PAH in Makkah, located ca. 85 km east of Jeddah, during an influx of approximately 2.8 million pilgrims to the city, in November 2010. They reported total particulate PAH concentrations in the range of 103.5 to 195.2 ng/m³, a factor of 17 to 33 times larger than Site A in this study. These high concentrations were attributed to various residential activity and traffic emissions. Makkah City, however, has been subject 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-Mubarak et al. (2014) reported PM10 PAH concentrations in Riyadh, located ca. 1000 km north east of
Jeddah, in December 2010. The authors reported extremely high concentrations of individual PAH congeners of up to 1003 ng/m$^3$, with an average concentration of B(a)P of 400 ng/m$^3$, three orders of magnitude larger than this study (0.39 ng/m$^3$ for site A). Furthermore, Abdallah et al. (2014) 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$^3$ in high population density areas. The large concentrations measured were attributed to vehicular exhaust emissions which was also highlighted by Hasan and Khoder (2012) who reported total mean concentrations for B(a)P and B(ghi)P of 159.55 and 219.32 ng/m$^3$, respectively; at a traffic related site in Giza, Egypt.

Concentrations reported from Middle Eastern countries other than Egypt and other parts of Saudi Arabia are also relatively higher than those reported in this study. Total mean concentrations of PHE, B(a)P and B(ghi)P in Tehran, Iran were 278.19, 18.71 and 34.38 ng/m$^3$ where the major emission sources are thought to be traffic-related (Halek et al., 2010). In Damascus, Syria, the concentration of particulate B(a)P and B(ghi)P was ~ 4.5 and 5.2 ng/m$^3$, respectively (Dimashki et al., 1996). However, PAH concentrations reported from Kuwait were lower than those in this study (Gevao et al., 2006), where average airborne concentrations were in the range of 2.63 ng/m$^3$ (for PHE) and 0.07 ng/m$^3$ (for D(ah)A). The authors also reported that approximately 70 to 90 % of the total PAH concentration 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.

The influences upon the partitioning of PAH between the vapour and condensed phases need to be considered as PAH are known to cycle actively between the particle and vapour phases. There have been various theoretical treatments of these processes reviewed in Keyte et al. (2013), the simplest being due to Yamasaki et al. (1982), which can be expressed as:
\[
\log[A(TSP)F^{-1}] = -mT^{-1} + c
\]

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 \((A/F\) decreases\).

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 µg m\(^{-3}\) (unpublished data).

### 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.

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 ($\sum$PAH) and B(a)P than at weekends (Figure 4).

Factor 2 was attributed to industrial sources, in particular the oil refinery, and accounted for up to 33% 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 Emissions Inventory (http://naei.defra.gov.uk/) reports relatively large emissions of FLU from refinery combustion between 2002 and 2006, in agreement with Factor 2 from this study. Kulkarni and 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 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 largest contribution at site A, which is located ca. 700 m from Jeddah’s oil refinery. Site specific plots and weekday-weekend variation are shown in Figure 4.

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 $\sum$PAH and B(a)P than at weekends (Figure 4). This factor was responsible for PAH concentrations in the order, site B > site A > site C. The predominance of PHE along with FLU, CHR and PYR have been 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 been attributed to oil combustion (Lee et al., 2004). In comparison to a previously reported diesel combustion derived source profile from the UK NAEI (Jang et al., 2013), factor 3 has a larger contribution of ANT, B(a)A and CHR, which may be explained by the use of different compositions of diesel fuels between the UK and Saudi Arabia. Alternatively, the enhanced levels of LMW PAH observed in factor 3 may be due to both oil combustion, originating from Jeddah’s desalination plant, and diesel traffic emissions, with a possible contribution from shipping, which burns predominantly 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 that the emissions from the plant may affect mainly the sites A and B.

4. CONCLUSION

The concentrations of PAH measured in Jeddah are overall surprisingly similar to those in Birmingham (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 decline from site A close to the oil refinery to site B which was close to the ring road, which are both 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 studies but shows some preferential partitioning into particles especially for low molecular weight 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 comparison to Birmingham with the influence of the higher temperatures in Jeddah being a secondary effect tending towards higher vapour concentrations.

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.

ACKNOWLEDGMENT

This paper was funded by King Abdulaziz University (KAU), Jeddah, under grant no. (3-10-1432/HiCi). The authors, therefore, acknowledge technical and financial support of KAU.
REFERENCES


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 various cities around the world.

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. 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.
**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>
<thead>
<tr>
<th></th>
<th>Vapour</th>
<th>Particulate</th>
<th>TOTAL</th>
<th>% Particulate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Site A</td>
<td>Site B</td>
<td>Site C</td>
<td>Site A</td>
</tr>
<tr>
<td>PHE</td>
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<td>8.60</td>
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<tr>
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<td>COR</td>
<td>BDL</td>
<td>BDL</td>
<td>BDL</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Σ_{14}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
Table 2. Average total (vapour and particulate) concentrations of PAH in ambient air measured at various cities around the world.

<table>
<thead>
<tr>
<th>Site</th>
<th>PHE (ng/m³)</th>
<th>ANT (ng/m³)</th>
<th>FLU (ng/m³)</th>
<th>PYR (ng/m³)</th>
<th>B(a)A (ng/m³)</th>
<th>CHR (ng/m³)</th>
<th>B(b)F (ng/m³)</th>
<th>B(k)F (ng/m³)</th>
<th>B(e)P (ng/m³)</th>
<th>B(a)P (ng/m³)</th>
<th>IND (ng/m³)</th>
<th>D(ah)A (ng/m³)</th>
<th>B(ghi)P (ng/m³)</th>
<th>COR (ng/m³)</th>
<th>∑14 PAH (ng/m³)</th>
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<td></td>
<td></td>
<td></td>
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*a* Abdallah et al. (2014); *b* Hassan and Khoder (2012); *c* Halek et al. (2010); *d* Gevao et al. (2006); *e* Huang et al. (2014); *f* Callen et al. (2008); *g* Alam et al. (2013)
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. 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.