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SOURCE APPORTIONMENT OF $PM_{2.5}$ EMISSIONS IN MAKKAH, SAUDI ARABIA: USING A POSITIVE MATRIX FACTORIZATION MODEL

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ABSTRACT:

In this paper, the sources of $PM_{2.5}$ are quantified in the Holy City of Makkah, applying a Positive Matrix Factorisation (PMF) Model. High Volume System (HVS) samplers for Particulate Matter (PM) were used to collect $PM_{2.5}$ 24 hour (10 am - 10 am) samples at two locations from September 2013 to August 2014 in Makkah. IC technique (model: 850 Professional IC_ Metrohm USA) was used to detect the concentrations of water soluble cations and anions, such as sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), nitrate (NO_3^-), ammonium (NH_4^+), chloride (Cl^-), and fluoride (F^-). ICP technique (model: 700 series ICP, OES spectrometers Agilent) was used to detect the concentrations of K, Al, Ba, Co, Cr, Cu, As, Mn, Cd, Ni, Pb, Se, Mo, Si, and Zn. Four main sources of $PM_{2.5}$ were identified: (1) Fossil-fuel Combustion - generated by burning of petrol, diesel, and coal in vehicles, factories, houses and restaurants. This group includes directly emitted pollutants like Pb, Ni, Cd, Cl^-, F^- and secondary pollutants which are formed from the conversion of gaseous pollutants, such as SO_2 and NOx to secondary aerosols like SO_4^{2-} and NO_3^- particles. This source contributed about 60 % of $PM_{2.5}$ in Makkah. (2) Industrial emissions - mainly industrial dusts generated by various industrial processes. These sources contributed 27 % of $PM_{2.5}$. The dominant species were As, K, Se and Si. (3) Soil particles - mainly generated by large scale digging of mountains, construction - demolition and wind. Soil particles contribute about 12 % of $PM_{2.5}$ and the main species were Cd, Cr and MO. (4) Miscellaneous – water-spray in the Holy Mosque and resuspension of roadside dust. Miscellaneous contribute about 2 % of $PM_{2.5}$ in Makkah and are dominated by Mn and Zn. These results are mostly in agreement with previous studies carried out in other cities of Saudi Arabia.

Keywords: *Receptor modelling, particulate matter, sources of $PM_{2.5}$, Makkah, air quality*

1. INTRODUCTION:

High levels of Particulate Matter (PM) concentrations in Makkah, especially during the Hajj periods, when millions of people visit the city to perform Hajj and Umrah have been reported by several authors (Munir et al., 2013a; Habeebullah, 2013a; Othman et al., 2010; Al-Jeelani, 2009). It is reported that PM concentrations exceed air quality standards in Makkah, hence may pose a potential threat to public health (Munir et al., 2013b; Munir et al., 2014; Munir et al., 2015; Munir, 2015; Sayegh et al., 2014; Habeebullah, 2013b; Habeebullah et al., 2014 a & b; Habeebullah et al., 2015). The reasons for the high PM concentrations in Makkah are most probably high volume of road traffic, construction-and-demolition work, resuspension of particles, windblown dust-and-sand particles and geographical conditions (Munir et al., 2013a). Most of the areas in Saudi Arabia are made of sandy deserts, which lead to a high background

concentration of dust in the air as wind blows into inhabited areas from the neighbouring desert lands (Munir et al., 2013b).

Continuous monitoring, modelling and health assessment of PM, especially PM_{10} and $PM_{2.5}$ are important for achieving a healthy air quality level and protecting public health from the adverse health effects of polluted air. Exposure to the high levels of PM_{10} and $PM_{2.5}$ are linked with health problems including respiratory diseases, such as asthma, bronchitis, lung inflammation and cardiovascular diseases (Aina et al., 2014; Zhou et al., 2014; Vinikoor-Imler et al., 2011; Hoek and Raaschou-Nielsen, 2014). In addition, PM exposure can lead to increased hospital admission and mortality. According to World Health Organisation (WHO, 2013) report 7 million premature deaths in 2012 were caused by air pollution. Air pollution is considered one of the most important environmental problems and reducing air pollution can simply save millions of lives annually. However, research shows that PM pollution is increasing in many countries in the world due to the fact that its emission sources (both natural and anthropogenic) have been increasing, especially in the countries with high levels of PM levels including Saudi Arabia. Saudi Arabia like other arid regions have high levels of background PM concentrations due to its arid nature, low rainfall and frequent sandstorms.

Habeebullah (2016) analysed the chemical composition of Particulate Matter (PM) in Makkah and reported that the average levels of total suspended particles (TSP), PM_{10} and $PM_{2.5}$ (μgm^{-3}) were about 366, 233 and 143, respectively during 2012 - 2013. Furthermore, the ratios of $PM_{2.5}$: PM_{10}, $PM_{2.5}$: TSP and PM_{10} : TSP were 0.61, 0.39, and 0.64, respectively (Habeebullah, 2016). Habeebullah (2016) reported that the most abundant anions in PM in Makkah were NO_3^- and SO_4^{2-}, which were about 30 % and 20 %, respectively, whereas arsenic (As) metal was over 40 %, which mostly comes from traffic and other combustion processes. Munir et al. (2013a) quantified temporal trends in the levels of various air pollutants in Makkah during 1997 to 2012 and reported a positive trend in the levels of PM_{10}. Likewise, Aina et al. (2014) using satellite derived $PM_{2.5}$ data analysed temporal trends during 2001 to 2010 and showed that several cities including Jeddah and Makkah had increasing trend in $PM_{2.5}$ concentrations. This probably shows that there is a need for further research work to identify the sources of PM and prepare and effective plan for air quality management in Makkah.

Source apportionment of PM helps identify the major air pollutants emission sources, which can lead to preparing and effective air quality management plan. No research work has been carried out so far on source apportionment of PM in Makkah, which is a major constraint for the effective management and control of particle pollution. This project intends to quantify the percent contribution of each emission source of particles, focusing on $PM_{2.5}$ in Makkah, which will lead to better understanding, modelling and management of particle pollution in Makkah.

2. METHODOLOGY:

High Volume System (HVS) Samplers were used to collect $PM_{2.5}$ samples at two locations in Makkah: Al-Azizia and Al-Haram (Figure 1). Al-Aziziah is a residential area, however there is a busy market nearby on Al-Haram Road. Al-Haram is the Holy Mosque which is situated in the centre of Makkah and is the busiest area in Makkah. Both

Al-Azizia and Al-Haram are considered urban background sites because the HVS samplers were installed away from the main roads in the background urban areas. The average rate of HVS sampling was 30 litre/minute for twenty four hours (10am-10am). $PM_{2.5}$ samples were collected for a whole year from September 2013 to August 2014. After collection, the samples were taken to a local laboratory and analysed for various elements and ions. The IC technique (model: 850 Professional IC_ Metrohm USA) was used to detect the concentrations of SO_4^{2-}, PO_4^{3-}, NO_3^-, NH_4^+, Cl^-, and F^-. For metals analysis $PM_{2.5}$ filters were digested three times (each 10 min.) with 10 ml of HNO_3 (1M) using ultrasonic water-bath. The obtained filtrate were analysed by using ICP technique (model: 700 series, ICP OES, spectrometers Agilent) to detect the concentration of K, Al, Ba, Co, Cr, Cu, As, Mn, Cd, Ni, Pb, Se, Mo, Si, and Zn. Each metal was quantified under specific wavelength conditions with the corresponding dilutions using deionized distilled water, and using standards which were simultaneously analysed with experimental samples.

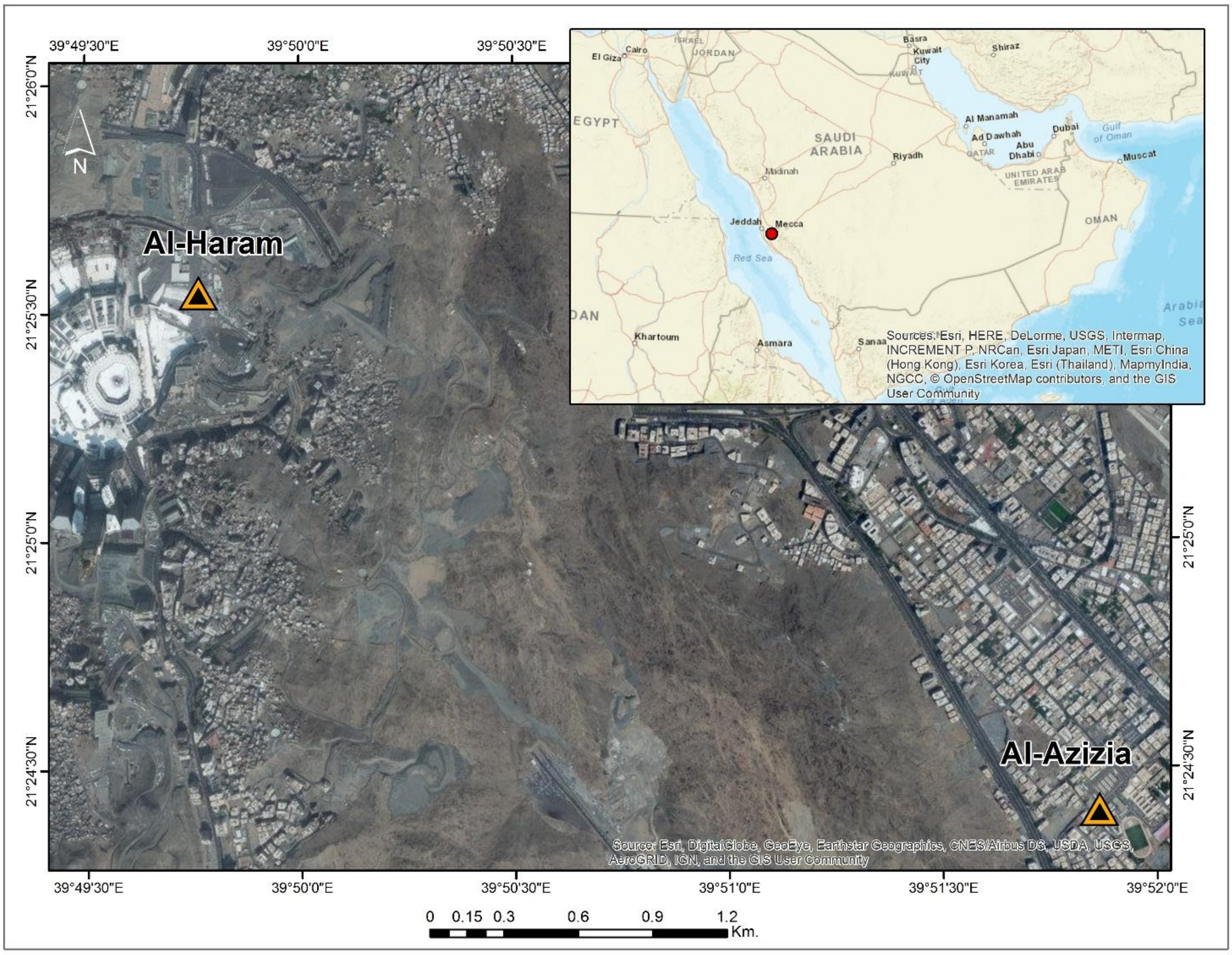


Figure 1. **Map of Makkah, showing monitoring stations Al-Haram and Azizia.**

The US EPA Positive Matrix Factorisation (PMF) receptor model version 5.0 was used to quantify the contribution of various emission sources. Various model runs were carried out using different number of factors, however in the run used in this study 4 factors were used. The concentrations of $PM_{2.5}$, water soluble cations and anions and various elements and their uncertainties were used as input data into the PMF model. Actually, the large numbers of input variables are reduced to combinations of species known as source types and source contributions by the PMF model. The PMF model calculates source profiles, source contributions and source profile uncertainties with the help of input data files. For air quality source apportionment PMF model is recommended by numerous authors (e.g., Nayebare et al., 2015; Kim et al., 2003).

For statistical analysis and developing Figures, R programming language (R Development Core Team, 2016) and one of its package 'openair' (Carslaw and Ropkins, 2012) was used. Histograms of $PM_{2.5}$ at both Al-Aiziah and Al-Haram are presented in Figure 2, which show non-normal and right skewed distribution of PM2.5 concentrations at both sites. Furthermore, Table 1 and 2 represent $PM_{2.5}$ and its various components' concentrations for the study period (September 2013 to August 2014) at Al-Haram and Al-Aziziah, respectively. The concentrations are presented in mean, median, minimum, maximum, first quartile (25th percentile), and 3rd quartile (75 percentile).

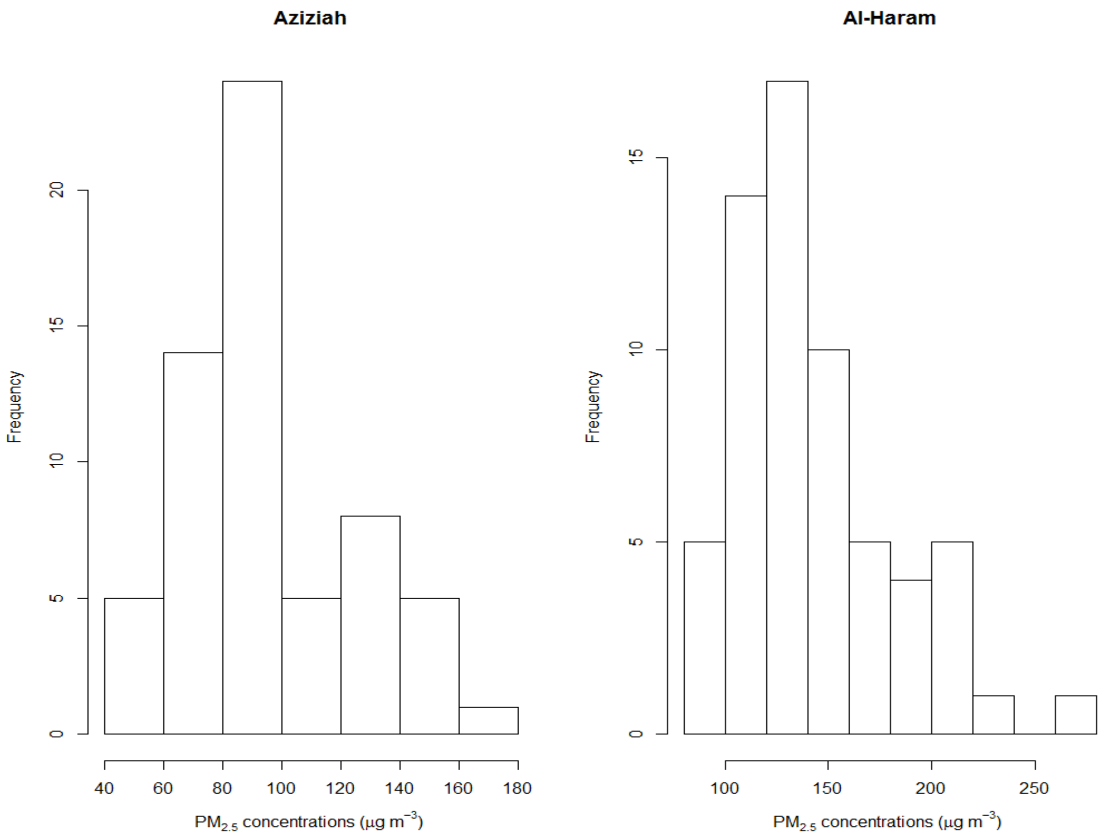


Figure 2. Histograms of $PM_{2.5}$ (µg/m3) at Al-Azizia and Al-Haram sites in Makkah, presenting mean daily data from September 2013 to August 2014.

Table 1. Summary of the data (µg/m3) at Al-Haram monitoring site in Makkah from September 2013 to August 2014.

Pollutant	Min.	1st Quartile	Median	Mean	3rd Quartile	Max.
$PM_{2.5}$	96.1	113.6	130.8	142.0	159.8	265.0
Cl^-	10.10	16.45	21.10	20.79	25.15	35.61
SO_4^{2-}	10.08	13.36	16.73	17.33	18.57	38.40
NO_3^-	12.80	17.93	22.10	22.27	25.28	39.58
NO_2^-	1.070	1.450	2.420	2.885	3.308	10.750
PO_4^{3-}	1.120	3.078	5.730	5.434	7.670	10.190
NH_4^+	0.500	2.500	3.200	3.608	4.378	8.880
Br	0.01	0.04	0.11	0.18	0.24	0.97
F	0.01	0.17	0.31	0.40	0.44	1.44
Al	0.0006	0.0068	0.0382	0.4021	0.4021	4.2134
As	0.0537	0.1175	0.1423	0.1843	0.1971	0.6816
Ba	0.0001	0.1743	1.9259	1.9259	1.9259	9.4515
Cd	0.0014	0.0606	0.1021	0.1317	0.1371	0.5316
Co	0.0018	0.1049	0.1446	0.1648	0.1648	0.9535
Cr	0.0008	0.0384	0.0659	0.1381	0.1613	0.7446
Cu	0.0037	0.0785	0.1811	0.5503	0.4435	8.8390
K	0.3297	1.1396	1.9974	1.9974	1.9974	9.3143
Mn	0.0002	0.0132	0.0543	0.0963	0.0963	1.5132
Mo	0.0025	0.1005	0.1488	0.2243	0.2713	1.0250
Ni	0.0068	0.2571	0.4188	0.4257	0.4741	1.7358
Pb	0.0170	0.1133	0.2912	0.2912	0.4181	0.8130
Se	0.0278	0.1202	0.1553	0.1841	0.2105	0.8231
Zn	0.0000	0.0516	0.3150	0.3150	0.3150	1.9266
Si	0.2138	0.6744	1.0390	1.1294	1.4405	2.9750

Table 2. Summary of the data (µg/m3) at Al-Aziziah monitoring site in Makkah from September 2013 to August 2014.

Pollutant	Min.	1st Quartile	Median	Mean	3rd Quartile	Max.
$PM_{2.5}$	48.00	77.00	88.00	95.48	111.00	162.00
Cl^-	6.58	10.94	12.84	13.00	14.51	19.32
SO_4^{2-}	7.30	10.78	13.40	13.04	15.24	19.32
NO_3^-	6.60	8.54	10.16	10.58	11.92	16.86
NO_2^-	1.03	3.62	5.38	5.41	7.45	10.95
PO_4^{3-}	1.10	1.80	2.48	2.92	3.80	8.02
NH_4^+	1.06	2.24	3.06	3.44	4.36	9.68
Br	0.11	1.40	1.80	1.85	2.14	3.80
F	0.02	0.37	0.51	0.51	0.72	0.98
Al	0.0011	0.0107	0.0687	0.7831	0.7831	7.9389
As	0.0122	0.1520	0.2116	0.2414	0.3245	0.6553
Ba	0.0001	0.0004	0.0225	1.1193	1.1031	6.2786
Cd	0.0033	0.0097	0.0132	0.0202	0.0208	0.0708
Co	0.0042	0.0156	0.0214	0.0909	0.1334	0.6021
Cr	0.0019	0.0059	0.0099	0.0701	0.0694	0.5117
Cu	0.0046	0.0132	0.0312	0.5922	0.5651	7.2404
K	0.2836	1.7796	2.4930	2.4930	2.7341	7.5112
Mn	0.0001	0.0016	0.0114	0.7859	0.63038	6.9169
Mo	0.0017	0.0184	0.0290	0.0592	0.0564	0.4767
Ni	0.0163	0.0453	0.0667	0.2974	0.3396	2.0975
Pb	0.0400	0.0778	0.1070	0.1540	0.1578	0.7539
Se	0.0999	0.1714	0.2200	0.2528	0.3162	0.6842
Zn	0.0003	0.0047	0.0098	0.7151	0.9432	5.6264
Si	0.2695	1.0592	1.4769	1.7358	2.2772	5.3300

3. RESULTS AND DISCUSSION

In Figure 3, the concentrations of $PM_{2.5}$ and its composition are compared at the two monitoring sites for the study period. The concentrations of $PM_{2.5}$, Cl^-, SO_4^{2-} and NO_3^- are higher at Al-Haram site, however the rest of the species show a mixed picture i.e. some species are higher at Al-Haram whereas others are higher at Al-Aziziah site. This is probably due to difference in emission sources. Total $PM_{2.5}$ concentration is higher at Al-Haram site, which is a busy site in terms of people, restaurants and is surrounded by busy roads from all four directions. Also, the largest expansion project of Al-Haram (the Holy Mosque), which commenced in 2011 and was going on during the whole period of this study, might have contributed to the high levels of $PM_{2.5}$ at Al-Haram site. This is one of the largest projects and is meant to expand the Tawaf area (the area around the Kaabah, where pilgrims circumambulate or circle around the Kaabah) and build a large block (known as King Abdullah block) towards the north in the Holy Mosque. The project involves demolition of the old

building, construction of the new building, large scale digging and running of large construction machineries. All these activities emit a huge amount of dust in the surrounding areas and are positively contributing to the observed $PM_{2.5}$ concentrations and its other components.

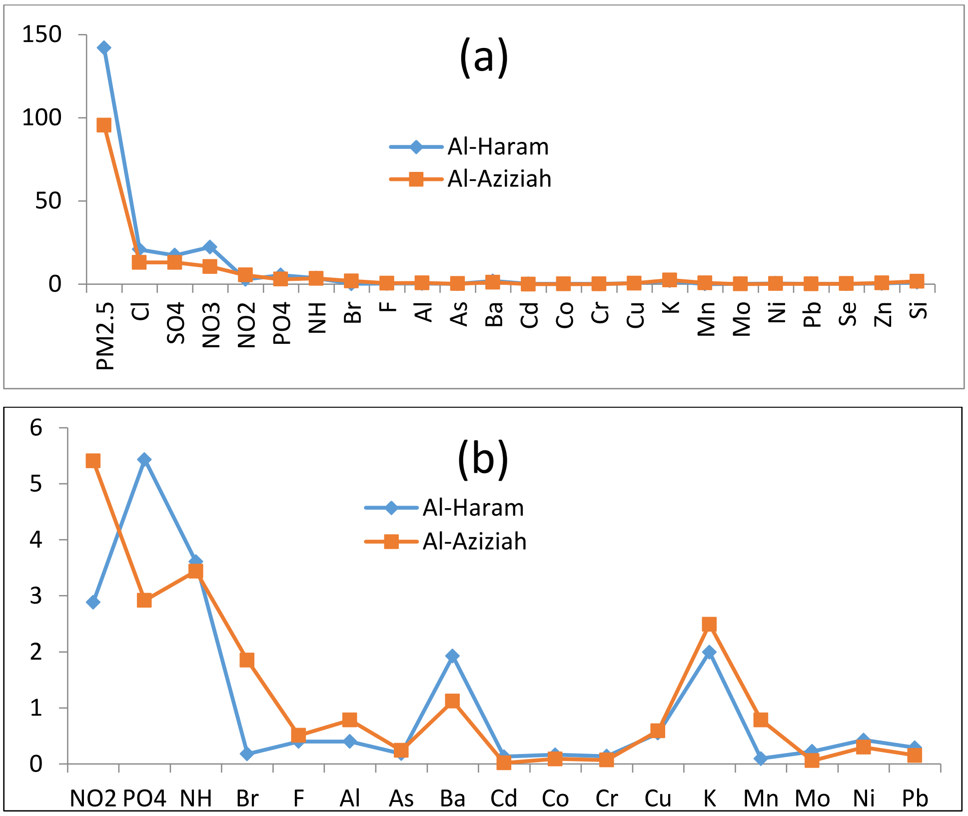


Figure 3. Comparing the concentrations of $PM_{2.5}$ and its composition at Al-Haram and Al-Aziziah monitoring sites in Makkah: the upper panel represents all heavy metals and ions, whereas the lower panel excludes $PM_{2.5}$, Cl, SO_4 and NO_3 to show more clearly the elements with low concentrations.

In Figure 4, the concentrations of $PM_{2.5}$ (µg/m^3) at Al-Haram and Aziziah monitoring sites are compared with each other and with WHO air quality standards (red solid line, 25 µg/m^3). Firstly, $PM_{2.5}$ concentration is higher at Al-Haram site that at Al-Aziziah site. The reasons are discussed above. Secondly, $PM_{2.5}$ concentrations at both sites are higher than the daily $PM_{2.5}$ limits of WHO by several folds. Figure 5, shows the weekly and annual cycles of $PM_{2.5}$ at both monitoring sites and demonstrates that $PM_{2.5}$ concentrations exhibit considerable temporal variations. Furthermore, the weekly and annual cycles are different at both sites, e.g., at Al-Haram site the lowest concentration is shown on Monday, whereas as at Al-Aziziah the lowest concentration is shown on Friday. Annual cycles show highest concentrations in July and April at Al-Haram and Al-Aziziah, respectively. These variations are due to local differences in emission sources, for example on Friday most of the shops are closed in Al-Aziziah and roads are quite, whereas in Al-Haram Friday is the most busy day in terms of people, traffic, and restaurants in the surrounding area as most people go to Al-Haram for Friday congregational pray and to do Tawaf and Umrah.

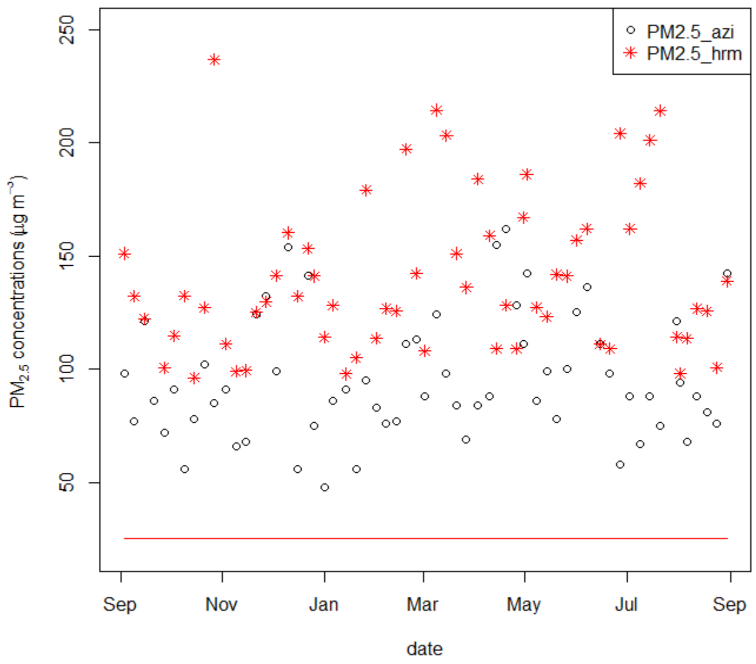
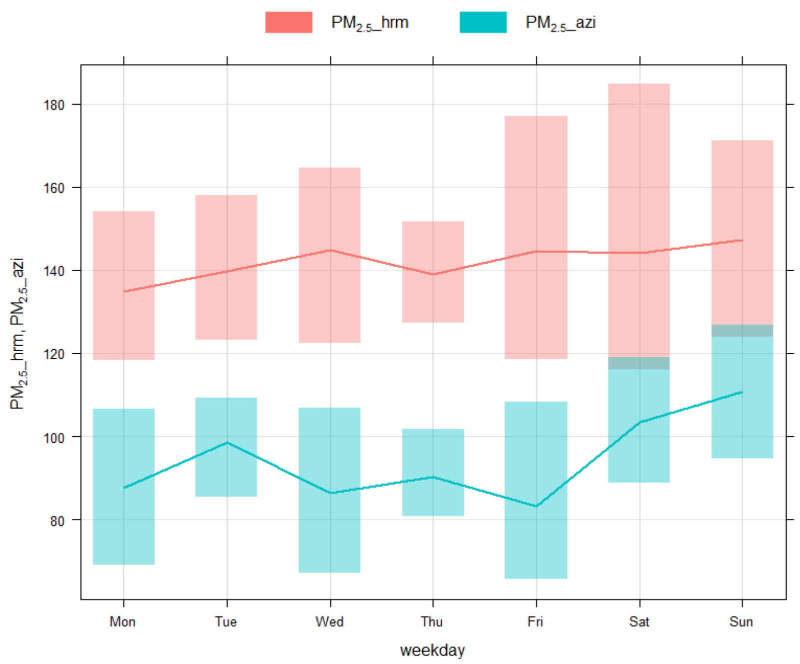


Figure 4. **Time series plot of $PM_{2.5}$ concentrations (µg/m^3) at Al-Haram (hrm) and Al-Azizia (azi) sites. The red solid line shows WHO 24-hour standard for $PM_{2.5}$.**



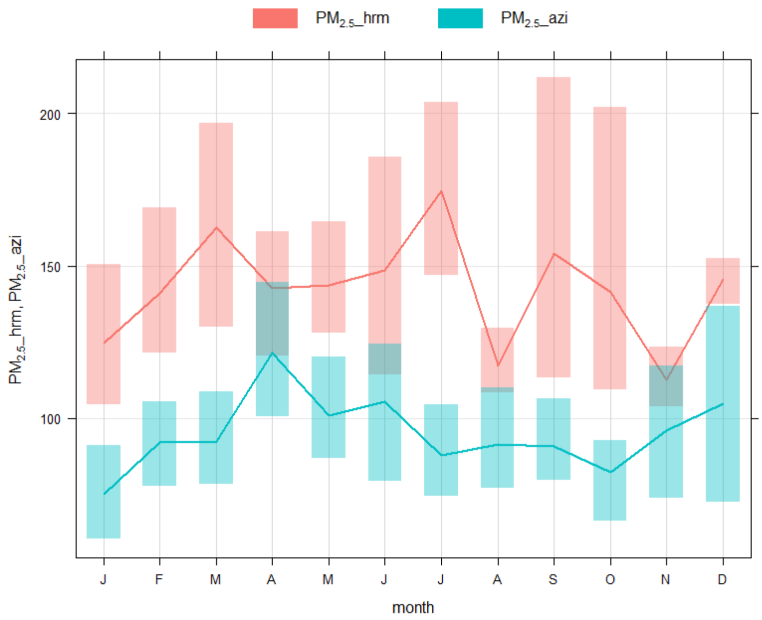


Figure 5. **The weekly (top) and annual (bottom) cycles of $PM_{2.5}$ concentrations (µg/m^3) at Al-Haram (hrm) and Al-Azizia (azi) sites.**

PMF base model was set at 4 source factors. Results for the PMF model are presented in Figure 6, which shows the emission sources contribution (%) to $PM_{2.5}$ and to its various species in Makkah. Different sources of $PM_{2.5}$ emit characteristic chemical species in the overall $PM_{2.5}$ aerosol. Thus, the chemical species measured in $PM_{2.5}$ aerosol can be used as markers for specific sources. The identification of these sources was entirely based on the relative abundances of different aerosol chemical species within each factor. The four main sources of $PM_{2.5}$ in Makkah (Figure 6) were: (1) Soil particles - mainly generated by large scale digging of mountains, construction - demolition and wind. Soil particles contribute about 12 % of $PM_{2.5}$ and the main species were Cd, Cr and MO; (2) Fossil-fuel combustion - generated by burning of petrol, diesel and coal in vehicles, factories and restaurants. Primary pollutants such as SO_2 and NOx are emitted by combustion processes which are then converted to secondary aerosols like SO_4^{2-} and NO_3^- particles in the atmosphere. This source is mainly dominated by secondary aerosols like SO_4^{2-} and NO_3^- and NO_4^+ and contributes 60 % of $PM_{2.5}$ in Makkah. Halogen ions such as Cl^- and F^- are emitted directly from coal fired combustion processes; (3) Industrial emissions - mainly non-gaseous industrial dusts which is generated by various industrial processes. These sources contribute about 27 % of $PM_{2.5}$. The dominant species are As, K, Se and Si; and (4) Miscellaneous - water-spray in the Holy Mosque and resuspension of roadside dust. Miscellaneous contribute about 2 % of $PM_{2.5}$ in Makkah and are dominated by Mn, Zn, Al, and Cu. It is reported previously that in Makkah PM predominantly comes from soil crust related particles and resuspended soil. This could be true in case of TSP and PM_{10} that come from construction - demolition, windblown dust etc. and are mainly in course particles range, whereas $PM_{2.5}$ (fine particles) mostly come from secondary aerosols or are mostly emitted by traffic and other combustion processes.

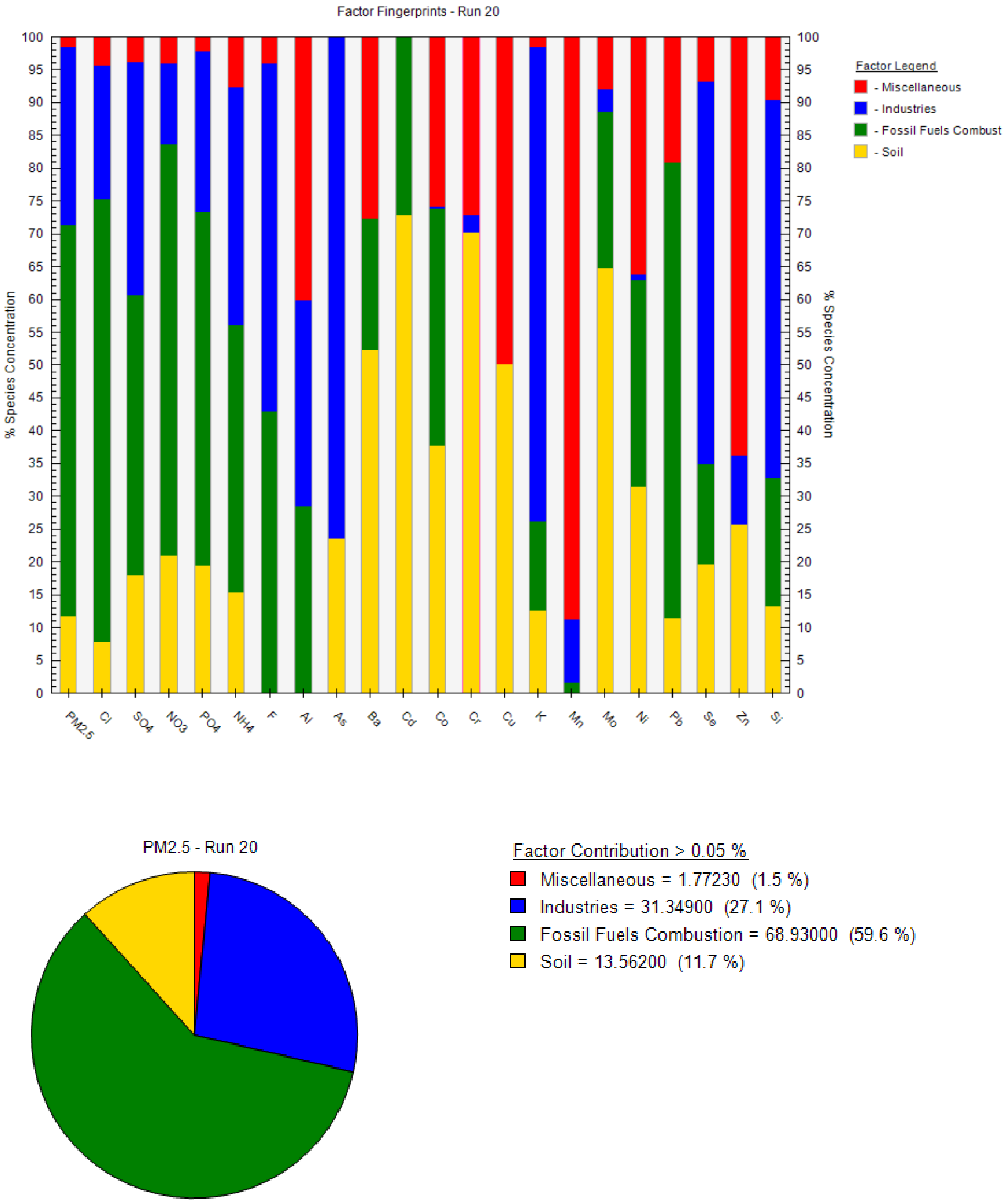


Figure 6. **Sources finger prints profile for various aerosol species (upper-panel) and sources contribution (%) to the emission of $PM_{2.5}$ in Makkah (lower-panel).**

Previously no source apportionment study is carried out in Makkah to quantify the sources of $PM_{2.5}$, which is one of the main barriers for preparing an effective air quality plan. However, a couple of studies are carried out in the surrounding areas, mainly Jeddah (Khodeir et al., 2012) and Rabigh region (Nayebare et al., 2015). Khodeir et al. (2012) analysed both $PM_{2.5}$ and PM_{10} data for four months (June to September, 2011) collected in Jeddah. They reported that during the study period average $PM_{2.5}$ concentration was about 28

µg/m^3, whereas the concentration of PM_{10} was 87 µg/m^3. Both species demonstrated considerable spatial and temporal variability. Khodeir et al. (2012) recognized five main sources of particulate matter in Jeddah: (1) Combustion of heavy oils; (2) Resuspension of dust particles; (3) Industrial sources; (4) Traffic sources; and (5) Marine aerosols. These emission sources are in agreement the sources identified in this paper, except marine sources which was considered a source for PM_{10} by Khodeir et al (2012). Firstly, in this current paper PM_{10} is not considered and only the sources of $PM_{2.5}$ are analysed, and second because Jeddah is situated by the Red Sea and is more affected by sea spray. In contrast, Makkah is about 70 km far from the Red Sea and is unlikely to be significantly affected by sea spray. Instead, in this paper the water spray program in the Holy Mosque is considered a potential source, which runs continuously to lower temperature and create a pleasant environment around the Holy Mosque.

Recently Nayebare et al., (2015) carried out a source apportionment investigation of $PM_{2.5}$ in Rabigh, Saudi Arabia. They used PMF model and Enrichment Factor (EF) analysis to analyse the chemical composition of $PM_{2.5}$ and delineate its main emission sources. The main weaknesses of the study are: (a) they did not use standard methods for $PM_{2.5}$ samples collections like High Volume Samplers (HVS) and rather used low volume air sampling pump; (b) the data were collected for a very limited time (May 6th–June 17th, 2013). Ideally the data should be collected for at least a year to account for seasonal variations. Nayebare et al., (2015) identified five main $PM_{2.5}$ emission sources: (i) Soil/earth crust; (ii) Industrial dust; (iii) Fossil-fuel combustion; (iv) Vehicular emissions; and (v) Sea sprays. They attributed 60 % of emission to two main sources (fossil-fuel combustion and soil). One thing common in these two previous studies (Nayebare et al., 2015; Khodeir et al., 2012) and the current study is that secondary aerosols, emission from fossil-fuel combustion and soil originated particles add a large proportion of atmospheric $PM_{2.5}$ in Saudi Arabia. The contribution of soil particles might be even greater in course particles. However, the levels and compositions of $PM_{2.5}$ demonstrate significant variability in both space and time, which is expected due to differences in local emission and geographical and climatic conditions.

4. CONCLUSION

This study which is based on laboratory analysis of $PM_{2.5}$ samples, collected at two sites in Makkah during 2013 and 2014 and PMF model is the first study of its kind in Makkah. $PM_{2.5}$ and its composition demonstrated significant temporal and spatial variability in Makkah and its levels at both monitoring sites are several folds higher than WHO air quality standards. The four main sources identified by PMF model were: Fossil fuels combustion (60%); Industrial dusts (27%); Soil particles (12%); and Miscellaneous sources (2%). The findings show that fine particles are mainly emitted by combustion sources and a large proportion of the $PM_{2.5}$ are made of secondary aerosols, such as NO_3^- and SO_4^{2-}.

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جرد مصادر وإنبعاثات الأتربة المستنشقة الدقيقة في مكة المكرمة، المملكة العربية السعودية: بإستخدام نموذج مصفوفة فاكتوريساتيون الموجبة

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الملخص العربي:

تطرق الباحث في هذا البحث إلى معرفة وجرد مصادر الأتربة المستنشقة الدقيقة ($PM_{2.5}$) في مدينة مكة المكرمة بإستخدام نموذج مصفوفة فاكتوريساتيون الموجبة (PMF). وتم إستخدام جهاز تجميع بيانات الأتربة (HVS) لتجميع الأتربة كل ٢٤ ساعة من الساعة العاشرة صباحاً وحتى العاشرة مساءً في موقعين متفرقين خلال الفترة من شهر سبتمير ٢٠١٣م إلى شهر أغسطس ٢٠١٤م في مدينة مكة المكرمة. كما تم إستخدام جهاز تقنية الأيون الكروموتغرافي موديل (850) لفحص عناصر الأنيونات والكتيونات مثل؛ السولفيت، الفوسفات، النيترات، أمونيوم، الكلورايد، الفلورايد. كذلك تم إستخدام جهاز تقنية الأيون الكروموتغرافي موديل (700) لفحص العناصر الكيميائية (K, Al, Ba, Co, Cr, Cu, As, Mn, Cd, Ni, Pb, Se, Mo, Si, Zn). وهناك أربع مصادر للأتربة المستنشقة الدقيقة تم تحديدها وهي (1) الإحتراق الغير كامل للوقود في السيارات، وأيضا إحتراق الوقود المنبعث من المصانع والمنازل والمطاعم، وهذا الإحتراق في الوقود أدى إلى إنبعاث بعض الملوثات في الهواء مثل؛ الرصاص والنيكل والكادميموم والكلورايد والفلورايد. وأيضاً تكون بعض الملوثات الثانوية نتيجة التفاعلات الكيموضوئية في الغلاف الجوية مثل؛ ثاني أكسيد الكبريت وأكاسيد النتروجين وتحويلها إلى مركبات السولفيت والنيترات. تمثل هذه العناصر والمركبات الكيمائية بواقع 60 % من نسبة الأتربة المستنشقة الدقيقة. (2) إنبعاثات المصانع والتي تنتجت من عدة عمليات صناعية، مصادرها مختلفه مثل؛ الزرنيخ والكالسيوم والسيلنيوم، وتمثل حوالي 27 % من نسبة الأتربة المستنشقة الدقيقة في مدينة مكة المكرمة. (3) الجسيمات المنبعثة من الغبار بواسطة إنتقالها من أماكن قريبة أو بعيدة ، وتمثل حوالي 12 % من نسبة الأتربة المستنشقة الدقيقة، ومصادرها مختلفه مثل؛ الكادميوم والكلورين. (4) وهناك مصادر مختلفة من الأتربة المتولدة من الطرق والمشاة وغيرها مثل؛ المانجنيز والزنك وتمثل حوالي 2 % من نسبة الأتربة المستنشقة الدقيقة في مدينة مكة المكرمة. وتعد هذه النتائج المتمثلة في هذه الدراسة متوافقة مع كثير من الدراسات في المملكة العربية السعودية.

الكلمات الدالة: *نمذجة المستقبلات، الجسيمات العالقة، مصادر الأتربة المستنشقة الدقيقة، مكة، جودة الهواء.*