

Spatiotemporal distributions of polycyclic aromatic hydrocarbons close to a typical medical waste incinerator

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Abstract Environmental contaminations by polycyclic aromatic hydrocarbons (PAHs) especially from incinerators occur subtly, and PAH contribution from this source is underestimated. However, as environmental PAH concentrations build up, this may be a serious concern around the incinerator vicinity due to the potential consequences of PAHs on ecosystems and human health. Thus, the contribution of selected (12) PAHs from the Obafemi Awolowo University Teaching Hospital medical waste incinerator (or source, HWI_0) was determined by sampling stack gas and ambient air around incinerator vicinity from June 2014 to May 2015. Results showed that the 12 PAH source (HWI_0) concentrations were in the range of NA (for phenanthrene, pyrene, anthracene, benz[e]acephenanthrylene, and indeno[2,1-b]chromene) to 10.9 ng/m³ (pyrene) and generally higher than the receptor points (hospital waste incinerators (HWIs)). The average total PAH concentrations per month at HWI_0 and the receptors—HWI_1, HWI_2, HWI_3, HWI_4 and HWI_5—were 73.0 ± 27.9, 60.4 ± 30.8, 42.5 ± 23.6,

38.7 ± 21.9, 35.0 ± 27.2, and 39.2 ± 22.9 ng/m³, respectively. These results and multivariate receptor model analysis indicated high correlations between source PAH contributions and the receptor points. The PAH concentrations in the dry season were higher than the wet season suggesting that hydrological condition affects ambient PAH concentrations. The average PAH concentrations in the HWIs as well as the cumulative exposure concentrations observed throughout the period are of major health concern because PAH concentrations detected are several times higher than both the European Union standard and the WHO guideline level.

Keywords Environmental pollution · Polycyclic aromatic hydrocarbons (PAHs) · Nigeria · Medical waste · Incinerator

Introduction

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous and introduced into the environment by various natural processes, but their concentrations have been enormously supplemented by various anthropogenic activities (Olu-Owolabi et al. 2014; Okoli et al. 2014; Qi et al. 2016). Industrialization-related activities have been the major culprit for recent environmental PAH increases (Baraniecka et al. 2010; Srogi 2007; Wang et al. 2006). Supplementation by anthropogenic activities is of serious concern because most PAHs are known to be toxic and some are mutagenic and/or carcinogenic; hence, several have been classified as priority pollutants (Adesina et al. 2017; ATSDR 1995; Hu et al. 2017; Olu-Owolabi et al. 2015; USEPA 2007). Their effect on biota can be amplified by bioaccumulation in the food chain because PAHs like most organic pollutants are very soluble in fat.

Understanding the source contributions to the environment is important and beneficial to the risk assessment and

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appropriate management of PAHs (Park et al. 2011). Incineration of wastes is one of such sources that release PAHs into the environment (Alawi and Al-Mikhi 2016; Srogi 2007; Wang et al. 2016; Anyakora et al. 2009). The PAHs from incinerators occur subtly, and their contribution is often underestimated (Adesina et al. 2017). However, as environmental PAH concentrations build up, this may be a serious concern around the incinerator vicinity due to their potential consequences on ecosystems and human health. Incineration is the preferred method of disposal of infectious and toxic hospital wastes in Nigeria, but one major challenge here is that most hospitals use locally fabricated incinerators without air pollution control unit. This with the attendant increase in medical wastes as human population grows in Africa's sub-Sahara might lead to unprecedented amounts of PAHs around the incineration facility.

Several studies have been carried out to determine the PAH contribution of various anthropogenic sources around the world (Alawi and Al-Mikhi 2016; Wang et al. 2012; Baraniecka et al. 2010; Adesina et al. 2017; Srogi et al. 2007; Zhao et al. 2008); however, there is dearth of such studies in sub-Saharan countries. Information on the various sources' contributions of PAHs in the environment is important because such data may be used for proper risk assessment and appropriate management of PAHs (ATSDR 1995; Park et al. 2011; USEPA 2007). Hence, in this study, we measured the spatial distributions and temporal variations of 12 PAHs around the vicinity of the Obafemi Awolowo University teaching Hospital Waste Incinerator (HWI_0) over every 28 days for a 1-year period (June 2014–May 2015). The 12 PAHs include seven priority PAHs (naphthalene (NAP), phenanthrene (PHEN), pyrene (PYR), anthracene (ANT), fluorene (FLU), benzo[k]fluoranthene (BkF), and benzo[a]pyrene (BaP)) and five other PAHs (azulene (AZU), benzo[e]pyrene (BeP), perylene (PER), benz[e]acephenanthrylene (BEA), and indeno[2,1-b]chromene (IDC)). These PAHs have also been grouped in this study based on their ring size into three rings and less (NAP, PHEN, ANT, AZU, and FLU), *benzo-* and *indeno-* substituents (BkF, BeP, BaP, BeA, and IDC), and greater than three rings without substituent (PYR and PER).

Material and methods

Sample collection, preparation, and instrumental analysis

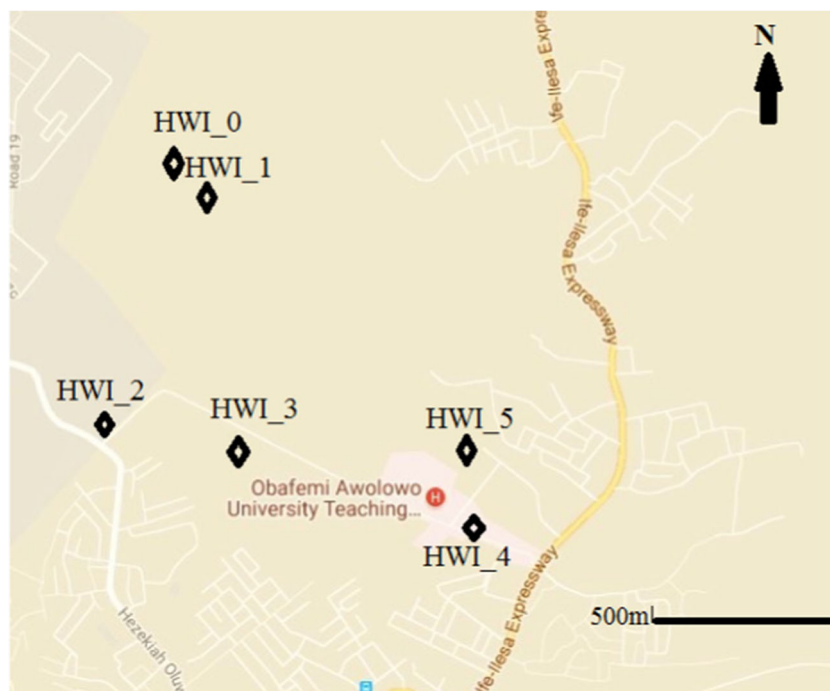
Air samples used in this study were obtained from within the vicinity of the Obafemi Awolowo University teaching Hospital Waste Incinerator (HWI_0) site (7° 51' 35" N; 4° 54' 57" E). The incinerator location is remote from known anthropogenic PAH-contributing sources such as cities and highways. The HWI_0 is a rotary kiln-type incinerator which uses electricity to generate the incinerating heat and equipped

with flue gas scrubbers. The operating temperature range from 500 to 1100 °C and designed with the capacity to incinerate liquid and solid wastes. Considering the prevailing meteorological conditions (wind speed and direction) around the HWI vicinity (Fig. 1) and the locations of major residential areas, five sampling locations (HWI_1 to 5) were selected around the HWI_0 (Fig. 1 and Table 1).

Ambient air samples were collected using polyurethane foam (PUF) passive samplers (Adesina et al. 2017; Gao et al. 2014). The PUF was locally fabricated following the modified Annex 3 of the South Pacific regional Project Passive Air Sampling protocol. The PUF consists of two different sizes of stainless steel bowls (30 and 24 cm) and polyurethane filters (14 cm diameter, 1.35 cm thick, with a surface area of 365 cm² and density of 0.030 g/cm³). Prior to deployment, PUF disks were pre-cleaned with distilled water and then washed with acetone in Soxhlet extractor for 24 h, followed by petroleum ether for another 24 h (Pozo et al. 2004). The disks were dried in a desiccator, covered in aluminum foil, and transported to the sampling locations. The duration of the sampling was 28 days. The filters in the PUF samplers were replaced after every 28 days for a 1-year period (June, 2014–May, 2015). This sampling period includes one dry season and one rainy/wet season, and samples were repeatedly collected from both source and receptor points during this period. Stack gas samples were collected by adopting a modified Hoyos et al. (2008) method; a filter-sorbent sampling system was used consisting of a sampling probe, filter, and a packed column of Amberlite XAD-2 resin (adsorbent material). Samples were iso-kinetically withdrawn from the stack gas stream of the HWI into the sample train.

The PAHs trapped in PUF disks, and Amberlite XAD-2 resin was extracted into dichloromethane using a Soxhlet extractor. Cleanup step was carried as described by Hoyos et al. (2008). The extracted PAHs were concentrated to 20 µL using a rotary evaporator under a gentle stream of nitrogen. Quantitative analysis of PAHs in the samples was carried out using gas chromatography/mass spectrophotometer (GC–MS). The GC (Agilent 7890) with mass detector (Agilent 5975) was operated in selected ion-monitoring mode and using electron impact ionization. The chromatographic column dimension is 30 m × 0.25 mm internal diameter × 0.25 µm film thickness. Injection of 1 µL of each extracted sample was achieved in splitless mode using helium as a carrier gas at a constant flow of 1.2 mL min⁻¹. The temperature program for the analysis was set as follows: the initial temperature (50 °C) was held for 2 min, ramped raised to 120 °C at 30 °C min⁻¹, then ramped again to 280 °C at 6 °C min⁻¹ for 15 min. Determination of PAHs in both laboratory and field blanks were carried out, and the internal standard method was used for both the calculation of the recovery (ranged between 70 and 120%) and quantification of the PAHs. All reagents used in this study were pesticide grade,

Fig. 1 Map showing incinerator site (HWI_0) and receptor points (HWI_1–5) sampled during the periods



and the method detection limit was calculated by multiplying standard deviation of each PAH congener by the Student's *t* values (at 99% confidence level).

Data treatment

Determination of air concentrations of the various PAHs was done by calculating the amount deposited in the PUF (ng sampler⁻¹) divided by the effective air volume (V_{air} , m³). Calculation of effective air volume was done using Global Atmospheric Passive Sampling (GAPS) network template (Harner et al. 2014). Data inputted into the template were deployment time, average temperature, sampling rate, and a default sampling rate of 4 m³ d⁻¹ (Harner et al. 2013; Pozo et al. 2009). Statistical analysis was carried out using principal component analysis (PCA) and Pearson correlation available on the XLSTAT program, while the geo-statistical interpolation technique was used to create a continuous map of PAH

concentrations from the air sample results, using ordinary Kriging algorithm. This was carried out with Golden Software Surfer 13.0 (USA).

Results and discussion

The spatial and temporal distributions of the 12 PAHs from within the Obafemi Awolowo University Teaching Hospital Waste Incinerator stack (HWI_0: 4° 55' E; 7° 518' N) and its sampled environs (HWI_1–5) have been studied. For the period under study (June 2014 through May 2015), the monthly compositions of these 12 PAHs in the air samples of the various HWIs are shown in Figs. 2, 3, and 4. Considering the location of the HWI_0 and its remoteness to known PAH contributors, we have assumed that the concentrations of PAHs in the selected sampling points (HWI_1–5) were largely from the stack (HWI_0), except otherwise stated.

Table 1 Descriptions of sampling locations

Sampling point	Sampling point description	Geographical coordinate	Distance from HWI_0 (km)
HWI_0	HWI stack	7° 51' 35" N; 4° 54' 57" E	0.00
HWI_1	Very close to HWI stack	7° 51' 35" N; 4° 55' 56" E	0.004
HWI_2	University staff estate entrance	7° 51' 21" N; 4° 54' 57" E	1.10
HWI_3	Vicinity of medical student hostel	7° 51' 54" N; 4° 55' 50" E	0.94
HWI_4	Vicinity of emergence department	7° 50' 59" N; 4° 56' 58" E	1.88
HWI_5	Teaching hospital staff estate	7° 51' 35" N; 4° 57' 02" E	1.84

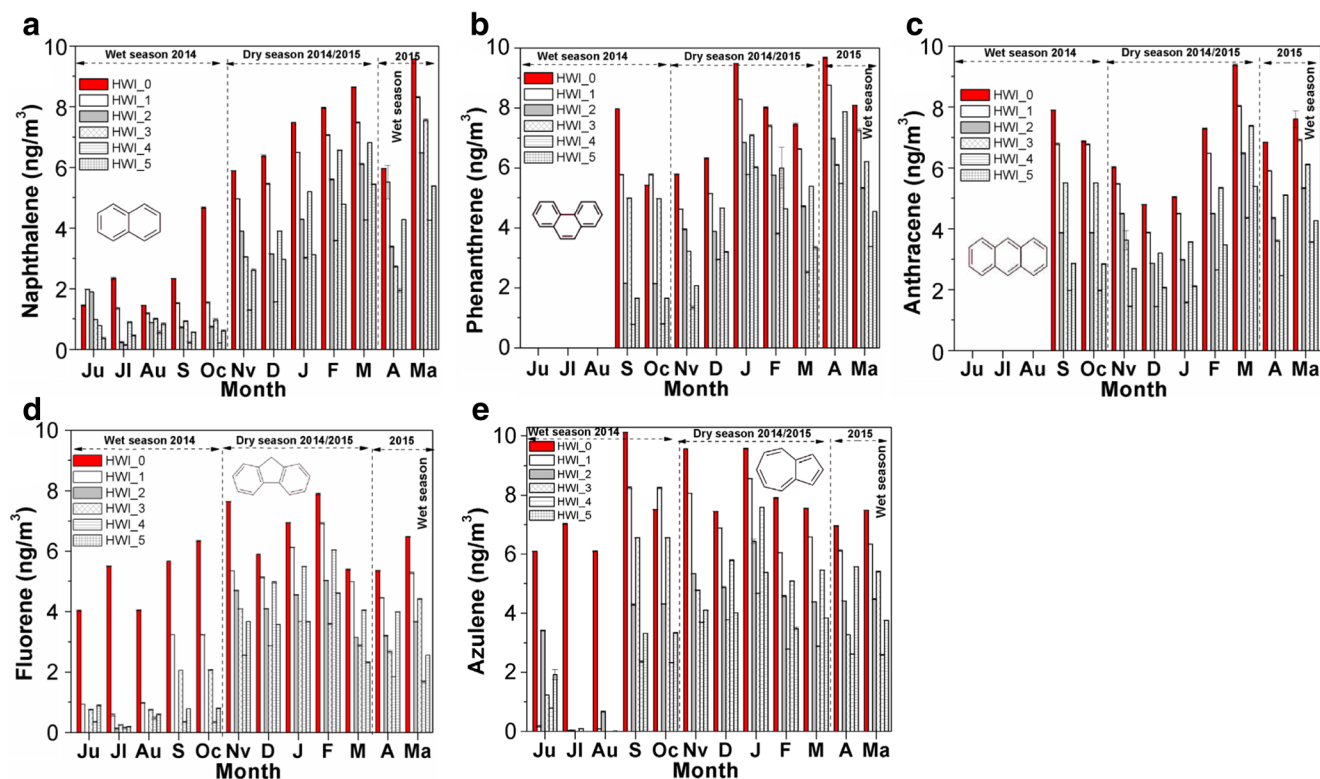


Fig. 2 Monthly concentrations of the two- and three-ring PAHs from the stack and various sampling points from June 2014 to May 2015. **a** NAP. **b** PHEN. **c** ANT. **d** FLU. **e** AZU, (inserts show the structural formula of each PAH and the division of the months of the year into wet and dry seasons)

Consequently, it was expected that the monthly concentrations of PAHs in the various HWI distances should be less than the HWI_0 concentrations but vary per site in relation to prevailing wind speed and direction as well as the differences in volatility and affinities of each PAH for adsorption onto particulate matter (PM) in the atmosphere.

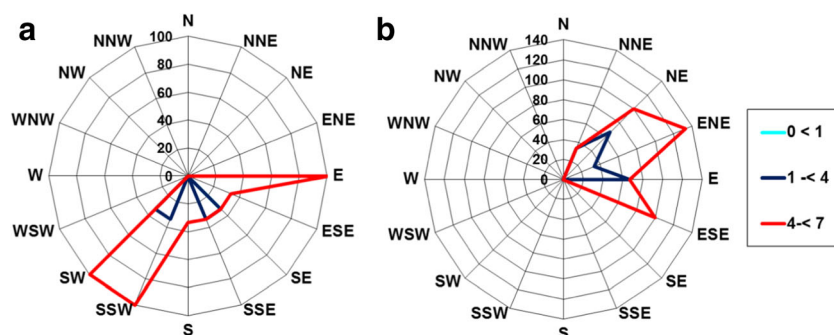
Spatial distributions of the various PAHs compared to the HWI_0 concentrations

The two- and three-ring PAHs

The monthly concentrations of the two- and three-ring PAHs (NAP, PHEN, ANT, AZU, and FLU) from the stack and

various receptor points are shown in Fig. 2a–e, respectively. It was observed that the HWI_0 (source) concentrations were usually the highest when compared with the receptor points for these PAHs. Comparing the concentrations of these PAHs at the various receptor points, a general trend of $HWI_1 > HWI_2 \geq HWI_3 > HWI_5 \geq HWI_4$ was observed. This trend was mainly due to proximity of the receptor points to HWI_0 but with the differences in meteorological conditions (wind speed and direction, Fig. 3) associated with the various receptor points resulting in unique deviations. Exceptions to this trend were observed for NAP (Fig. 2a) and PHEN (Fig. 2b) in the months of June and October 2014, respectively, where the concentrations of HWI_1 for both PAHs and HWI_2 for NAP were slightly higher than HWI_0. This exceptional trend was

Fig. 3 Wind rose plot of the HWI sites. **a** Wet season. **b** Dry season



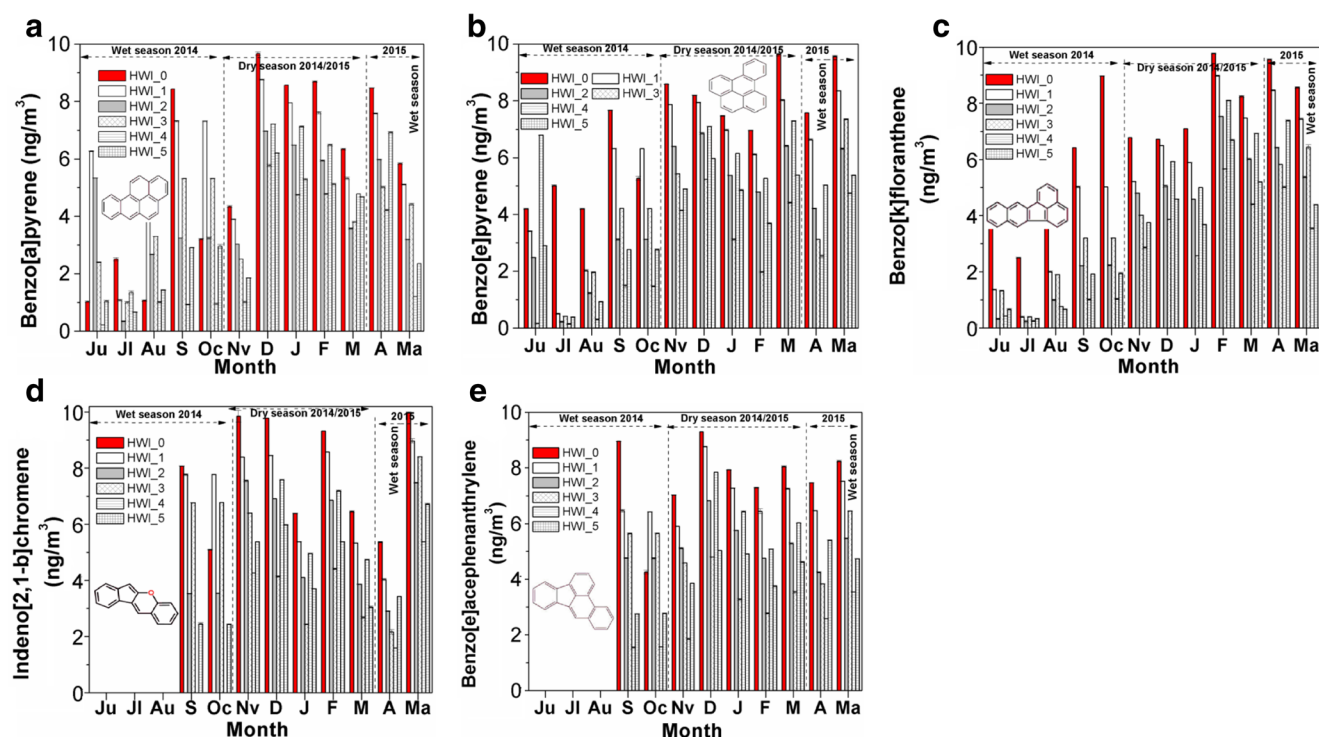


Fig. 4 Monthly concentrations of the benzo- and indeno-substituted PAHs from the stack and various sampling points from June 2014 to May 2015. **a** BaP. **b** BeP. **c** BkF. **d** IDC. **e** BeA, (inserts show the structural formula of each PAHs and the division of the months of the year into wet and dry seasons)

attributed to rarely occurring contributions from other source(s) such as windblown PAHs from distant sources. The monthly HWI_0 concentrations ranged from 1.4 to 10.1 ng/m³ for these PAHs with a monthly mean concentration of 5.5 ± 2.0 ng/m³.

Another obvious trend in the result was observed in the months of June, July, and August of 2014, where ANT (Fig. 2c) and PHEN were not observed in the gases of the HWI_0 neither were they detected in the sampling points. Though the waste types incinerated were not sorted or recorded in this study, but this trend may not be unconnected to the waste type incinerated (Durlak et al. 1998; Li et al. 2001; Lee et al. 2002; Park et al. 2009; Chen et al. 2003).

The highest concentrations of these PAHs both in the HWI_0 and receptor points were usually observed in the dry season between the months of November and March with a general concentration trend of AZU (Fig. 2e) $\geq$ PHEN $>$ ANT $>$ NAP $>$ FLU (Fig. 2d). An exception to this was observed for NAP (Fig. 2a) where the highest concentration was observed in May 2014 during the wet season.

The benzo- and indeno-substituted PAHs

The results of the monthly concentrations of the benzo- and indeno-substituted PAHs (BaP, BeP, BkF, IDC, and BeA) are shown in Fig. 4a–e, respectively. Of these substituted PAHs, BaP (Fig. 4a) commands special attention because it is a potent carcinogen. The monthly HWI_0 concentrations of BaP

ranged from 1.1 to 9.7 ng/m³ (mean of 5.7 ± 3.0), and the highest concentration was observed in December 2015. Similar to most PAHs, the HWIs had lower concentrations than the HWI_0 following the trend HWI_1 (6.0 ± 2.1 ng/m³) $>$ HWI_2 (4.2 ± 1.9 ng/m³) $>$ HWI_3 (4.0 ± 1.4 ng/m³) $\geq$ HWI_5 (3.5 ± 2.0 ng/m³) $\geq$ HWI_4 (3.0 ± 2.6 ng/m³). Generally, these concentrations were similar to those reported in several polluted cities around the world (Wang et al. 2006; Fraser et al. 1998). Benzo[a]pyrene is used as a general index for whole PAH carcinogenicity by the World Health Organization (Wang et al. 2005). But it is easily degraded in the presence of oxidants or sunlight; thus, its concentration alone may lead to underestimation of the hazards posed by other PAHs (Matsumoto et al. 1998). Hence, it is a useful venture to determine other PAHs present in the environment.

Similar to the two- and three-ring PAHs, it was observed that the HWI_0 concentrations of BeP, BkF, IDC, and BeA were usually the highest in comparison to the receptor points (Fig. 4b–e). Concentrations of the substituted PAHs at the various receptor points usually followed the trend: HWI_1 $>$ HWI_2 $\geq$ HWI_3 $>$ HWI_4 $>$ HWI_5, which was attributed to the proximity of the receptor points to HWI_0 and partially to the differences in meteorological conditions. Exceptions to this trend were observed for BaP (in July, August, and October; Fig. 4a), IDC, and BeA (both in October; Fig. 4d, e) where the concentrations of the HWI_0 were lower than some receptor points. This trend may be due contributions from other windblown

PAH source(s) or possibly post-combustion formation of these substituted PAHs outside the incinerator (Adesina et al. 2017).

The IDC and BeA (Fig. 4d, e) were also not detected both in the HWI_0 and HWIs in the months of June, July, and August of 2014; this trend was attributed to the waste-type incinerated (Durlak et al. 1998; Li et al. 2001; Lee et al. 2002; Park et al. 2009; Chen et al. 2003). Generally, the highest concentrations of all substituted PAHs in both the HWI_0 and receptor points were usually observed in the dry season (Fig. 4a–e).

More than three-ring PAHs

The monthly concentrations of non-substituted PAHs with greater than three rings are shown in Fig. 5. Only pyrene, a precursor of benzo[a]pyrene (Fig. 5a), and pyrene (Fig. 5b) fall within this group among the selected PAHs. Both PAH data indicate similar results as other PAHs, but perylene HWI_0 concentrations showed the widest range (0.4–10.9 ng/m³) compared with other PAHs. The perylene monthly HWI_0 mean was 6.9 ± 2.6 ng/m³. The highest concentration was observed in June 2014; however, the concentration of perylene was not proportionally distributed around the sampled sites especially in the months of June and July with highest concentrations in the sampled sites being over 1500 lower than the HWI_0's. Generally, the various HWIs had lower perylene concentrations than the HWI_0 with trend HWI_1 (4.7 ± 2.7 ng/m³) > HWI_2 (3.2 ± 2.2 ng/m³) > HWI_3 (2.7 ± 1.9 ng/m³) > HWI_4 (2.6 ± 2.5 ng/m³) ≥ HWI_5 (2.5 ± 2.0 ng/m³) except for August 2014.

The concentration trend of HWI_1 > HWI_3 > HWI_2 > HWI_5 ≥ HWI_4 was observed for most receptor points both PAHs, and this was attributed to HWI_0 proximity and meteorological conditions (wind speed and direction, Fig. 3) of the different receptor points. The very low concentrations of PER detected at the various receptor points in comparison with the HWI_0 during the months of June, July, and August 2014 was attributed to the possible washing of PER out of the atmosphere by rain or precipitation which occurs during the wet season. This resulted in the very low concentration of PER getting to the various HWIs. Similar to the results for PHEN (Fig. 2b), ANT (Fig. 2c), IDC (Fig. 4d), and BeA (Fig. 4e), PYR (Fig. 5a) was not detected HWIs as well as the HWI_0 in the months of June, July, and August 2014, and this may not be unconnected to the waste type incinerated (Chen et al. 2003; Lee et al. 2002; Park et al. 2009).

Generally, these data suggest that incineration of medical wastes, and likely other incineration activities, leads to substantial PAH emission, in addition to other toxic chemicals such as flame retardants, dioxins, and heavy metals (Wang et al. 2012). The concentrations of these PAHs in Fig. 2 showed that monthly contributions of the HWI_0 were

significant and within similar range as those detected on the five HWI locations. Results also indicate that people living within the vicinity of the HWIs are exposed to PAH concentrations that are alarmingly high and several times higher than international limits. Individually, these PAHs pose serious harm, but cumulatively (Fig. 5c), the challenge is higher. This is due to the fact that the PAH concentrations for all HWIs exceeded the European Union standard (1 ng/m³) and the WHO guideline level (1 ng/m³) (Ravindra et al. 2008; Wang et al. 2012). Hence, these average concentrations of PAHs in the HWIs observed throughout the sampling period are of major health concern. Within the limits of human error and other uncertainties, this assessment gives a general evaluation of the condition of PAH pollution in the vicinity of a typical waste incinerator in Nigeria.

Temporal evaluation

Figures 2, 4, and 5 (broken lines and arrows) also showed the differences of PAH concentrations as the months progressed. The dry season in the sampling locations is usually from November to March while from April to October is the wet season. It was observed that the concentrations of PAHs in the dry season were higher than those recorded in the wet season. Generally, the hydrological condition could be the main factor causing fluctuation of PAHs in the ambient air samples. The PAHs could be washed out of the air by precipitation in the wet season, resulting in the lower PAH concentration observed in this season for the HWIs compared to the dry season. Hence, though approximately similar concentrations of PAHs were generated from the HWI_0 during both seasons, the dilution effect of precipitation was the main reason for the concentration differences in the HWIs during both seasons. Similar result was reported by Lv et al. (2014).

The color legend in the map (Fig. 6a, b) depicts the different concentration ranges of the summation of PAHs in the study area; the increasing intensity of red denotes higher concentrations (up to 460 ng/m³) while increasing intensity of blue depicts lower concentrations (down to 210 ng/m³). More intense red color or highest concentrations of PAHs were observed around the HWI_0 at both seasons. Figures 3 and 6 also showed that the PAH distributions were dependent on distance of sampling point from HWI_0 as well as the wind direction. During the wet season, concentrations at the various sampling locations were more dependent on the distance from the HWI_0 as well as influenced by the southwesterly wind; this resulted in the low concentration detected in HWI_4. However, during the dry season, this trend changed as northeasterly wind basically dictated the PAH concentration distributions resulting in the lower concentrations detected in HWI_2 and HWI_5.

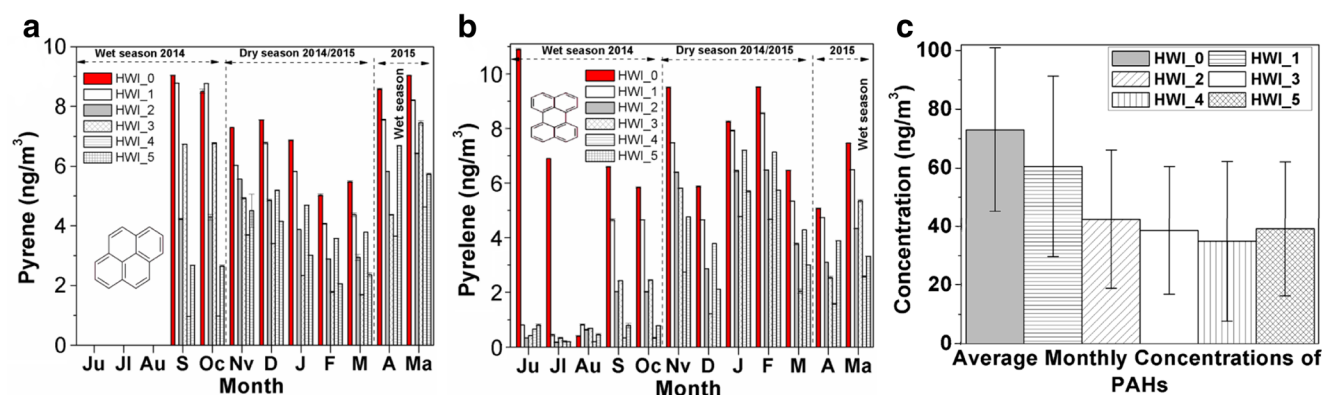


Fig. 5 Monthly concentrations of greater than three-ring PAHs without substituent from the stack and various sampling points from June 2014 to May 2015. **a** Pyrene. **b** Pyrene (inserts show the structural formula of

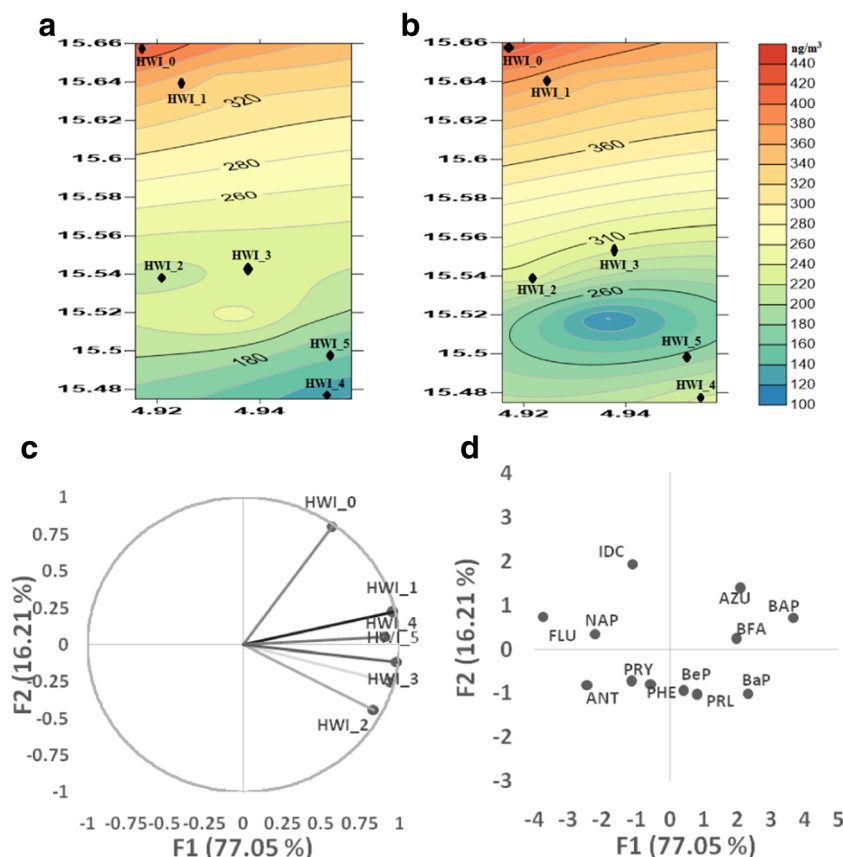
each PAH and the division of the months of the year into wet and dry seasons). **c** Average monthly concentrations of $\Sigma(\text{PAHs})$ for all HWI points

Correlation between the HWI_0 emissions and other HWI concentrations

Multivariate receptor model analysis (principal component analysis—PCA) was used in this study for the source (HWI_0) identification and contributions to ambient air receptors (HWIs) of the various PAHs. It is worthy to note that in describing a typical PCA score plot, variables with similar source will be localized with close proximity, while those with divergent sources will be sparse (Jambu 1991; Lee et al.

2004). Figure 6c shows the PCA variable plot in which Factor 1 explains 77.1% of the total variance while Factor 2 explains 16.2% of the total variance and a cumulative total variance of 93.3%. Following this, it is possible to attempt an explanation of the variability in the PAH concentrations observed. For variables that are close to each other but far from the center, they may be said to be significantly positively correlated. However, if both variables are on the opposite side of the center, then they are significantly negatively correlated; but for variables that are orthogonal, they are not correlated.

Fig. 6 Contour maps of spatial distribution of the PAHs during the **a** wet and **b** dry seasons; the color legend depicts the different concentration ranges of the summation of PAHs in the study area; the increasing intensity of red denotes higher concentrations (up to 460 ng/m³) while increasing intensity of blue depicts lower concentrations (down to 210 ng/m³). **c** Variables plot for PCA showing all HWIs. **d** Observation plot of PCA indicating the positions of naphthalene (NAP), phenanthrene (PHEN), pyrene (PYR), anthracene (ANT), azulene (AZU), fluorene (FLU), benzo[k]fluoranthene (BkF), benzo[e]pyrene (BeP), benzo[a]pyrene (BaP), perylene (PER), benz[e]acephenanthrylene (BeA), and indeno[2,1-b]chromene (IDC)



From the proximity (Fig. 6c) between the HWI_0 and the HWI_1, HWI_2, HWI_3, HWI_4, and HWI_5, it may be inferred that there was a correlation between PAH concentrations in the stack emission and the ambient air at these sampling locations (Lee et al. 2004; Wang et al. 2005), implying that HWI_0 was the source of PAHs at these HWIs. Considering the distance of HWI_2 relative to other HWIs (Fig. 6c), there is the possibility that the HWI_2 which is the University Staff Estate entrance may be prone to other PAH emission sources, possibly from vehicular traffic (El-Shahawi et al. 2010). Figure 6d shows the PCA observation plot; considering the proximity of each PAH from the middle of the plot, it can be inferred that these PAHs were from the HWI_0.

The risks associated with exposure to airborne PAHs are greatest at sites close to the source (HWI_0); however, continuous exposure to indoor particulate matter, with aerodynamic diameter less than 2.5 μm ($\text{PM}_{2.5}$), has been recognized as a major health problem because most people spend approximately 90% of their time indoors (Adesina et al. 2017; Srogi 2007). Considering the fact that these PAHs were detected within human habitats (HWI_3 and HWI_4) all year round, the long-term effects of their presence are of serious health concern. Interestingly, the studied area receives relatively little PAH supplementation from other sources while medical waste incineration plays a dominant role in waste disposal in Nigeria, and this is unlikely to change soon; thus, as population grow in nearby vicinities and residences get denser around these sites, ambient concentrations of these PAHs will increase correspondingly resulting in higher chronic or even acute effects.

Conclusion

The spatial and temporal distributions of the 12 PAHs from within the Obafemi Awolowo University Teaching Hospital Waste Incinerator stack and its sampled environs have been studied from June 2014 through May 2015. Results showed that the 12 PAH source (HWI_0) concentrations were in the range of NA to 10.9 ng/m^3 and generally higher than the receptor points (HWIs); a trend attributed to either proximity of HWIs to HWI_0 or differences in meteorological conditions of the HWIs. The average monthly concentrations (ΣPAHs) at HWI_0 and the receptors—HWI_1, HWI_2, HWI_3, HWI_4 and HWI_5—were 73.0 ± 27.9 , 60.4 ± 30.8 , 42.5 ± 23.6 , 38.7 ± 21.9 , 35.0 ± 27.2 , and $39.2 \pm 22.9 \text{ ng}/\text{m}^3$, respectively. These results and multivariate receptor model analysis indicated high correlations between source and the receptor points, and that PAH concentrations in the dry season were higher than those recorded in the wet season. This means that hydrological condition affects ambient PAH concentrations. These data suggest that incineration of medical wastes lead to substantial PAH exposure and

concentrations observed here are similar to those reported in several polluted cities around the world. The average PAH concentrations in the HWIs as well as the cumulative exposure concentrations observed throughout the period are of major health concern because PAH concentrations detected are several times higher than international limits. Within the limits of human error and other uncertainties, this assessment gives a general evaluation of the condition of PAH pollution in the vicinity of a typical waste incinerator in Nigeria.

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References

- Adesina OA, Sonibare JA, Diagboya PN, Adejuwon A, Famubode T, Bello JO (2017) Periodic characterization of alkyl-naphthalenes in stack gas and ambient air around a medical waste incinerator. *Environ Sci Pollut Res* DOI: <https://doi.org/10.1007/s11356-017-9828-1>
- Alawi, M.A., Al-Mikhi, N.E 2016. Levels of polycyclic aromatic hydrocarbons in waste incineration ash of some Jordanian hospitals using GC/MS. 42, 298–307.
- Anyakora CA, Ogbache KA, Palmer P, Coker H, Ukpo G, Ogah C (2009) GC/MS analysis of polynuclear aromatic hydrocarbons in sediment samples from the Niger Delta region. *Chemosphere* 60:990–997
- ATSDR (1995) Toxicological profile for polycyclic aromatic hydrocarbons (PAHs). <http://www.atsdr.cdc.gov/toxprofiles/tp69.pdf>.
- Baraniecka J, Pyrzynska K, Szewczynska M, Posniak M, Dobrzynska E (2010) Emission of polycyclic aromatic hydrocarbons from selected processes in steelworks. *J Hazard Mater* 183:111–115
- Chen SJ, Hsieh LT, Chiu SC (2003) Emission of polycyclic aromatic hydrocarbons from animal carcass incinerators. *Sci Total Environ* 313:61–76
- Durlak SK, Biswas P, Shi J, Bernhard MJ (1998) Characterization of polycyclic aromatic hydrocarbon particulate and gaseous emissions from polystyrene combustion. *Environ Sci Technol* 32:2301–2307
- El-Shahawi MS, Hamza A, Bashammakh AS, Al-Saggaf WT (2010) An overview on the accumulation, distribution, transformations, toxicity and analytical methods for the monitoring of persistent organic pollutants. *Talanta* 80:1587–1597
- Fraser MP, Cass GR, Simoneit BRT, Rasmussen RA (1998) Air quality model evaluation data for organics: 5. C6–C22 nonpolar and semipolar aromatic compounds. *Environ Sci Technol* 32:1760–1770
- Gao L, Zhang Q, Liu L, Li C, Wang Y (2014) Spatial and seasonal distributions of polychlorinated dibenzo-p-dioxins and dibenzofurans and polychlorinated biphenyls around a municipal solid waste incinerator, determined using polyurethane foam passive air samplers. *Chemosphere* 114:317–326
- Harner T, Mitrovic M, Ahrens L, Schuster J (2014) Characterization of PUF disk passive air samplers for new priority chemicals: a review. *Organohalogen Compd* 76:442–445
- Harner T, Su K, Genualdi S, Karpowicz J, Ahrens L, Mihele C, Schuster J, Charland JP, Narayan J (2013) Calibration and application of PUF disk passive air samplers for tracking polycyclic aromatic compounds (PACs). *Atmos Environ* 75:123–128
- Hoyos A, Cobo M, Aristizabal B, Cordoba F, de Correa CM (2008) Total suspended particulate (TSP), polychlorinated dibenzodioxin (PCDD) and polychlorinated dibenzofuran (PCDF) emissions from

- medical waste incinerators in Antioquia, Colombia. *Chemosphere* 73:137–142
- Hu J, Liu C, Guo Q, Yang J, Okoli CP, Lang Y, Zhao Z, Li S, Liu B, Song G (2017) Characteristics, source, and potential ecological risk assessment of polycyclic aromatic hydrocarbons (PAHs) in the Songhua River Basin, Northeast China. *Environ Sci Pollut Res* 24:17090–17102
- Jambu, M., 1991. Exploratory and multivariate data analysis. Academic Press, Boston.
- Lee WJ, Liow MC, Tsai PJ, Hsieh LT (2002) Emission of polycyclic aromatic hydrocarbons from medical waste incinerators. *Atmos Environ* 36:781–790
- Lee WS, Yuan CS, Wang LC, Chen CK, Lin C, Chang-Chien GP (2004) Evaluating the influence of PCDD/F emission from municipal solid waste incinerators on ambient air by PCDD/F concentration isopleths and principal component analysis. *J Chinese Inst Environ Eng* 14:1–10
- Li CT, Zhuang HK, Hsieh LT, Lee WJ, Tsao MC (2001) PAH emission from the incineration of three plastic wastes. *Environ Int* 27:61–67
- Lv J, Xu J, Guo C, Zhang Y, Bai Y, Meng W (2014) Spatial and temporal distribution of polycyclic aromatic hydrocarbons (PAHs) in surface water from Liaohe River Basin, northeast China. *Environ Sci Pollut Res* 21:7088–7096
- Matsumoto Y, Sakai S, Kato T, Nakajima T, Satoh H (1998) Long-term trends of particulate mutagenic activity in the atmosphere of Sapporo: 1. Determination of mutagenic activity by the conventional tester strains TA98 and TA 100 during an 18-year period. *Environ Sci Technol* 32:2665–2671
- Okoli CP, Guo Q, Adewuyi GO (2014) Application of quantum descriptors for predicting adsorption performance of starch and cyclodextrin adsorbents. *Carbohydr Polym* 101:40–49
- Olu-Owolabi BI, Diagbaya PN, Adebawale KO (2014) Evaluation of pyrene sorption-desorption on tropical soils. *J Environ Manag* 137:1–9
- Olu-Owolabi BI, Diagbaya PN, Adebawale KO (2015) Sorption and desorption of fluorene on five tropical soils from different climates. *Geoderma* 239–240:179–185
- Park JM, Lee SB, Kim JP, Kim MJ, Kwon OS, Jung DI (2009) Behavior of PAHs from sewage sludge incinerators in Korea. *Waste Manag* 29:690–695
- Park SU, Kim JG, Jeong MJ, Song BJ (2011) Source identification of atmospheric polycyclic aromatic hydrocarbons in industrial complex using diagnostic ratios and multivariate factor analysis. *Arch Environ Contam Toxicol* 60:576–589
- Pozo K, Harner T, Lee SC, Wania F, Muir DCG, Jones KC (2009) Seasonally resolved concentrations of persistent organic pollutants in the global atmosphere from the first year of the GAPS study. *Environ Sci Technol* 43:796–803
- Pozo K, Harner T, Shoeib M, Urrutia R, Barra R, Parra O (2004) Passive-sampler derived air concentrations of persistent organic pollutants on a north–south transect in Chile. *Environ Sci Technol* 65:29–37
- Qi Y, Owino AA, Makokha VA, Shen y, Zhang D, Wang J (2016) Occurrence and risk assessment of polycyclic aromatic hydrocarbons in the Hanjiang River basin and the Danjiangkou Reservoir, China. *Hum Ecol Risk Assess* 5:1183–1196
- Ravindra K, Sokhi R, van Grieken R (2008) Atmospheric polycyclic aromatic hydrocarbons: source attribution, emission factors, and regulation. *Atmos Environ* 42:2895–2921
- Srogi K (2007) Monitoring of environmental exposure to polycyclic aromatic hydrocarbons: a review. *Environ Chem Lett* 5:169–195
- USEPA (2007) Treatment technologies for site cleanup: annual status report (ASR). Twelfth Edition. (EPA 542-R- 07-012).
- Wang G, Huang L, Zhao X, Niu H, Dai Z (2006) Aliphatic and polycyclic aromatic hydrocarbons of atmospheric aerosols in five locations of Nanjing urban area, China. *Atmos Res* 81:54–66
- Wang H, Liu Z, Sun L, Wang Y, Luo Q, Wu H, Wang X (2016) Characterization and risk assessment of polycyclic aromatic hydrocarbons in surface water from Liaohe River, northeast China. *Polycycl Aromat Compd*. <https://doi.org/10.1080/10406638.2016.1220960>
- Wang MS, Wang LC, Chang-Chien GP, Lin LF (2005) Characterization of polychlorinated dibenzo-p-dioxins and dibenzofurans in the stack flue gas of a municipal solid waste incinerator, in the ambient and in the banyan leaf. *Aerosol Air Qual Res* 37:171–184
- Wang J, Chen S, Tian M, Zheng X, Gonzales L, Ohura T, Mai B, Simonich SLM (2012) Inhalation cancer risk associated with exposure to complex polycyclic aromatic hydrocarbon mixtures in an electronic waste and urban area in South China. *Environ Sci Technol* 46:9745–9752
- Zhao L, Zhang F, Hao Z, Wang H (2008) Level of polycyclic aromatic hydrocarbon in different types of hospital waste incinerator ashes. *Sci Total Environ* 397:24–30