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Source apportionment and seasonal variation of $PM_{2.5}$ in a Sub-Sahara African city: Nairobi, Kenya

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Abstract

Sources of airborne particulate matter and their seasonal variation in urban areas in Sub-Sahara Africa are poorly understood due to lack of long-term measurement data. In view of this, airborne fine particles matter (particle diameter ≤ 2.5 µm, $PM_{2.5}$) were collected between May 2008 and April 2010 at two sites (urban background site and suburban site) within the Nairobi metropolitan area. A total of 780 samples were collected and analyzed for particulate mass, black carbon (BC) and thirteen trace elements. The average $PM_{2.5}$ concentration at the urban background site was $20 \pm 8\,\mu g\,m^{-3}$ whereas the concentration at the suburban site was $13 \pm 8\,\mu g\,m^{-3}$. The daily $PM_{2.5}$ concentrations exceeded $25\,\mu g\,m^{-3}$ (the World Health Organization 24 h guideline value) 29 % of the days at the urban background site and 7 % of the days at the suburban site. At both sites, BC, Fe, S and Cl accounted for approximately 80 % of all detected elements. Positive Matrix Factorization analysis identified five source factors that contribute to $PM_{2.5}$ in Nairobi; traffic, mineral dust, secondary aerosol, industrial and combustion. Mineral dust and traffic factors were related to approximately 74 % of $PM_{2.5}$. Identified source factors exhibited seasonal variation though traffic factor was prominently consistent throughout the sampling period. The results provide information that can be exploited for policy formulation and mitigation strategies to control air pollution in Sub-Sahara African cities.

1 Introduction

The air quality in major cities within Sub-Saharan Africa (SSA) is deteriorating due to several factors which include; an increasing urban population, unregulated traffic activities, poorly maintained vehicles, inadequate regulations and air pollution control policies (UN, 2010; van Vliet and Kinney, 2007; Zachariadis et al., 2001). In order to draft environmental regulations to control air pollution, high quality and long-term measurement data are required. However, such data are not readily available in the SSA

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region due to a lack of long-term air pollution monitoring (Petkova et al., 2013; UNEP, 2013). Most studies on aerosols in cities within SSA are limited and usually based on short term measurements (Gatari et al., 2009; Mkoma et al., 2010; Odhiambo et al., 2010; Sawyer, 2010). As a result, there is poor understanding of long-term concentrations of airborne particulate pollutants (PM) and little is known about their sources, elemental constituents and seasonal variation.

Vehicular related emissions (both exhaust and non-exhaust) account for a large portion of urban air pollution in developing countries (Kinney et al., 2011; van Vliet and Kinney, 2007). A study conducted in Nairobi by Kinney et al. (2011) reported that concentration levels of $PM_{2.5}$ at street level, next to a city road, frequently exceeded the World Health Organization (WHO) 24 h guideline of 25 $\mu g\,m^{-3}$. This poses serious questions concerning health risks for people who frequent the city on a daily basis. Vehicular related emissions in the SSA region are exacerbated by the importation of second-hand vehicles which for instance in Kenya can be up to eight years old (KEBS, 2013b). In addition, the road network in Nairobi is progressively improving and this has translated into increased motorized traffic activities with a large part of the increased traffic load coming from old and poorly maintained vehicles. This improving road network has led to severe congestion problems and air pollution exposure to the many pedestrians especially during morning and evening rush hours (van Vliet and Kinney, 2007). Recently, there has been a rapid increase (from 50 000 units in 2008 to 140 000 units in 2011) in importation and use of motorcycles in urban and rural areas (KEBS, 2013a).

Mineral dust accounts for a significant portion of PM and come from unpaved road surfaces as well as wind-blown dust during dry seasons (Boman et al., 2009; Lindén et al., 2012; Reeves et al., 2010). The natural background concentration of mineral dust in Africa is bound to be influenced by increasing episodes of droughts (WMO, 2013) as well as increased anthropogenic activities which are related to economic growth. This will pose a challenge to formulation of strategies aimed at mitigating mineral dust effects on air quality. However, quantification of the contribution of mineral dust to urban

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PM will provide necessary information that can be used in drafting relevant air quality legislation.

On a regional level, emissions from biomass burning are also significant and dependent on season (wet or dry). Savannah fires account for a large percentage of carbonaceous aerosols detected in regional PM (Andreae and Merlet, 2001; Cachier et al., 1998; Cahoon et al., 1992). It is interesting to note that the draft of air quality regulations in Kenya allows for burning of savannah grassland as part of cultural and traditional practices (NEMA, 2013).

This paper presents results from a long-term measurement campaign initiated in 2008/2009 at two sites in the Nairobi metropolitan area. Samples were analyzed for their elemental content using X-ray fluorescence spectroscopy and the results were evaluated using Positive Matrix Factorization (PMF). The results are compared with available data from previous short-term studies in Nairobi and their implications for urban air pollution mitigation strategies are discussed. The overall aim is to identify sources of $PM_{2.5}$ and evaluate their seasonal variations.

2 Materials and methods

2.1 Description of the sampling area

Nairobi City lies some 200 km south of the equator and occupies an area of about 684 km^2. It has a population of about 3.2 million people with a daytime population of about 4 million (KOD, 2012). The larger Nairobi metropolitan area had a population of 6.1 million as of 2007 and it is expected to grow to over 12 million by 2030 (MoNMD, 2008). This increase in population results in an increase in commercial, traffic and industrial activities, especially within the central business district. The peri-urban areas of the city continue to experience both controlled and uncontrolled development in buildings and infrastructure, especially mushrooming of informal settlements (Karanja and Makau, 2012). In these settlements, solid waste is usually burned in open air and

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a majority of the households use kerosene and biomass based fuels (charcoal, wood and vegetation) for domestic cooking (Egondi et al., 2013). The city's industrial area is dominated by small and medium-sized industries include food processing, power generation, chemical processing industries, battery manufacturing and scrap metal recycling. Most of the recycling is done in the informal "Jua Kali" sector. To ensure service delivery to the growing population, the government of Kenya drew a long-term strategic plan, Kenya Vision 2030, with the aim of transforming the country into an industrialized, middle-income country by 2030 (KV2030, 2007) and as a way of addressing implementation of the Millennium Development Goals (MDGs) (United Nations, 2013).

2.2 Climate of the study area

Nairobi City experiences a moderate climate even though it is located along the equator. At a height of about 1795 m above the sea level, the city has a subtropical high climate according to the Köppen climate classification (Peel et al., 2007) as opposed to the expected tropical climate. The regional climate of East Africa is influenced by the seasonal displacement of the inter-tropical convergence zone (ITCZ) (Henne et al., 2008). The north-south-north annual shift of the ITCZ is driven by the apparent annual motion of the sun and results in monsoon trade winds, which give rise to well-defined wet and dry seasons (KMD, 2013). Severe changes in this cycle usually results in droughts or flooding in the East African region (WMO, 2013).

On a diurnal scale, the region being astride the equator has the number of sunshine hours per day which do not vary significantly. The average annual rainfall is approximately 900 mm but varies from less than 500 mm to more than 1500 mm between years. The average daily temperature varies from about 17 °C in July and August to 20 °C in March. The daily temperature range is quite large and vary from 10 °C in May to 15 °C in February (KMD, 2013).

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2.3 Sampling sites

Sampling of $PM_{2.5}$ was carried out at two sites within the Nairobi metropolitan area. The first site was at the University of Nairobi main campus (1.279° S, 36.817° E) (herein referred to as university and marked S1 in Fig. 1), which is within the city center. The second sampling site was established in a suburban area, within the compound of the United Nation Environmental Programme headquarter (1.234° S, 36.818° E) (herein referred to as UNEP and marked as S2 in Fig. 1) and about 5 km to the north of the university site.

Cyclone samplers (Casella, Bedford, UK) were used to collect fine particles ($PM_{2.5}$) on pre-weighed polycarbonate filters with 0.4 µm pore size (Whatman International Ltd., Maidstone, UK). Samples were collected for 24 h per sample at a flow rate of 3 L min^{-1}, except on weekends when samples were collected for 48 h per sample. At both the university and UNEP sites, sampling started at 10.00 a.m., local time (UTC +3). At the university site, $PM_{2.5}$ samples were collected from 22 May 2008 to 2 April 2010, and the sampler was mounted on the rooftop of the Engineering building at about 17 m above ground level (a.g.l.). This site being at an elevated location and close to the city center represents an urban background setting.

At the UNEP site, sampling was carried out from 16 April 2009 to 30 March 2010. The cyclone setup was placed on the rooftop of the Administration block about 10 m a.g.l. The site is in a suburban area compared to the university site and it is surrounded by two local forests (Karura to the east and Gigiri to the south), and comprises of office blocks and low-density residential houses.

A total of 780 valid samples were collected, of which 502 and 278 were from the university and UNEP sites, respectively. Loaded filters were analyzed for $PM_{2.5}$ mass concentration, black carbon (BC) and trace elements (from S to Pb). The $PM_{2.5}$ mass concentration was determined gravimetrically using a microbalance (Mettler Toledo model TM5). Empty and loaded filters were weighed after being conditioned at a relative humidity of 50 ± 10 % and a temperature of 20 ± 2 °C for 24 h. The BC concentration was

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analyzed using a BC reflectometer (ESM Emberline, model FH62 1-N). The reflectometer measures the absorption and reflection properties of the sample-loaded filter, whereby the reflected light intensity at 650 nm is observed to non-linearly decrease as BC concentration increases on the filter.

Trace elements were analyzed using Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy. The spectrometer uses a Philips diffraction X-ray tube and a Mo secondary target. The secondary target consists of a 1 mm thick Mo plate of 99.99 % purity. Fluoresced secondary X-rays propagate through two Ag collimators giving a relatively focused beam of near monochromatic X-rays for sample excitation. The spectrometer is laboratory built (University of Gothenburg, Sweden) in an optimized three axial geometry that gives good signal to noise ratios for the analyzed elements (Boman, 1991). It was operated at a voltage of 50 kV and a current of 20 mA and spectral information was acquired for a live time of 1000 s. The spectra were analyzed using Analysis of X-ray spectra by Iterative Least-square fitting (AXIL) which is a subprogram of the Quantitative X-ray Analysis System (QXAS) software from International Atomic Energy Agency (Bernasconi et al., 2000). The subprogram assists in spectrum conversion and fitting. In this study, a calibration file was created using single element standards. The standards were run, fitted and evaluated for element's net peak area (P_A) and associated background area (B_A). The obtained P_A and B_A together with the known concentration (C_A) of the element were used to calculate the detection limit (DL_i; see Table 1) using the IUPAC equation below (van Grieken and Markowicz, 1993):

$$DL_i = 3 \times C_i \times \frac{\sqrt{B_A}}{P_A}$$

2.4 Data treatment and analysis

$PM_{2.5}$, trace element and BC concentrations were further analyzed using Positive Matrix Factorization (PMF) for purposes of source apportionment. PMF is a multivariate

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factor analysis method that decomposes a matrix of speciated sample data into factor contributions and profiles, which are then interpreted as to what source types they represent (Paatero, 1997). The EPA PMF 3.0 program from USEPA (Norris et al., 2008) was used for the analysis. Data below the detection limit (DL) were substituted with one-half of the respective DL and uncertainty was set to ±5/6 times the DL (Polissar et al., 2001). During PMF analysis the number of factors was varied between three and nine, and the five factor solution was concluded to give physically meaningful results for all factors and is presented here.

Meteorology data for this study were collected from Jomo Kenya International Airport (JKIA) that is approximately 13 km to the southeast of the university site (data was purchased from AccuWeather Enterprise Solutions, New York, USA). In addition, back-trajectories of air masses arriving at 100 m above the sampling sites were generated using the HYSPLIT_4 model (Draxler and Hess, 1998). Daily back-trajectories were run for 72 h, clustered on a monthly basis and compared with monthly averages of measured wind speed and direction.

3 Results and discussion

3.1 $PM_{2.5}$ mass and elemental concentrations

Results for $PM_{2.5}$, BC and 13 trace elements mass concentrations from the university and UNEP sites are presented in Table 1. At the university site, $PM_{2.5}$ mass concentration ranged between 3 to 53 $\mu g\,m^{-3}$ with an overall mean of 20 $\mu g\,m^{-3}$. The average $PM_{2.5}$ mass concentration exceeded the annual WHO guideline limit of 10 $\mu g\,m^{-3}$ by a factor of two. Elemental composition of $PM_{2.5}$ at the university site was dominated by BC, Fe, S and Cl. Average BC mass concentration accounted for 18 % of the of the total $PM_{2.5}$ mass concentration whereas Fe, S and Cl accounted for 9 % of the of the total $PM_{2.5}$ mass concentration.

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At the UNEP site $PM_{2.5}$ mass concentration ranged between 1.9 to 36 $\mu g\,m^{-3}$ with an overall mean of 13 $\mu g\,m^{-3}$. The average $PM_{2.5}$ mass concentration was about 30 % higher than the annual WHO guideline. The 24 h WHO guideline was exceeded 7 % of the sampling days. BC had the highest average concentration of the identified components and individually accounted for 11 % of the total $PM_{2.5}$ mass concentration whereas other trace elements combined together accounted for 15 % of the $PM_{2.5}$ mass concentration. The average concentration of S was the second highest followed by the concentrations of Cl, Fe and K in that order.

Average $PM_{2.5}$ concentration at the university site was about 50 % higher than at the UNEP site. This observed difference indicates the importance of the location of the measurement site, which in this case was in a sub-urban area surrounded by forests. Albeit the close proximity of the sites, the university site, an urban background site, was under greater influence from PM sources compared to the UNEP site. Observed range and standard deviation from the two sites indicates variability of the $PM_{2.5}$ concentration and respective sources during the sampling period. The average BC concentration at the university site was more than twice the BC concentration at the UNEP site and had a similar concentration difference between the sites could be noted for Ca, Mn, Fe and Br.

From all the filters collected, approximately 29 % of the elemental contents were detected with the balance of 71 % attributed to the contribution from organic matter, nitrates aluminosilicates and oxides of both detected and undetected elements. BC had the highest average concentration and accounted for 17 % of the $PM_{2.5}$ mass concentration whereas trace elements accounted for 14 % of the mass. The average concentration of Fe was highest in concentration of the elements followed by S and Cl in that order. Lead concentrations are well below the WHO annual guideline concentration of 500 $ng\,m^{-3}$ (WHO, 2000). This is probable due to the phasing out of leaded gasoline in 2006 in Kenya. Due to the high altitude of Nairobi a Tel-B mixture was being used (before 2006) as an anti-knock additive in the gasoline resulting in a Br/Pb ratio of 0.77 in particulate matter from fresh exhaust (Harrison and Sturges, 1983).

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To illustrate the overall wide range of concentrations and the difference between the university and UNEP sites the relative concentrations of K, Ca and BC are plotted in the ternary diagram in Fig. 2. Samples from the university site are marked as squares while samples from the UNEP site are marked by circles and only the 661 samples where all of the concentrations of K, Ca or BC are above their detection limits are included in the diagram. The BC concentrations have been divided by ten to get a better spread among the data in the figure. The ellipse with a solid line shows that several of the samples from the UNEP site are relatively low in K and high in Ca regardless of the BC concentration, suggesting different sources for these components. On the other hand more of the samples from the university site (the ellipse with a dotted line) have high concentrations of K and relatively low concentration of Ca within a narrower BC concentration span for these samples. This might imply a contribution of particles from incomplete combustion, including biomass burning. On the lower left-hand side of the plot, the circled samples show that the highest BC and Ca concentrations and low K concentrations were found at the UNEP site. These samples might originate from combustion processes involving a lower proportion of biomass burning. The different colors of the samples illustrate days with (purple circles, green squares) and without (blue circles, black squares) rain. In general the different samples are well mixed, with the exception of the enclosed samples at UNEP on non-rainy days. These samples contain less K and more Ca than the other samples which can be explained by a lower influence of particles from biomass burning but with higher dust content on these days.

3.2 Positive Matrix Factorization analysis and source apportionment

Positive Matrix Factorization was applied to the combined data from the two sites to identify major $PM_{2.5}$ sources. The results from a five-factor solution are shown in Figs. 3–8 and the individual factors are discussed hereinafter.

The first factor is attributed to both exhaust and non-exhaust traffic emissions (Fig. 3). The factor is characterized by a high contribution of BC, S, K, Fe and Zn and accounts for 39 % of the $PM_{2.5}$. The factor shows a similar pattern as that of elemental profile of

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$PM_{2.5}$ samples collected from a traffic polluted site in Connecticut, USA (Gent et al., 2009). The factor is identified with exhaust traffic emissions due to the presence of S and BC (Arku et al., 2008; Lestari and Mauliadi, 2009; Zachariadis et al., 2001). The high S concentration comes from diesel sold in Kenya that contains 0.5 % S and the visible black smoke from the exhaust pipes of many vehicles indicates incomplete combustion resulting in high emissions of BC. Furthermore, there are no regulations on vehicular emissions and a majority of the cars are imported as second-hand although there is an age-limit of 8 years. Non-exhaust traffic emissions such as re-suspension of road dust (Fe, K, Ca and traces of Pb) and tire abrasion (Zn) (Chueinta et al., 2000; Salma and Maenhaut, 2006; Pant and Harrison, 2013) also contributes to this factor.

The second factor is attributed to mineral dust (Fig. 4). It is dominated by crustal elements (Fe, Ca, K and Ti) and has a pattern similar to that of elements from soil samples collected across SSA which were analyzed using Total X-ray Fluorescence technique (Towett et al., 2013). This factor highlights the contribution of local soil to $PM_{2.5}$ in Nairobi. The prolonged dry periods during the campaign contributes to the increased mineral dust loading to the sampled $PM_{2.5}$. The absence of S, Zn and Pb in this factor marks the difference between the origin of the mineral dust in this factor and the re-suspended road dust in the first factor hence justifying both dust components as separate entities.

The third factor is attributed to the formation of secondary aerosol particles. It is characterized by Cl, S and K and accounts for 13 % of the mass concentration (Fig. 5). The presence of both Cl and S together with observed back trajectories (see below) implying that one way that sulfate aerosol particles in Nairobi may be formed is in contact with the sea salt particles from the Indian Ocean. Sea salt particles are known to lose Cl due to reaction with acidic compounds (Nyanganyura et al., 2007) like sulfuric acid, to form sulfate aerosol particles from S that originate from diesel and heavy fuel oil consumption within the Nairobi region.

The fourth factor is attributed to combustion processes. It is characterized by BC, S, K and Fe (Fig. 6) and accounts for 6 % of the mass concentration. It shows similarity with

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a combustion factor from a study in Skopje, Macedonia (Kovacevik et al., 2011), which was associated with biomass and fossil fuel combustion. Combustion activities that are likely to contribute to $PM_{2.5}$ in Nairobi include use of heavy fuel oil in industries and in thermoelectric power generation (BC, S), solid waste burning (BC, Zn, Pb), domestic charcoal/wood fires/biomass burning (BC, K, Br) in the low income households and slums which account for over 80 % of settlements in Nairobi metropolitan area (Egondi et al., 2013; Karanja and Makau, 2012).

The fifth factor is attributed to industrial emissions. It is characterized by Zn, Fe, Cl and K and accounts for 7 % of the mass concentration (Fig. 7). Specifically, it is identified with emissions from smelting industries that depend on scrap metals as raw materials, (Querol et al., 2007). These smelting industries are located on the eastern and southeastern parts of the city which coincide with the general wind and air mass flow directions (Fig. 8).

Figure 9 summarizes the percentage composition of the identified $PM_{2.5}$ source factors. It is evident that traffic and mineral contribute approximately 74 % of $PM_{2.5}$ in Nairobi. This observation points to the significance of anthropogenic influence on air quality given that traffic is purely human-related and mineral dust contribution originates from both natural and human-related activities.

3.3 Seasonal variation

Figure 8 illustrates the relative stability of the weather patterns influencing Nairobi during the measurement period. Clustered back trajectories show two main wind directions with winds coming from either southeast or east depending on season. The hot and dry and the short rainy season are characterized by north-easterly to easterly winds while south-easterly winds dominate the long rainy and the cool and dry seasons. Figures 10 and 11 show the seasonal variation of the PMF factors at the university site and the UNEP site, respectively. The seasons are demarcated based on the description of the Nairobi climate by Kenya Meteorological department (KMD, 2013).

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3.3.1 University site

Traffic and mineral dust factors dominate at the university site (Fig. 10). Generally, traffic and mineral dust factors are inherent during the entire sampling period. It is important to note that the dip observed during the short rain season in 2009 was partly due to high uncertainty as a result of majority of the filters collected at that time being below the detection limit. The disappearance of the mineral dust factor during this season is attributed to the rainout effect. During the same period in 2009, the factor is prominent due to the then on going drought. The drought effect is evident in that during the long rainy season in 2009 no significant change in mineral dust contribution is noted when compared with the cool and dry season in the same year. A low amount of rainfall (223 mm) was recorded compared to the normally expected amount (450 mm).

The traffic factor is almost consistent throughout the sampling period except during the short rainy season of 2009. The factor's contribution is seen to dominate in the beginning of 2010. Further statistical analysis of data in relation to traffic factor, shows that average ratio for Pb to $PM_{2.5}$ obtained for different seasons is similar except for the hot and dry season in 2009, which is 25 % higher than the ratio for the entire sampling period. In addition, average Br/Pb ratio is 0.64 compared to a ratio of 0.77 from fresh vehicular exhaust, (Harrison and Sturges, 1983). During this season, wind blows mainly from northeastern direction (same direction as the Thika highway and the Globe roundabout which is the entry point of vehicles from central and northern Kenya). Furthermore, contribution from tire abrasion was also a possibility (Salma and Maenhaut, 2006) given that many on road vehicles rely on second-hand tires.

The secondary aerosol factor though not prominent, it is consistent throughout the sampling period but slightly pronounced during the short rainy season in 2009. During this season wind direction is usually easterly to northeasterly and therefore vehicular emission from the city center contributes S to this factor due to prevailing high temperature and humidity which enhance oxidation of SO_2 (Querol et al., 2001). In addition,

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marine influence from Indian Ocean is evident as shown in Fig. 8 in that back trajectories of air mass arriving in Nairobi principally originate from Indian Ocean.

The combustion factor was not consistent through the sampling period, but was prominent during the hot and dry season in 2009. This observed trend in combustion factor is an indication of the complexity of combustion sources in Nairobi, such as biomass burning in Savannah plains, burning of solid waste, extensive domestic use of kerosene and charcoal in slum areas for cooking and traffic emissions from diesel combustion engines (Reinard et al., 2007; Salma and Maenhaut, 2006).

The industrial factor showed a seasonal variation in that it was prominent during the cool and dry seasons as well as during the long rainy season in 2009. This observation highlighted contribution of metallurgical industries since local winds and regional air masses were generally easterly to southeasterly, bringing emissions from the said industries, which are located in that direction relative to the sampling site.

3.3.2 UNEP site

Figure 11 shows the trend in source factors at the UNEP site. Contribution of the factors is highest during the cool and dry season in 2009 and is dominated by the mineral dust, traffic and industrial factors. The contribution decreases towards the beginning of 2010. Wind direction during the cool and dry season is generally southerly to easterly which is the same direction as the city center and industrial area in relation to this site. During the hot and dry season in 2010, contribution from the mineral dust factor is minimal. This coincided with the observation that the UNEP site recorded 19 rainy days during that season. This observation highlights the erratic nature of rainfall pattern in Kenya during the sampling period (WMO, 2013) and its influence on the airborne particulate matter levels.

The traffic factor is consistently distributed throughout the sampling period but prominent during the cool and dry season. This is identified as resulting from re-suspension of road dust from the neighboring motorways. As was the case at the university site, calculated $Pb/PM_{2.5}$ ratio shows seasonal variation. However the $Pb/PM_{2.5}$ ratio is

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slightly higher (about 28 %) than at the university site indicating significance of the traffic factor compared to other sources at the UNEP site. At the UNEP site the Br/Pb ratio is 0.43. Lead remains in the soil for a long time and soil dust will be a source of Pb containing particles (Datko-Williams et al., 2014), among other anthropogenic sources.

The secondary aerosol factor is prevalent during the hot and dry season. During this season the wind direction is usually north-easterly and thus traffic related emissions are transported from Thika highway towards UNEP site and its environs. Furthermore, since the UNEP site is located to the northwest of the city center, it is likely to be influenced by secondary aerosol related sources within the city center.

The industrial factor is prominent during the latter part of the long rainy season as well as during the cool and dry season. This pattern is similar to what is observed at the university site. Therefore, this observation is attributed to the reasons given as for the university site.

Lastly, the combustion factor is consistent throughout the sampling period but shows minimal contribution to $PM_{2.5}$ at this site. It does not show any seasonal variability and thus indicates to be dependent on contribution from regional sources. This observation is attributed to the fact that the site is in a suburban area where combustion activities such as solid waste burning, domestic cooking using biomass among others are not common practice since the area is in uptown and enjoy essential services such as waste collection.

3.4 Weekly trend of PMF factors

Figure 12 shows classification of PMF factors by days of the week. All the five factors have lower values on weekends suggesting that anthropogenic activities impacts on all of them. The trend is similar to observed human activities in the city center on a typical week. Weekdays are usually busy with both human and traffic activities compared to weekends (Kinney et al., 2011).

Considering individual factors, the mineral dust factor shows the least difference between weekdays and weekends. This observation points to the fact that contribution of

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dust particles to airborne $PM_{2.5}$ is influenced by both anthropogenic activities and natural phenomena. The traffic factor has a trend similar to the mineral dust factor and this highlights the significance of road dust contribution to the Nairobi $PM_{2.5}$ despite less traffic in the city center on weekends. This observation is supported by previous short term studies which focused on traffic related emissions (van Vliet and Kinney, 2007).

The observed similarity between the combustion and industrial factors points to the connection between the two given that a majority of metallurgy industries in Kenya still use the open-hearth furnaces inherited from the colonial periods. More so these industries rely on both heavy fuel oil and electricity for smelting scrap metals.

The secondary aerosol factor was about 50 % lower on weekends compared to weekdays and this implied that the factor was greatly influenced by anthropogenic activities compared to natural phenomena. This observation is supported by the fact that traffic activities reduce to a minimum during weekends and thus there is less emission of S from the high sulfur-content fuel used in Kenya.

3.5 Comparison of $PM_{2.5}$ with other studies

Since there were no other long-term studies of $PM_{2.5}$ and their elemental content in urban areas of Sub-Sahara Africa to compare with, $PM_{2.5}$, elements and BC concentrations from this study were compared with values from a selection of available short term studies, Table 2.

$PM_{2.5}$ concentration at the university site in the month of July 2009 was comparable to the $PM_{2.5}$ concentration reported by Gatari et al. (2009) from a study conducted at an industrial background site in Nairobi during July 2001. However in the month of July 2008, the value was 30 % lower. The agreement between the $PM_{2.5}$ concentrations in July 2001 and July 2009 and the difference compared to July 2008 illustrates the influence of drought on PM concentration since there was a severe drought in July 2001 as was the case in 2009. The abundance of PM in the air in July 2001 can be seen in the higher concentrations of many elements in the study by Gatari et al. (2009) compared to the average concentrations at the university site in this study. A clear exception is

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the concentration of Pb, which was more than three times higher in 2001 compared to this study. This demonstrates the effect of banning Pb from the gasoline in 2006.

The listed African cities in Table 2, exhibited similar characteristics to Nairobi and are reported to have their air quality influenced largely by mineral dust, combustion activities and vehicular emissions. $PM_{2.5}$ concentration from this study was half of that reported from measurements in 2006 and 2007 at a semi-rural area of Accra City, Ghana (Aboh et al., 2009). The main difference is probably the influence of the dust filled Harmattan winds blowing from the Saharan desert to Accra. The same can be seen in a comparison between this study and the study in 2007 in Ouagadougou, Burkina Faso (Boman et al., 2009). In another study in Accra the Harmattan conditions were not present and the $PM_{2.5}$ concentration in this study are similar to the $PM_{2.5}$ concentration reported from a 3 week study conducted in 2006 at a low income residential area in Accra City, Ghana (Arku et al., 2008). The proximity to the desert is also reflected in the high $PM_{2.5}$ concentration in a nine month study conducted between September 2010 and May 2011 at Cairo City center (Boman et al., 2013).

In comparison with a two weeks' study (not in Table 2) conducted at street level in Nairobi by Kinney et al. (2011), the average $PM_{2.5}$ concentration from the university site was 50 % lower. Also, the university site $PM_{2.5}$ concentration was a factor of 15 lower than the value reported from a one week measurement campaign carried out along one of the major roads in Nairobi (Thika Road) by van Vliet and Kinney (2007). Observations from these two comparisons point to the discrepancy between background $PM_{2.5}$ concentrations and those from curb side concentrations in Nairobi City.

The elemental composition of $PM_{2.5}$ from the semi-rural area of Accra City had large concentrations of S, K and Fe as was the case with the composition of $PM_{2.5}$ in Nairobi in both this study and the study by Gatari et al. (2009) in 2001 pointing to a similarity in the sources of particles. A noticeable difference between this study and the ones by Gatari et al. (2009), Aboh et al. (2009) and Arku et al. (2008) is the higher concentration of Fe in the $PM_{2.5}$ particles at the university site in this study. This might partly be due to a difference between mineral dust compositions in the two cities but differences in

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measurement periods also play a role. The elemental concentrations at the low income area in Accra (Arku et al., 2008) are comparable to the concentrations at the UNEP site in this study, illustrating the importance of the distance between the measurement site and major pollution source, like city center and busy roads.

In comparison to Cairo City, the elemental concentrations from this study was about 3 times lower than the concentration reported from the nine month study conducted between September 2010 and May 2011 at a city center site (Boman et al., 2013). $PM_{2.5}$ in Cairo City had a large contribution from Ca, Cl and S. Since the city is within the Sahara region, its air quality is likely to be influenced by a mineral dust contribution from the desert. The higher concentrations of S and Cl in Cairo might be due to its location close to the Mediterranean Sea. The Pb concentration in Cairo is comparable to the Pb concentration in Nairobi in 2001, but lower than in this study. Egypt is one of the few countries in Africa where leaded gasoline is still allowed and the comparison points to the importance of banning leaded gasoline to decrease the health burden of the city inhabitants.

4 Conclusions

This study has shown that traffic related emissions (both exhaust and non-exhaust) and mineral dust (both natural and anthropogenic) have significant contribution to $PM_{2.5}$ in Nairobi City. It can also be concluded that policies such as banning of Pb in gasoline have shown positive effect on reducing Pb concentration in $PM_{2.5}$ and hence reducing the risk of Pb pollution to the urban inhabitants. Similarly a reduction of sulfur from the diesel fuel could lead to an improved air quality situation in Nairobi. More so, prevailing weather and climate patterns have been found to play a significant role by influencing the concentration and composition of airborne PM as is the case in other cities in SSA. As shown from wind direction and air mass back trajectories analysis, industrial emissions should be firmly controlled as the industrial area in Nairobi is located in the upwind direction. Since this study points at factors contributing to the air quality

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situation in Nairobi the outcome of this study can be used as a background for further policy actions. Contribution of $PM_{2.5}$ from traffic factor can be controlled by inclusion of emission checks as part of annual vehicle inspection and this would significantly reduce air pollution in the city. On the other hand, natural background concentrations of mineral dust as well as prevailing weather condition would give guidance when formulating any policy aimed at air pollution mitigation. In conclusion, the study has shown that enactment and adherence to air pollution regulations on identified source factors can significantly reduce air pollution levels in cities within SSA.

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References

Aboh, I. J. K., Henriksson, D., Laursen, J., Lundin, M., Ofosu, F. G., Pind, N., Selin Lindgren, E., and Wahnström, T.: Identification of aerosol particle sources in semi-rural area of Kwabenya, near Accra, Ghana, by EDXRF techniques, X-Ray Spectrom., 38, 348–353, doi:10.1002/xrs.1172, 2009.

Andreae, M. O. and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochem. Cy., 15, 955–966, doi:10.1029/2000GB001382, 2001.

Arku, R. E., Vallarino, J., Dionisio, K. L., Willis, R. T., Choi, H., Wilson, J. G., Hemphill, C., Agyei-Mensah, S., Spengler, J. D., and Ezzati, M.: Characterizing air pollution in two low-income neighborhoods in Accra, Ghana, Sci. Total Environ., 402, 217–231, doi:10.1016/j.scitotenv.2008.04.042, 2008.

Bernasconi, G., Tajani, A., and Kregsamer, P.: Manual for QXAS/AXILVersion 3.5, IAEA, Vienna, 2000.

Boman, J.: Sample area dependence in quantitative EDXRF analysis, X-Ray Spectrom., 20, 321–324, doi:10.1002/xrs.1300200613, 1991.

ACPD
14, 9565–9601, 2014

Boman, J., Lindén, J., Thorsson, S., Holmer, B., and Eliasson, I.: A tentative study of urban and suburban fine particles ($PM_{2.5}$) collected in Ouagadougou, Burkina Faso, X-Ray Spectrom., 38, 354–362, doi:10.1002/xrs.1173, 2009.

Boman, J., Shaltout, A. A., Abozied, A. a. M., and Hassan, S. K.: On the elemental composition of $PM_{2.5}$ in central Cairo, Egypt, X-Ray Spectrom., 42, 276–283, doi:10.1002/xrs.2464, 2013.

Cachier, H., Ruellan, S., Liousse, C., Gaudichet, A., Masclet, P., and Lacaux, J.: Biomass burning aerosols in tropical Africa, J. Aerosol Sci., 29, S23–S24, doi:10.1016/S0021-8502(98)00088-3, 1998.

Cahoon, D. R., Stocks, B. J., Levine, J. S., Cofer, W. R., and O'Neill, K. P.: Seasonal distribution of African savanna fires, Nature, 359, 812–815, 1992.

Chueinta, W., Hopke, P. K., and Paatero, P.: Investigation of sources of atmospheric aerosol at urban and suburban residential areas in Thailand by Positive Matrix Factorization, Atmos. Environ., 34, 3319–3329, doi:10.1016/S1352-2310(99)00433-1, 2000.

CSUD: 2005 Nairobi Land Use & Roads Network, Center for Sustainable Urban Development, Columbia University, New York, 2010.

Datko-Williams, L., Wilkie, A., and Richmond-Bryant, J.: Analysis of US soil lead (Pb) studies from 1970 to 2012, Sci. Total Environ., 468–469, 854–863, doi:10.1016/j.scitotenv.2013.08.089, 2014.

Draxler, R. R. and Hess, G. D.: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition, Aust. Meteorol. Mag., 47, 295–308, 1998.

Egondi, T., Kyobutungi, C., Ng, N., Muindi, K., Oti, S., Vijver, S., Ettarh, R., and Rocklöv, J.: Community perceptions of air pollution and related health risks in Nairobi slums, International Journal of Environmental Research and Public Health, 10, 4851–4868, 2013.

Gatari, M. J., Boman, J., and Wagner, A.: Characterization of aerosol particles at an industrial background site in Nairobi, Kenya, X-Ray Spectrom., 38, 37–44, doi:10.1002/xrs.1097, 2009.

Gent, J. F., Koutrakis, P., Belanger, K., Triche, E., Holford, T. R., Bracken, M. B., and Leaderer, B. P.: Symptoms and medication use in children with asthma and traffic-related sources of fine particle pollution, Environ. Health Persp., 117, 1168–1174, doi:10.1289/ehp.0800335, 2009.

Harrison, R. M. and Sturges, W. T.: The measurement and interpretation of BrPb ratios in airborne particles, Atmos. Environ., 17, 311–328, doi:10.1016/0004-6981(83)90048-3, 1983.

ACPD
14, 9565–9601, 2014

Henne, S., Junkermann, W., Kariuki, J. M., Aseyo, J., and Klausen, J.: Mount Kenya Global Atmospheric Watch Station (MKN): installation and meteorology characterization, J. Appl. Meteorol. Clim., 47, 2946–2962, 2008.
Karanja, I. W. and Makau, J.: Nairobi Slum Inventory, available at: http://www.irinnews.org/pdf/nairobi_inventory.pdf (last access: 21 November 2012), 2012.
KEBS: Registered Vehicles: 2001–2009, Kenya National Bureau of Statistics, Nairobi, 2013a.
KEBS: Regulations on Vehicle Importation, Kenya National Bureau of Statistics, Nairobi, 2013b.
Kinney, P. L., Gichuru, M. G., Volavka-Close, N., Ngo, N., Ndiba, P. K., Law, A., Gachanja, A., Gaita, S. M., Chillrud, S. N., and Sclar, E.: Traffic impacts on $PM_{2.5}$ air quality in Nairobi, Kenya, Environ. Sci. Policy, 14, 369–378, doi:10.1016/j.envsci.2011.02.005, 2011.
KMD: Nairobi Climate, Kenya Meteorological Department, Nairobi, 2013.
KOD: Rural and Urban Population Census: 2009, Kenya Open Data, Nairobi, 2012.
Kovacevik, B., Wagner, A., Boman, J., Laursen, J., and Pettersson, J. B. C.: Elemental composition of fine particulate matter ($PM_{2.5}$) in Skopje, FYR of Macedonia, X-Ray Spectrom., 40, 280–288, doi:10.1002/xrs.1337, 2011.
KV2030: Kenya Vision 2030: Popular version, Government Press, Nairobi, 2007.
Lestari, P. and Mauliadi, Y. D.: Source apportionment of particulate matter at urban mixed site in Indonesia using PMF, Atmos. Environ., 43, 1760–1770, doi:10.1016/j.atmosenv.2008.12.044, 2009.
Lindén, J., Boman, J., Holmer, B., Thorsson, S., and Eliasson, I.: Intra-urban air pollution in a rapidly growing Sahelian city, Environ. Int., 40, 51–62, doi:10.1016/j.envint.2011.11.005, 2012.
Mkoma, S. L., Chi, X., and Maenhaut, W.: Characteristics of carbonaceous aerosols in ambient PM_{10} and $PM_{2.5}$ particles in Dar es Salaam, Tanzania, Sci. Total Environ., 408, 1308–1314, doi:10.1016/j.scitotenv.2009.10.054, 2010.
MoNMD: A World Class African Metropolis – Building a Safe, Secure and Prosperous Metropolitan, Government Press, Nairobi, 2008.
NEMA: Draft Air Quality Regulation, 2008, National Environment Management Authority, Nairobi, Kenya, 2013.
Norris, G., Vedantham, R., Wade, K., Brown, S., Prouty, J., and Foley, C.: EPA Positive Matrix Factorization (PMF) 3.0 Fundamentals & User Guide, U.S. Environmental Protection Agency: Washington,DC, EPA/600/R-08/108, 2008.

ACPD
14, 9565–9601, 2014

Nyanganyura, D., Maenhaut, W., Mathuthu, M., Makarau, A., and Meixner, F. X.: The chemical composition of tropospheric aerosols and their contributing sources to a continental background site in northern Zimbabwe from 1994 to 2000, Atmos. Environ., 41, 2644–2659, doi:10.1016/j.atmosenv.2006.11.015, 2007.

Odhiambo, G. O., Kinyua, A. M., Gatebe, C. K., and Awange, J.: Motor vehicles air pollution in Nairobi, Kenya, Research Journal of Environmental and Earth Sciences, 2, 178–187, 2010.

Paatero, P.: Least squares formulation of robust non-negative factor analysis, Chemometr. Intell. Lab., 37, 23–35, doi:10.1016/S0169-7439(96)00044-5, 1997.

Pant, P. and Harrison, R. M.: Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review, Atmos. Environ., 77, 78–97, doi:10.1016/j.atmosenv.2013.04.028, 2013.

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633–1644, doi:10.5194/hess-11-1633-2007, 2007.

Petkova, E., Jack, D., Volavka-Close, N., and Kinney, P.: Particulate matter pollution in African cities, Air Qual. Atmos. Health, 6, 603–614, doi:10.1007/s11869-013-0199-6, 2013.

Polissar, A. V., Hopke, P. K., and Poirot, R. L.: Atmospheric aerosol over Vermont?: chemical composition and sources, Environ. Sci. Technol., 35, 4604–4621, doi:10.1021/es0105865, 2001.

Querol, X., Alastuey, A., Rodriguez, S., Plana, F., Ruiz, C. R., Cots, N., Massagué, G., and Puig, O.: PM_{10} and $PM_{2.5}$ source apportionment in the Barcelona Metropolitan area, Catalonia, Spain, Atmos. Environ., 35, 6407–6419, doi:10.1016/S1352-2310(01)00361-2, 2001.

Querol, X., Viana, M., Alastuey, A., Amato, F., Moreno, T., Castillo, S., Pey, J., de la Rosa, J., Sánchez de la Campa, A., Artíñano, B., Salvador, P., García Dos Santos, S., Fernández-Patier, R., Moreno-Grau, S., Negral, L., Minguillón, M. C., Monfort, E., Gil, J. I., Inza, A., Ortega, L. A., Santamaría, J. M., and Zabalza, J.: Source origin of trace elements in PM from regional background, urban and industrial sites of Spain, Atmos. Environ., 41, 7219–7231, doi:10.1016/j.atmosenv.2007.05.022, 2007.

Reeves, C. E., Formenti, P., Afif, C., Ancellet, G., Attié, J.-L., Bechara, J., Borbon, A., Cairo, F., Coe, H., Crumeyrolle, S., Fierli, F., Flamant, C., Gomes, L., Hamburger, T., Jambert, C., Law, K. S., Mari, C., Jones, R. L., Matsuki, A., Mead, M. I., Methven, J., Mills, G. P., Minikin, A., Murphy, J. G., Nielsen, J. K., Oram, D. E., Parker, D. J., Richter, A., Schlager, H., Schwarzenboeck, A., and Thouret, V.: Chemical and aerosol characterisation of the tropo-

ACPD
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sphere over West Africa during the monsoon period as part of AMMA, Atmos. Chem. Phys., 10, 7575–7601, doi:10.5194/acp-10-7575-2010, 2010.
Reinard, M. S., Adou, K., Martini, J. M., and Johnston, M. V.: Source characterization and identification by real-time single particle mass spectrometry, Atmos. Environ., 41, 9397–9409, doi:10.1016/j.atmosenv.2007.09.001, 2007.
Salma, I. and Maenhaut, W.: Changes in elemental composition and mass of atmospheric aerosol pollution between 1996 and 2002 in a Central European city, Environ. Pollut., 143, 479–488, doi:10.1016/j.envpol.2005.11.042, 2006.
Sawyer, R. F.: Vehicle emissions: progress and challenges, J. Expo. Sci. Env. Epid., 20, 487–488, doi:10.1038/jes.2010.44, 2010.
Towett, E. K., Shepherd, K. D., and Cadisch, G.: Quantification of total element concentrations in soils using total X-ray fluorescence spectroscopy (TXRF), Sci. Total Environ., 463–464, 374–388, doi:10.1016/j.scitotenv.2013.05.068, 2013.
UN: World Urbanization Prospects: The 2009 Revision, United Nations, New York, 2010.
UNEP: Eastern Africa Regional Framework Agreement on Air Pollution (Nairobi Agreement – 2008), United Nations Environmental Programme, Nairobi, 2013.
United Nations: Millennium Development Goals Indicators, New York, 2013.
van Grieken, R. E. and Markowicz, A. A.: Handbook of X-Ray Spectrometry, Marcel Dekker, New York, 1993.
van Vliet, E. D. S. and Kinney, P. L.: Impacts of roadway emissions on urban particulate matter concentrations in Sub-Saharan Africa: new evidence from Nairobi, Kenya., Environ. Res. Lett., 2, 045028, doi:10.1088/1748-9326/2/4/04502, 2007.
WHO: Air quality guidelines for Europe, 2nd Edn., World Health Organization, Copenhagen: 2000.
WMO: The Global Climate 2001–2010: a Decade of Climate Extremes, 61, World Meteorological Organization, Geneva, 2013.
Zachariadis, T., Ntziachristos, L., and Samaras, Z.: The effect of age and technological change on motor vehicle emissions, Transport. Res. D-Tr. E., 6, 221–227, 2001.

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Table 1. Summary of the results from the University and the UNEP sites showing detection limits, range, mean concentrations and standard deviations (SD) for detected trace elements, BC ($ng\,m^{-3}$) and $PM_{2.5}$ ($\mu g\,m^{-3}$). *N* is the number of valid samples.

Element	Detection limit ($ng\,m^{-3}$)	University (22 May 2008–2 Apr 2010) Range ($ng\,m^{-3}$)	Mean (SD) ($ng\,m^{-3}$)	*N*	UNEP (16 Apr 2009–30 Mar 2010) Range ($ng\,m^{-3}$)	Mean ($ng\,m^{-3}$)	*N*
S	250	220–1600	640 (250)	132	250–1700	620 (280)	184
Cl	110	110–1800	510 (210)	253	110–1600	430 (170)	259
K	50	56–840	330 (140)	265	50–760	270 (160)	239
Ca	30	32–2700	360 (260)	268	30–1300	200 (150)	228
Ti	14	21–180	59 (25)	241	14–110	40 (18)	156
Mn	9.5	11–190	47 (23)	267	10–90	28 (14)	236
Fe	10	33–1800	650 (340)	270	11–1200	320 (240)	278
Ni	0.8	1–10	4 (2)	153	1–17	4 (2)	191
Cu	0.7	2–82	12 (6)	269	2–55	9 (4)	275
Zn	6.6	7–760	99 (110)	270	7–640	76 (97)	272
Br	2.5	3–340	14 (25)	240	3–70	7 (5)	215
Rb	0.5	1–5	3 (1)	160	1–5	2 (1)	123
Pb	1.5	2–160	25 (19)	202	2–79	17 (14)	186
BC		36–9500	3600 (1900)	270	70–5700	1500 (1000)	267
$PM_{2.5}$ ($\mu g\,m^{-3}$)		3–53	20 (8)	270	1.9–36	13 (7.3)	278

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Table 2. $PM_{2.5}$, BC, and trace element concentrations from this study (Nairobi) compared with concentration from other cities in Africa and Europe. Concentrations are in ng m^{-3}. Values enclosed in brackets are the standard deviations.

	This study				Gatari et al. (2009)		Aboh et al. (2009)		Boman et al. (2009)		Arku et al. (2008)		Boman et al. (2013)	
Site/ Elements	University (urban background)		UNEP (suburban)		Industrial background, Nairobi		Semi-rural area, Accra		City center, Ouagadougou		Low income area, Accra		Urban center, Cairo	
S	660	(240)	620	(280)	1300	(400)	462	(290)			909	(267)	1200	(870)
Cl	520	(200)	430	(170)			123	(133)	960	(290)	706	(423)	2200	(2200)
K	340	(160)	270	(160)	730	(220)	377	(325)	670	(210)	694	(188)	470	(260)
Ca	370	(270)	200	(150)	70	(34)	144	(322)	1400	(570)	57	(22)	2900	(3200)
Ti	62	(27)	40	(18)	8.7	(4.4)	37.5	(64.8)	240	(81)	6	(3)	100	(89)
Mn	53	(23)	28	(14)	12	(3.9)	7.6	(11.4)	61	(25)	6	(2)	24	(20)
Fe	730	(340)	320	(240)	130	(43)	289	(504)	3000	(1400)	69	(27)	1000	(1000)
Ni	4	(1)	4	(2)	2.6	(1.1)	3.2	(2.8)					6.8	(1.7)
Cu	12	(7)	9	(4)	3.5	(2.2)	4.1	(3.9)	19	(6.4)	9	(15)	16	(9.8)
Zn	120	(120)	76	(97)	100	(69)	6.5	(5.7)	45	(35)	32	(13)	200	(180)
Br	16	(30)	7	(5)	36	(18)	5.9	(3.5)	7.3	(2.7)	30	(16)	21	(15)
Rb	3	(1)	2	(1)	1.56	(0.5)	1.4	(1.4)	4.2	(1.9)	2	(1)	4.4	
Pb	23	(16)	17	(1)	76	(30)	2.5	(1.7)	8.8	(4.2)	18	(25)	86	(180)
BC	3900	(800)	1500	(1000)	4800	(1800)	1900	(1100)	4900	(1700)			3700	(2100)
$PM_{2.5}$	21 000	(950)	13 000	(7300)	30 000	(9400)	40 800	(54 400)	86 000	(42 000)	22 700	(5700)	51 000	(39 000)

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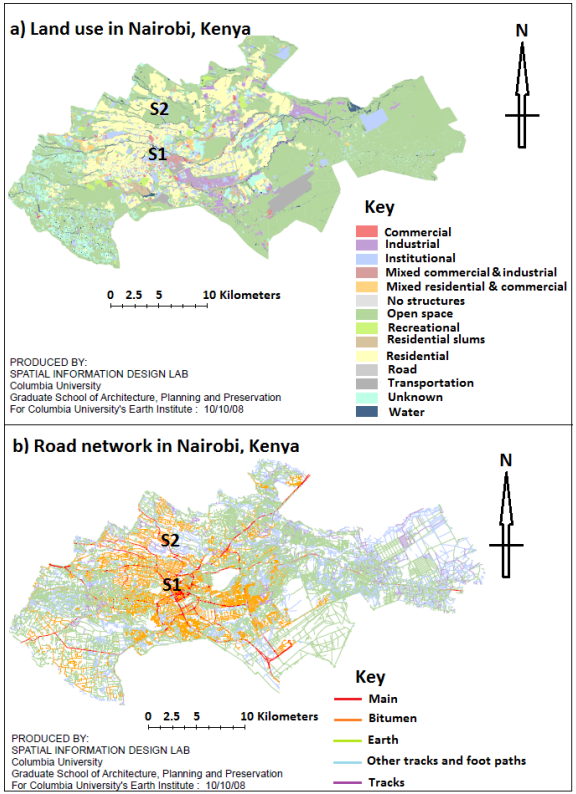

Fig. 1. GIS map of the Nairobi metropolitan area showing land use pattern **(a)** and transportation network **(b)**. Original maps were modified to include sampling sites as shown on both maps; University of Nairobi (S1) and United Nations Environmental. Programme (UNEP) headquarters (S2). (Original maps reproduced from Center for Sustainable Urban Development's Nairobi GIS maps and database website, CSUD, 2010).

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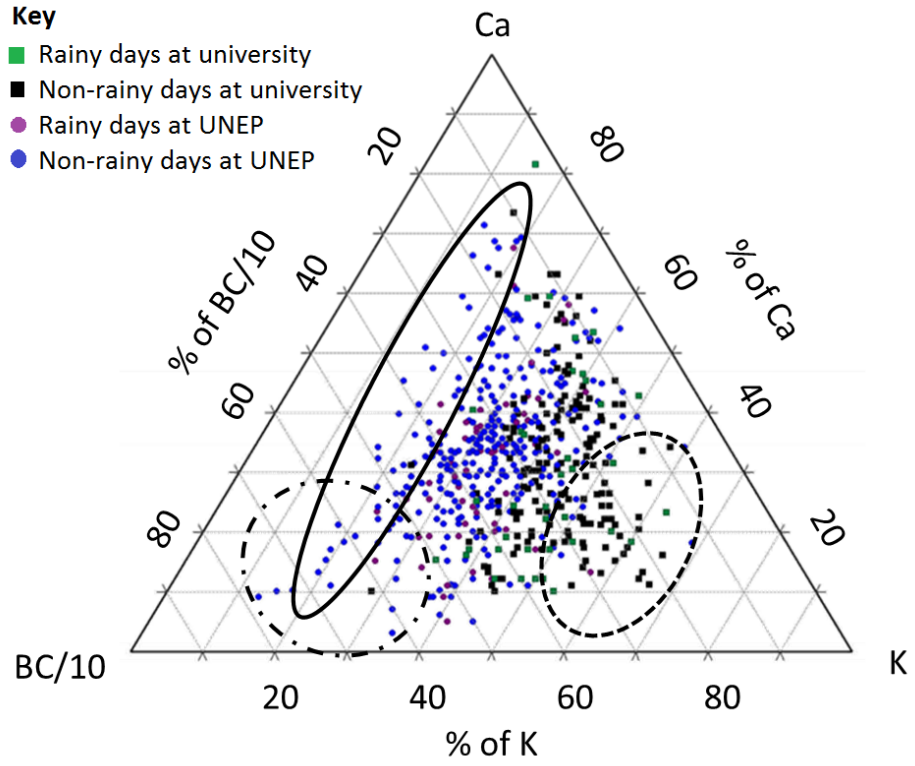

Fig. 2. A ternary diagram illustrating the relative concentrations of K, Ca and BC from the 661 samples from which none of the detected components were below their respective detection limit. The intention was to highlight the difference in elemental concentrations between rainy and non-rainy days at both university and UNEP site.

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Source apportionment and seasonal variation of $PM_{2.5}$

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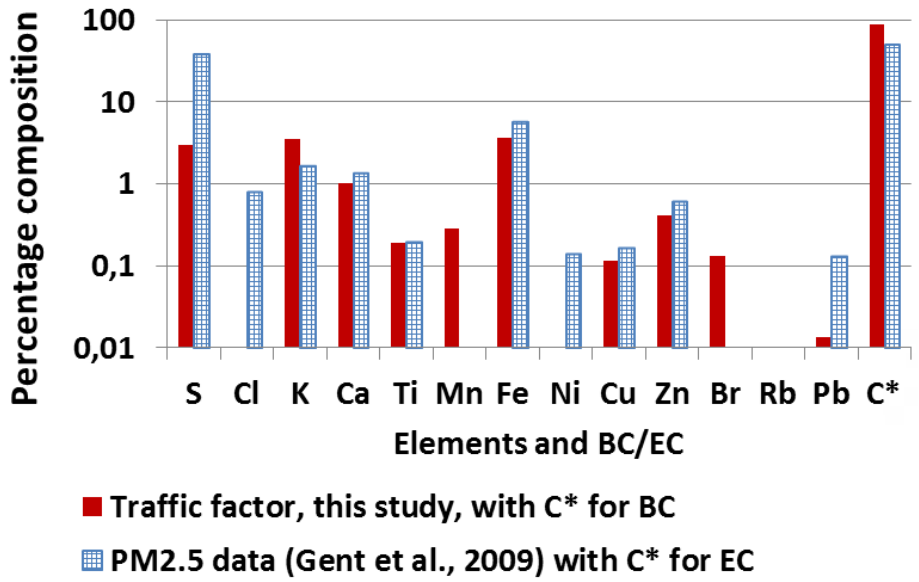

Fig. 3. Traffic factor from PMF analysis of $PM_{2.5}$ from this study compared with $PM_{2.5}$ from a traffic polluted site in Connecticut, USA (Gent et al., 2009).

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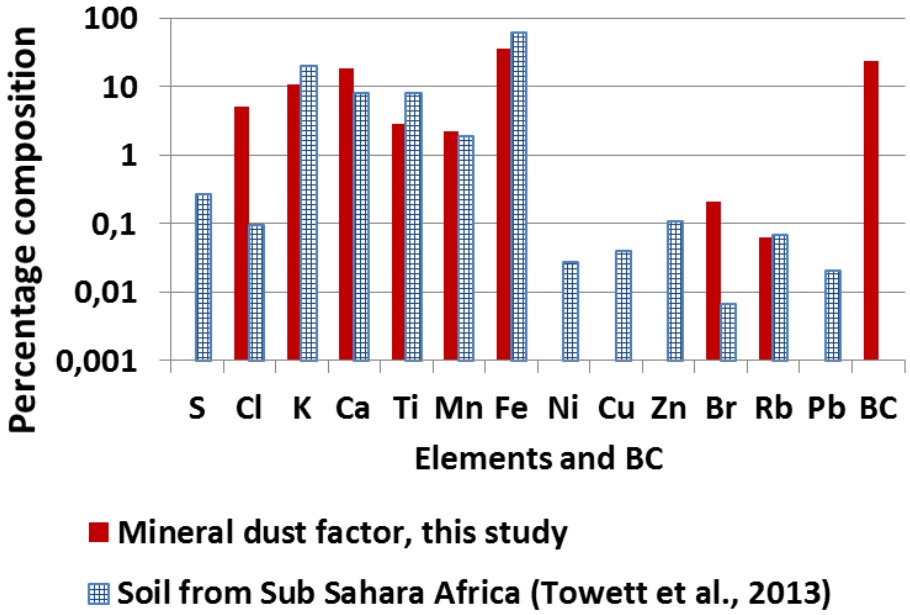

Fig. 4. Mineral dust factor from the PMF analysis of $PM_{2.5}$ from this study compared with elements from soil samples from SSA countries (Towett et al., 2013).

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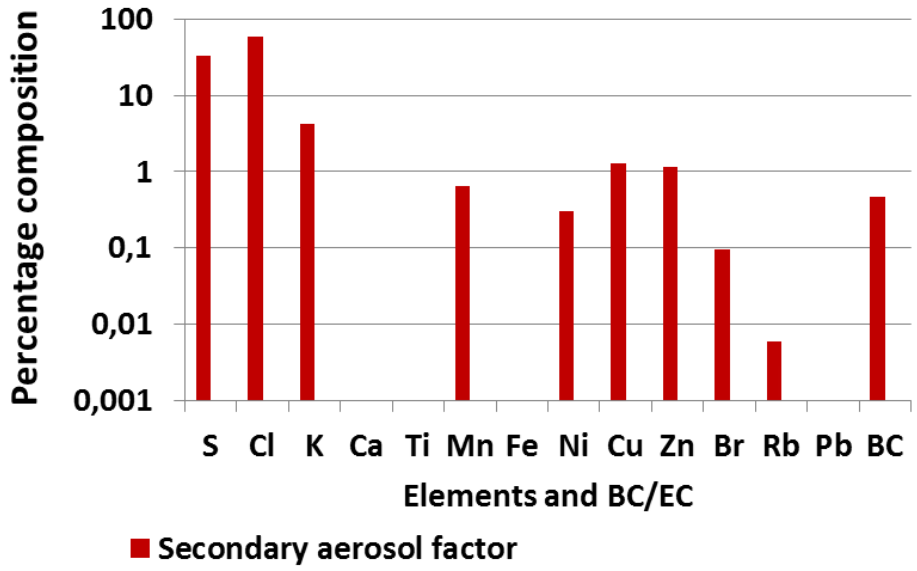

Fig. 5. Secondary aerosol factor from analysis of sampled $PM_{2.5}$ marked by S and Cl showing the contribution from regional sources.

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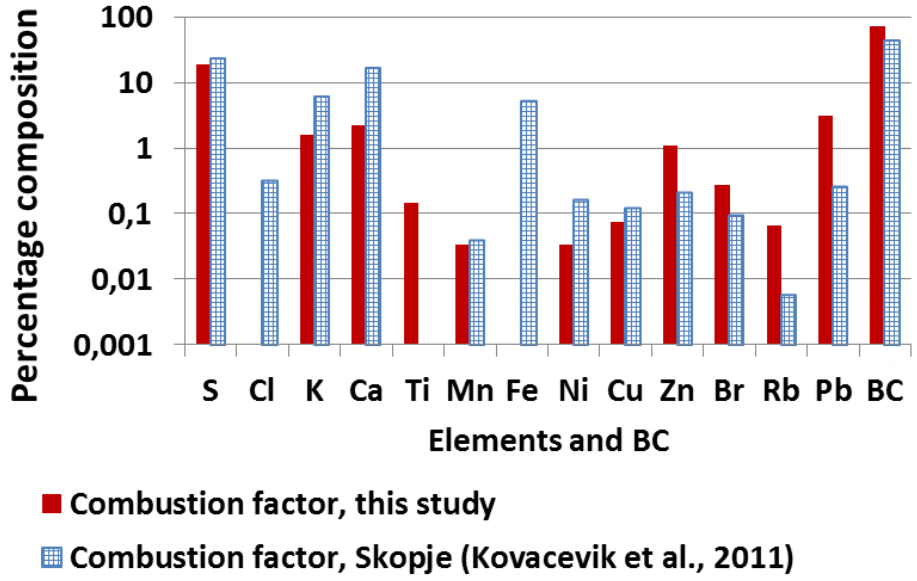

Fig. 6. Combustion factor from the PMF analysis of $PM_{2.5}$ from this study compared with combustion factor from Skopje, Macedonia (Kovacevik et al., 2011).

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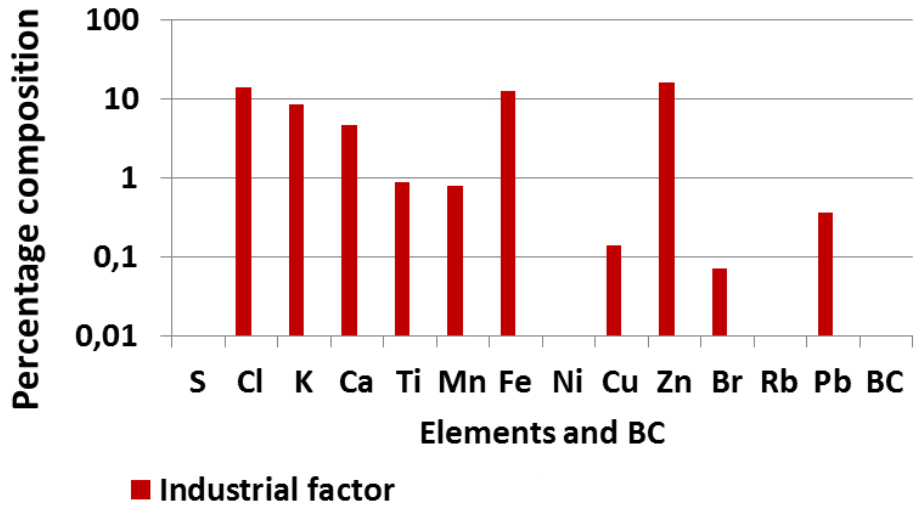

Fig. 7. Industrial factor from analysis of sampled $PM_{2.5}$ showing the contribution of metallurgy industries (Fe and Zn) to aerosol in Nairobi.

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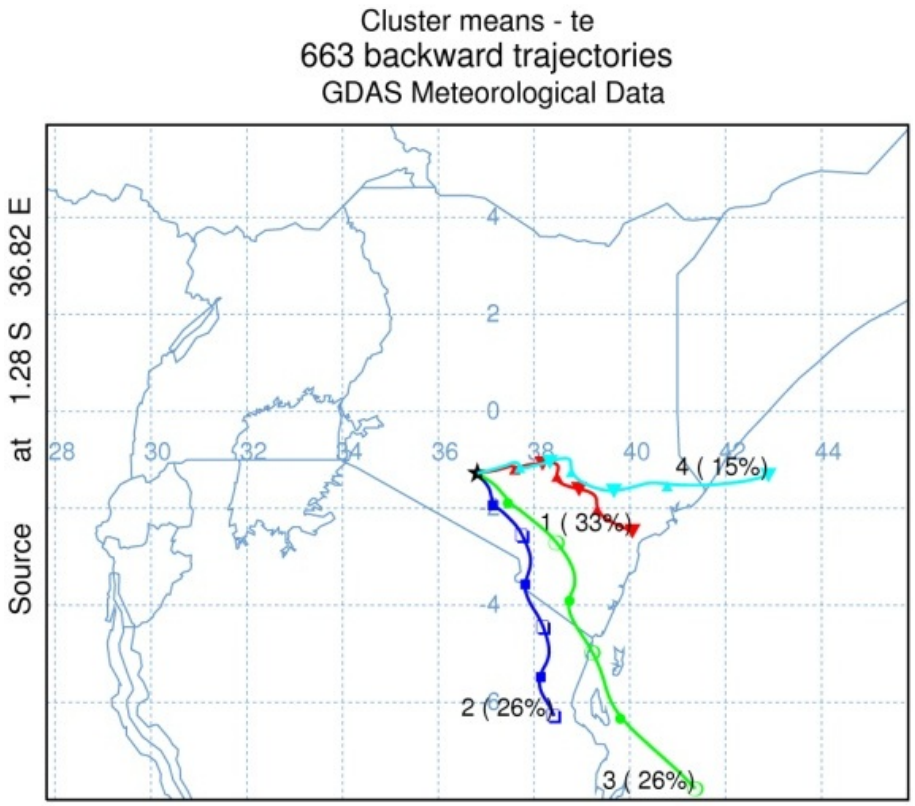

Fig. 8. Clustered 72 h back trajectories ending in Nairobi at 100 m height above the ground for the period, 22 May 2008 to 3 March 2010. Calculated back trajectories originates principally from southeast (trajectories 2 and 3) and east (trajectories 1 and 4).

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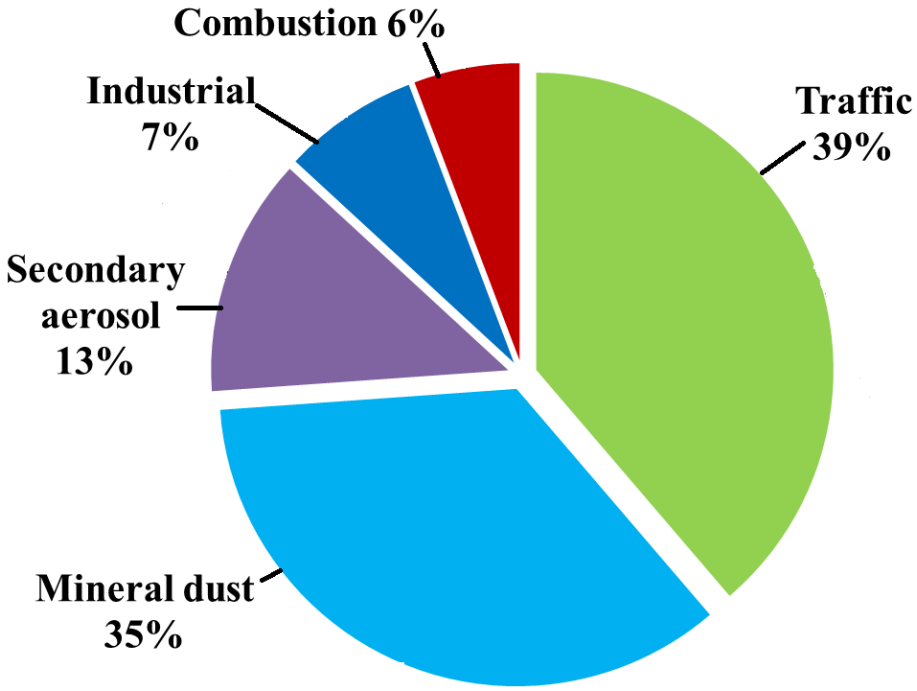

Fig. 9. Percentage composition of source factors from PMF analysis of $PM_{2.5}$ collected in Nairobi, Kenya. Traffic and mineral dust factors have major contribution to airborne particulate pollutant.

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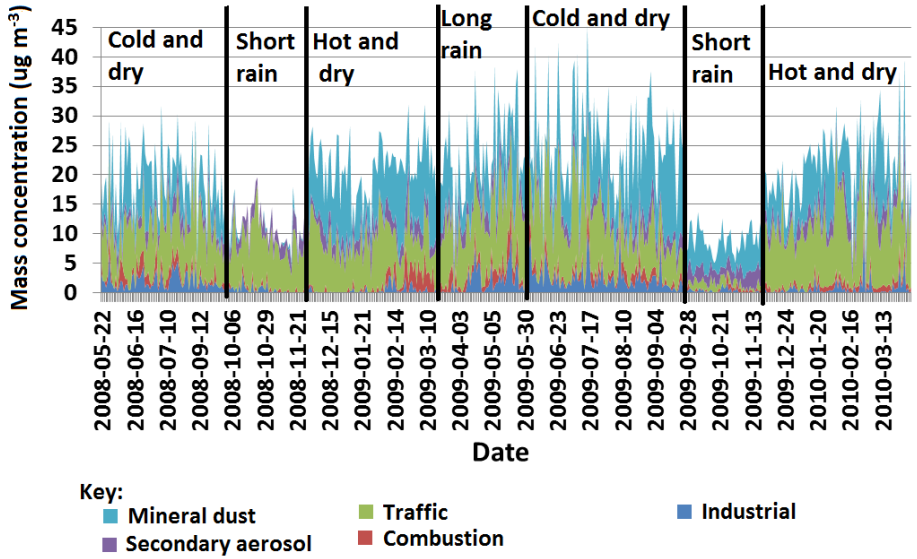

Fig. 10. Seasonal variation of the five factors obtained from the PMF analysis of the $PM_{2.5}$ composition at the university site. Traffic factor shows consistency throughout the sampling period highlighting the significant of vehicular emission to urban air pollution. Seasons have been demarcated for clarity.

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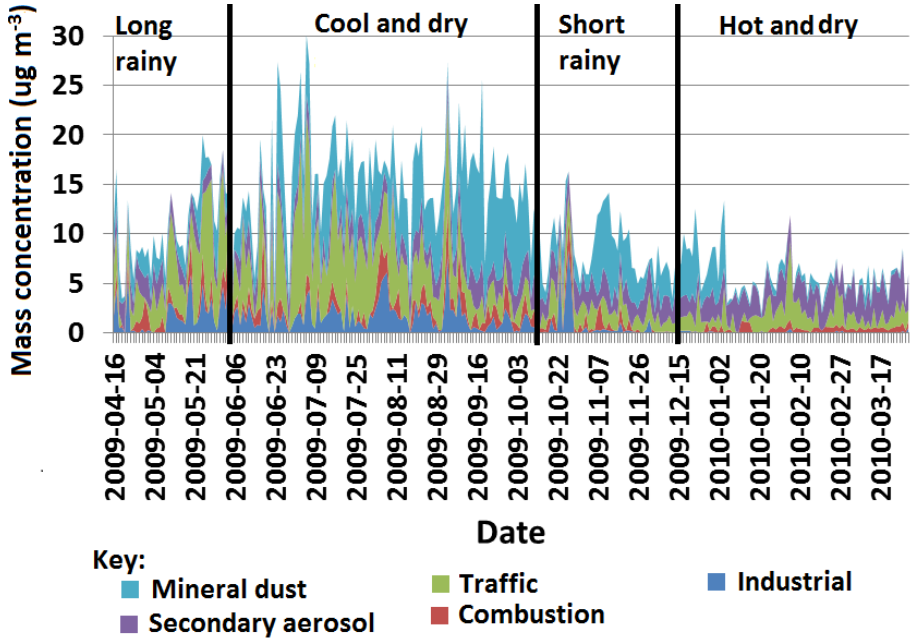

Fig. 11. Seasonal variation of the five factors obtained from the PMF analysis of the $PM_{2.5}$ composition at the UNEP site. The effect of erratic weather pattern is evident from the dampened contribution of mineral dust factor in 2010. Seasons have been demarcated for clarity.

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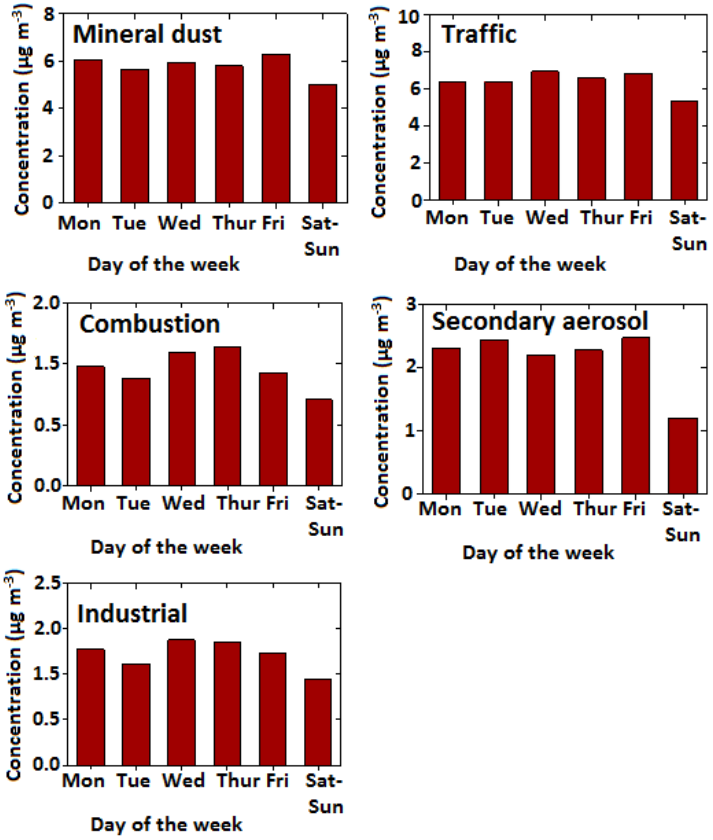

Fig. 12. Weekly series of the five factors obtained from the PMF analysis of sampled $PM_{2.5}$. The difference between weekdays and weekends highlights the anthropogenic contribution to air pollution in Nairobi.

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