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Elemental Composition of $PM_{2.5}$ Aerosol in a Residential–Industrial Area of a Mediterranean Megacity

Abdallah A. Shaltout[1,2] · Johan Boman[3] · Salwa K. Hassan[4] · Asmaa M. Abozied[1] · Emad A. Al-Ashkar[1] · Omar H. Abd-Elkader[5,6] · M. A. Yassin[7] · J. H. Al-Tamimi[8]

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Abstract

Very little is known about the elemental composition and possible sources of fine aerosol particles from Mediterranean megacities. Fine aerosol particles were collected at a residential-industrial area in Greater Cairo, Egypt, during the period from October 2010 to May 2011. The elemental compositions of the collected samples were quantified by using a home-made energy dispersive x-ray fluorescence spectrometer, whereas black carbon was quantified by a black smoke detector. Fifteen elements have been quantified. Of these constituents, Ca, C, Cl, S, and Fe had the highest concentrations: greater than 1 μg m^{-3}. The overall mean mass concentration of the collected samples equals 70 μg m^{-3}; this value exceeds the European Union annual Air Quality Standard levels. The individual elemental concentrations of the fine particles were found to be dominated by elements linked to mineral dust. Most of the monthly variations of elemental concentrations can be attributed to seasonal meteorological conditions. Other possible sources were vehicle-exhaust and industrial activities. The results pinpoint the problem of identifying different sources when one source, in this case, the nearby deserts, is dominant. The results from this study contribute to the growing knowledge of concentrations, composition, and possible sources of ambient fine particulate matter.

✉ Abdallah A. Shaltout
shaltout_a@hotmail.com

1 Spectroscopy Department, Physics Division, National Research Centre, El-Behooth St., Dokki, Cairo 12622, Egypt

2 Physics Department, Faculty of Science, Taif University, P.O. Box 888, Taif 21974, Kingdom of Saudi Arabia

3 Department of Chemistry and Molecular Biology, Atmospheric Science, University of Gothenburg, 412 96 Gothenburg, Sweden

4 Air Pollution Research Department, National Research Centre, El-Behooth St., Dokki, Cairo 12622, Egypt

5 Physics & Astronomy Department, Science College, King Saud University, P.O. Box 2455, Riyadh 11451, Kingdom of Saudi Arabia

6 Physics Division, Electron Microscope & Thin Films Department, National Research Centre, El Behooth St., Giza 12622, Egypt

7 Botany & Microbiology Department, Science College, King Saud University, P.O. Box 2455, Riyadh 11451, Kingdom of Saudi Arabia

8 Zoology Department, Science College, King Saud University, P.O. Box 2455, Riyadh 11451, Kingdom of Saudi Arabia

The particulate matter is among the criteria pollutants because of their negative effects on visibility, natural ecosystems, cultural heritages, acidification of precipitation, earth's radiation balance, global warming, climate change, and human health (Stanek et al. 2011; Jahn et al. 2011; Yuan et al. 2006; Kaufman and Koren 2006). The particulate matter with aerodynamic diameters ≤2.5 μm ($PM_{2.5}$) are usually formed by the processes of combustion, such as the emissions from vehicles, fossil fuel burning during power generation, and other industrial activities but can also be formed by gas-to-particle conversions (Horvath 1998; Vallero 2014). $PM_{2.5}$ aerosols can remain in the atmospheric for a long time, which facilitates their transportation to thousands of kilometers in the atmosphere. Furthermore, they can penetrate the lungs and reach the deepest part. Therefore, the impact of the particulate matter is due to not only the mass concentrations but also to its chemical contents (Almeida et al. 2006). Elements are one of the most important chemical compositions of particulate matter. Naturally derived trace elements are usually found in coarse particles (Horvath 1998; Vallero 2014), while trace elements of anthropogenic origin are mainly found in fine particles like $PM_{2.5}$ (Fang et al. 2006). At low concentrations, some trace elements

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in the particulate matter are harmless and others are toxic and initiators in many diseases (Shaltout et al. 2013a, 2014; Seaton et al. 2010). A remarkable correlation between the mass concentration of the $PM_{2.5}$ aerosols and the different types of adverse health outcomes, such as cardiovascular mortality, hypertension, respiratory mortality, influenza, and lung cancer, was reported (Miller and Xu 2018). Therefore, their chemical compositions provide important information about the origins of the $PM_{2.5}$ aerosols and whether they were emitted as secondary or primary particles (Engelbrecht et al. 2009).

Greater Cairo (GC) is the largest city in the continent of Africa; its population approaches 22 million and is located in the subtropical climatic region. Cairo's climate is cold and moist in winter, whereas during summer, the temperature, solar radiation, and wind speed are remarkably high. The air quality degradation is elevated by the city's poor dispersion of air pollutants due to its location in the Nile valley and the low rate of rainfall during the whole year (Elminir et al. 2006). The atmospheric environment in the city has experienced critical contamination due to many factors: namely, the dramatic growth of population, the continuous industrial development, the extrapolation of construction projects, and the simultaneous increase in traffic flow. Due to the different sources of air pollution in the city, a dark cloud was recognized for most of the year.

The concentration and composition of airborne particulate matters, their polycyclic aromatic hydrocarbon content and volatile organic compounds have been investigated in urban areas in GC (Abu-Allaban et al. 2007; Favez et al. 2008; Safar and Labib 2010; Hassan and Khoder 2017; Shaltout et al. 2018a). Besides, $PM_{2.5}$ aerosols were collected from different industrial and residential areas in GC and analyzed using energy dispersive x-ray fluorescence (EDXRF) spectrometer and high-resolution continuum source atomic absorption spectrometry (HR-CS-AAS). The hazardous trace elements were found below the annual standards of air quality defined by the European Commission (Boman et al. 2013; Shaltout et al. 2014, 2018b), although high elemental concentrations were detected at industrial locations (Shaltout et al. 2018b).

There is still a remarkable lack of information on the levels of $PM_{2.5}$ as well as its elemental composition collected from a complicated residential-industrial area that has high population density, such as the Shubra El-Kheima district. Therefore, the purpose of the present study was to determine the level of $PM_{2.5}$ and its elemental composition collected from the Shubra El-Kheima area during three different seasons: autumn, winter, and spring. This study also was designed to estimate the contribution of anthropogenic sources to the concentration levels of these elements. Furthermore, a systematic explanation of the source apportionment of the inorganic content of the present $PM_{2.5}$ aerosols using enrichment factor and principal component analysis was presented.

Materials and Methods

Study Area

The sources of air pollution in GC are thought to be natural sources, trash burning, vehicle emissions, and large-scale urban industrial operation (Abu-Allaban et al. 2002; Abu-Allaban et al. 2007). The present study area is a complicated residential and industrial location at the same time, and it is called Shubra El-Kheima at the northern boundary of Cairo, north of downtown. The study area is characterized by different industrial activities in terms of textile, cotton ginning, chemical, ceramics, glasses, and plastics (Zakey et al. 2008). In addition, it is characterized by high population density, with more than one million inhabitants. An additional industrial area called Mostorod district is located northeast of Shubra El-Kheima. The area also accommodates two big thermal power plants. The study area is very close to the main Cairo-Alexandria highway, which is characterized by heavy traffic during the whole day with private and commercial cars, trucks, buses, and minibuses.

Sample Collection

Figure 1 shows the sampling site's location. At an elevated site of 20 m from the floor, the particulate matters were collected in the period from October 2010 to May 2011, one sample per week, covering three different seasons (autumn, winter, and spring) using a homemade sampling device. Unfortunately, the sampling during the fourth season (summer) was canceled due to some critical circumstances at the sampling location. In total 32 $PM_{2.5}$, samples were collected. Most of them were collected on Mondays from 11:00 AM to 11:00 AM on the second day. Each $PM_{2.5}$ sample was collected for 24 h. Atmospheric $PM_{2.5}$ aerosols were collected on polycarbonate filters of a diameter 25 mm and pore size of 0.4 μm (Whatman, Maidstone, UK) loaded inside a Dewell–Higgins type cyclone (Casella CEL, Bedford, UK). A sampling pump connected with a critical orifice that restricts the air flow to 3 L min^{-1} was used. The present flow rate was selected to take advantage of a diameter threshold of 2.5 μm on the collected aerosols and to ensure the $PM_{2.5}$ sampling.

Gravimetric and Elemental Analysis Methods

Before and after $PM_{2.5}$ sampling, the polycarbonate filters were weighed to determine the mass concentration of the collected particulate matter using a microbalance (Sartorius

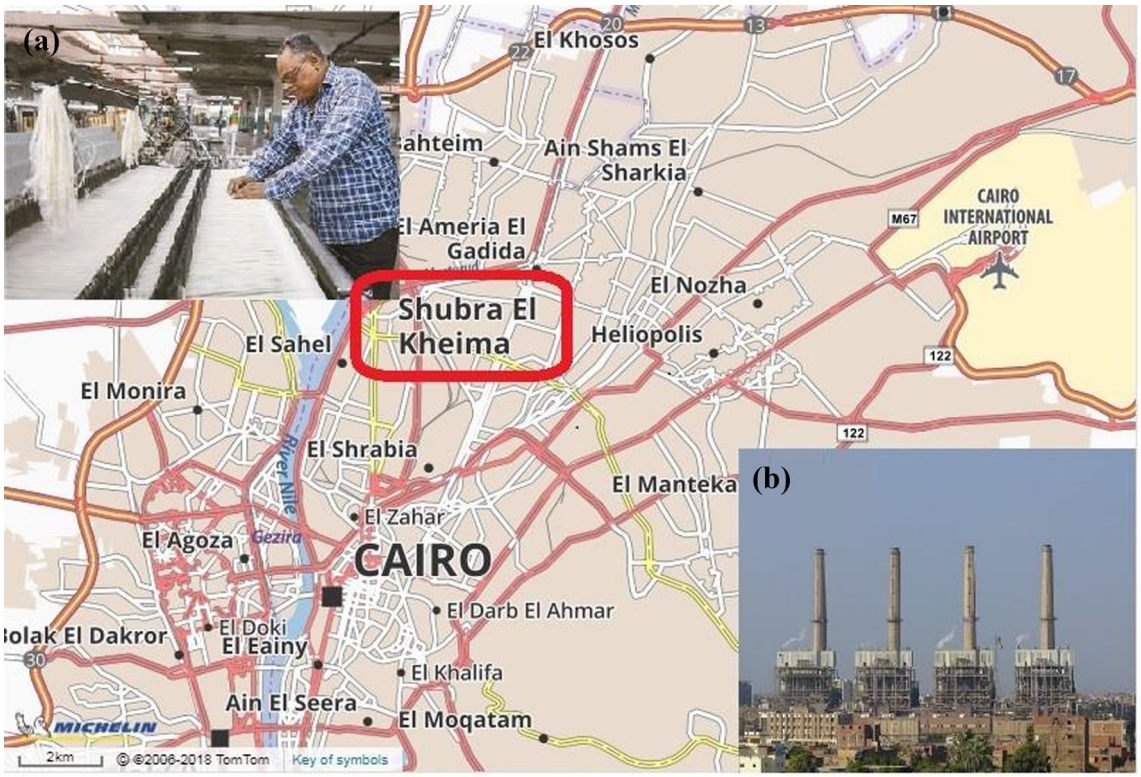

Fig. 1 The residential-industrial sampling location (Shubra El-Kheima) in Cairo, Egypt, including some anthropogenic activities: **a** textile industries; **b** electricity power plant

CC50, Switzerland). The polycarbonate filters were kept in a desiccator to stabilize the mass concentrations of $PM_{2.5}$ aerosols. The carbon concentration in the $PM_{2.5}$ samples was quantified by a black smoke detector (FH621-N, ESM Emberline, Erlangen, Germany). More details can be found elsewhere (Boman et al. 2013; Shaltout et al. 2013b). The present $PM_{2.5}$ aerosols were quantitatively analyzed for the elements: S, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Sr, Br, Rb, and Pb using a lab-built EDXRF spectrometer (University of Gothenburg, Gothenburg, Sweden). The present EDXRF spectrometer has a three-axial arrangement built around a silver, fine-focus, x-ray tube. A secondary target of Mo was used to make the x-ray beam nearly monochromatic before it reaches the $PM_{2.5}$ filter (Boman 1990; Chimidza 2001). The quasi-monochromatic excitation of a Mo secondary target enhances the sensitivity and selectivity than can be achieved with the 45°–45° EDXRF setup. Figure 2 shows the x-ray fluorescence spectra and the related fitting function for one of the particulate matters collected during March 2011. The coherent and incoherent scattering of the Mo secondary target was located above 16 keV, and it was not included in the fitting function. The EDXRF spectra were further processed by the PyMca software algorithm (Solé et al. 2007). For quantification, the relationship between elemental sensitivity and the atomic number of 29 single element standard filters (MicroMatter Co., Vancouver, Canada) was used. The elemental sensitivity equals (net peak counts × absorption factor)/(live time × tube current × concentration). The validation of the calibration was performed using SRM2783 air particulate on filter media (National Institute of Standards and Technology, USA). A good agreement between the measured and the certified values was obtained. The limits of detection for the EDXRF analyses were estimated depending on the procedure given by the International Union of Pure and Applied Chemistry (IUPAC 1976). These data were mentioned in our previous studies (Boman et al. 2013; Shaltout et al. 2013b, 2015). Quantitative analysis results of fifteen elements, including black carbon, were determined and converted into ng m^{-3}.

Results

$PM_{2.5}$ Concentrations

The monthly average mass concentrations of $PM_{2.5}$ at Shubra El-Kheima (Fig. 3) vary substantially from month to month, ranging from 17 μg m^{-3} in October 2010 to 110 μg m^{-3} in March 2011 with an overall average of 70 μg m^{-3}. The overall average is lower than concentrations reported by Cheng

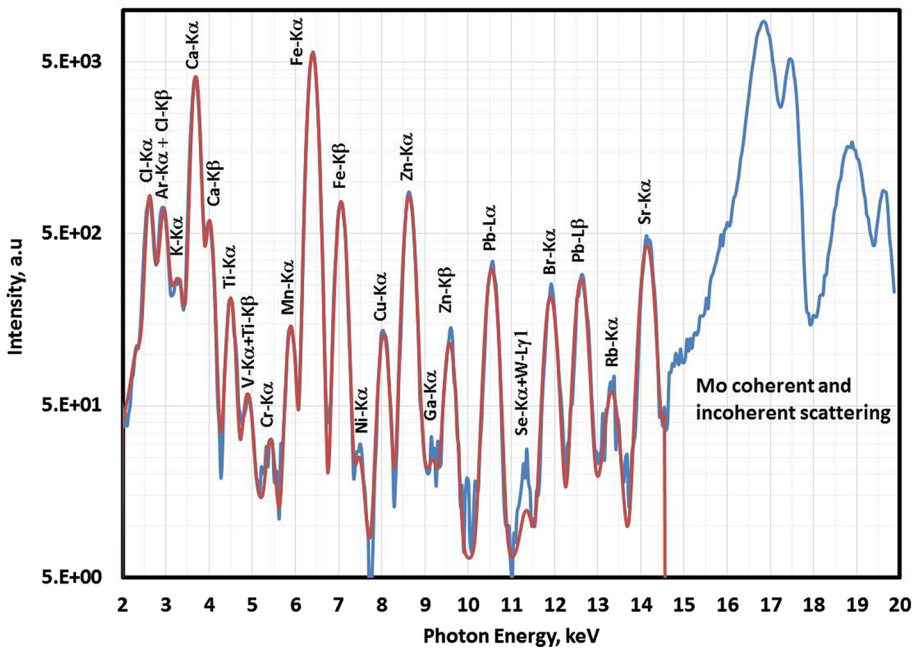

Fig. 2 EDXRF spectra and the fitting function for the characteristic lines of the identified trace elements in $PM_{2.5}$ collected at Shubra El-Kheima, Cairo, during the period of study

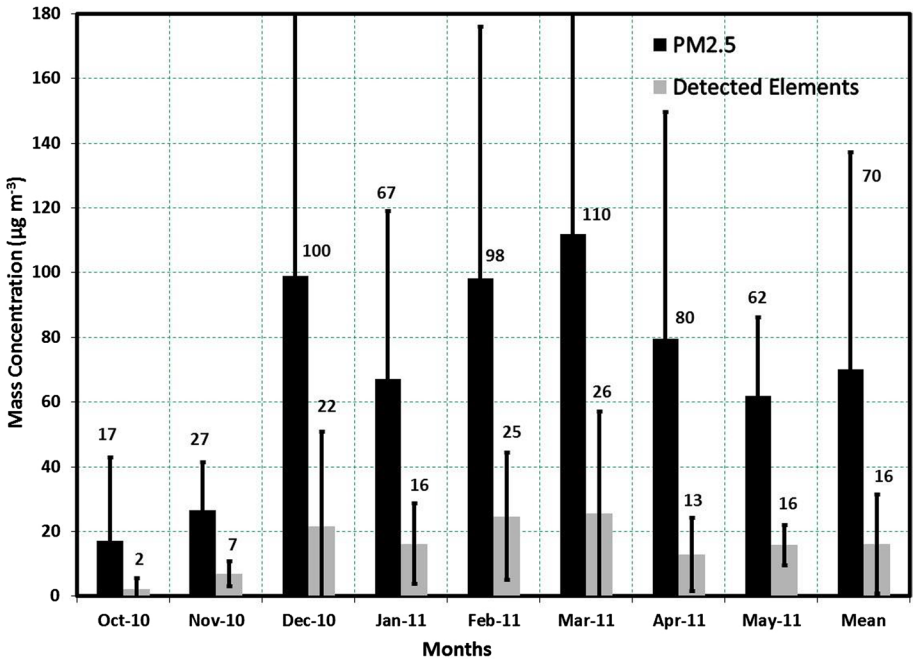

Fig. 3 Monthly averages of the total mass concentrations and total elemental concentrations in $PM_{2.5}$ during the period of study

et al. (2016b) where Cairo was said to be the second most polluted megacity in the world with an annual $PM_{2.5}$ concentration of 109.6 ± 27.7 μg m^{-3}. Krzyzanowski et al. (2014) reported an annual average of $PM_{2.5}$ concentration in Cairo of 80 μg m^{-3}, showing the high variability of the reported concentrations and thus the need for continued high quality monitoring of $PM_{2.5}$ in Cairo. The differences can also be due to different measurement years since the mean annual exposure to $PM_{2.5}$ in Egypt has increased from 90 μg m^{-3} in 2010 to 126 μg m^{-3} in 2016 (World Bank 2018). High $PM_{2.5}$ concentrations also were recorded in the winter months (December 2010 (99 μg m^{-3}) and February 2011 (98 μg m^{-3})). Emissions from industrial sources in the study area are anticipated to be the same for the whole year.

Elemental Concentration in $PM_{2.5}$

Table 1 illustrates the great variability of the monthly concentration averages of fourteen elements (S, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Br, Rb, Sr, and Pb) and black carbon

Table 1 Monthly average and total elemental concentrations of $PM_{2.5}$ (ng m^{-3}). Four samples were collected per month at the Shubra El-Kheima, residential-industrial site in GC, Egypt

El	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Average
S	440 ± 0	420 ± 230	1860 ± 1600	1470 ± 690	1850 ± 1360	1230 ± 890	810 ± 0	1650 ± 0	1220 ± 590
Cl	770 ± 30	1100 ± 250	2520 ± 3200	4010 ± 2750	3930 ± 1570	8770 ± 9880	1800 ± 2860	1620 ± 0	3070 ± 2600
K	160 ± 90	430 ± 35	1060 ± 1500	710 ± 310	1210 ± 900	570 ± 460	470 ± 400	870 ± 0	690 ± 350
Ca	500 ± 40	2500 ± 944	8500 ± 13720	4830 ± 4760	9640 ± 9880	7840 ± 13560	6400 ± 5730	7620 ± 0	5980 ± 3150
Ti	20 ± 1	100 ± 45	300 ± 450	190 ± 180	390 ± 440	160 ± 240	150 ± 120	220 ± 0	190 ± 120
Mn	10 ± 1	20 ± 4	60 ± 100	30 ± 30	60 ± 60	50 ± 70	30 ± 30	40 ± 0	40 ± 20
Fe	210 ± 15	900 ± 200	3100 ± 5300	1480 ± 1400	2880 ± 3000	2020 ± 3300	1600 ± 1100	1860 ± 0	1750 ± 950
Ni	10 ± 0	6 ± 2	11 ± 10	10 ± 3	10 ± 1	10 ± 3	10 ± 7	< DL	10 ± 2
Cu	15 ± 2	10 ± 4	40 ± 60	30 ± 14	40 ± 30	40 ± 40	20 ± 12	10 ± 0	25 ± 15
Zn	35 ± 3	200 ± 15	570 ± 1000	370 ± 170	320 ± 85	320 ± 230	100 ± 50	70 ± 0	240 ± 180
Br	10 ± 1	10 ± 4	20 ± 20	30 ± 12	30 ± 6	50 ± 30	30 ± 2	40 ± 0	30 ± 15
Rb	< DL	2 ± 1	10 ± 8	10 ± 1	4 ± 2	4 ± 0	4 ± 1	< DL	4 ± 1
Sr	2 ± 0	20 ± 0	40 ± 60	25 ± 20	50 ± 45	40 ± 70	30 ± 30	30 ± 0	30 ± 10
Pb	< DL	20 ± 0	80 ± 100	65 ± 40	80 ± 50	100 ± 70	60 ± 50	110 ± 0	70 ± 35
BC	< DL	1130 ± 595	3410 ± 4400	2940 ± 1860	4230 ± 1020	4520 ± 3230	1380 ± 280	1730 ± 0	2760 ± 1400
∑ El	2200	7000	22000	16000	25000	26000	13000	16000	16100
$PM_{2.5}$	17100	26600	99100	67200	98300	111800	79700	61800	70200
$\sum El / PM_{2.5}$	13%	26%	22%	24%	25%	23%	16%	26%	23%

Average and standard deviation of the whole study period are listed in the last column. Monthly average mass concentrations of black carbon (BC), sum of elemental concentrations (∑ El), and $PM_{2.5}$ in ng m^{-3} also are included. The last row shows the mass contribution of total measured element concentrations related to the $PM_{2.5}$ mass, in percentage

< DL below detection limit

(BC) in the $PM_{2.5}$ samples. Among these elements, Ca has a maximum concentration of 9640 ng m^{-3} in February 2011. The overall averages of the elemental concentrations show the following pattern: Ca > Cl > C > Fe > S > K > Zn > Ti > Pb > Mn > Sr > Br > Cu > Ni > Rb. The highest average concentrations of S, K, Ca, Ti, Mn, Fe, Zn, Rb, and Sr were recorded during December 2010 and February 2011, whereas the lowest average concentrations of these elements were found in October and November 2010. The monthly differences of elemental concentrations probably occur under the effect of seasonal meteorological variations since the variation is similar to the differences in $PM_{2.5}$ mass concentrations. These results are in agreement with results from other parts of GC (Khoder 1997; Hassan 2006; Boman et al. 2013; Hassan et al. 2013). Compared with the study in central Cairo (Boman et al. 2013), Ca and Fe are the only elements with significantly higher average concentrations in Shubra El-Kheima, indicating possible local anthropogenic contribution.

A monthly difference in the sum of elemental concentrations, including BC in $PM_{2.5}$ similar to the differences in $PM_{2.5}$ mass concentrations, can be seen with average concentrations ranging from 2200 ng m^{-3} in October 2010 to 26,000 ng m^{-3} in March 2011 and a mean value of 16,100 ng m^{-3}. The overall average of the ratio between total elemental concentrations and $PM_{2.5}$ mass concentration was 23%, with monthly ratios varying between 13% in October 2010 and 26% in November 2010 and May 2011. The same ratio determined at the residential area Dokki by Boman et al. (2013) was 16%. The difference between the studies can be explained by the higher concentration of Ca at Shubra El-Kheima in the present study. On the analyzed elements, only Pb is regulated in the Egyptian air quality standards (EEAA 2011). The limit is 1000 ng m^{-3} as a yearly average, which is almost ten times higher than the highest monthly average concentration in this study, 110 ng m^{-3} in May 2011. In addition, the Pb annual mean air quality level from the European Commission (500 ng m^{-3}) is five times higher than the highest detected Pb in the present samples (European Commission 2017). Therefore, exposure to airborne Pb is thus not at alarming levels.

Discussion

$PM_{2.5}$ Mass Concentration

The higher concentration of $PM_{2.5}$ during winter months may be attributed to a higher frequency of inversions and low wind speed, which leads to reducing the dispersion of particulate matter in the air. It was found that average wind speed during winter ranges from 5.8 km/h to 7.2 km/h,

which is the lowest value during the period of study. Also, the average temperatures during the winter season vary from 10 to 16 °C, and it is also the lowest temperature during the whole year. These results agree with other studies in Cairo (Khoder 1997; Safar and Labib 2010). In the spring months, the high $PM_{2.5}$ concentrations may be an effect of the hot Khamsin southerly wind, which occurs in Egypt predominantly during spring and when the air is loaded with dust and sand (Zakey et al. 2008; Boman et al. 2013). The average monthly $PM_{2.5}$ concentrations during December 2010, February 2011, and March 2011 (Fig. 3) exceed the Egyptian air quality limit for $PM_{2.5}$ (80 μg m^{-3} for 24 h) (EEAA 2011; Cheng et al. 2016a). However, the average monthly $PM_{2.5}$ concentrations of all months (except October 2010) exceed the annual air quality standard of the world health organization (WHO 2006) and the European Commission (European Commission 2017). Comparing the $PM_{2.5}$ mass concentration collected previously from the same location (Safar and Labib 2010; Abu-Allaban et al. 2007; Zakey et al. 2008), a remarkable decrease of the $PM_{2.5}$ mass concentration can be recognized in the last few years. However, the present overall $PM_{2.5}$ mass concentration is still higher than other industrial locations in Cairo (Shaltout et al. 2018b). Therefore, the $PM_{2.5}$ mass concentration in Shubra El-Kheima indicates that serious health problems can occur.

Also, Fig. 3 illustrates the variation of mass concentration of the total detected elements with months, which varies from 12.7 to 25.7% with an overall average of 23 ± 15%. The rest of the $PM_{2.5}$ mass concentrations represent ~ 77%, and it most probably consists of sulfates, nitrates, and organic compounds, such as the volatile organic compounds (VOCs) and the polycyclic aromatic hydrocarbons (PAHs).

Based on WHO's interim targets for daily ambient $PM_{2.5}$ concentrations (WHO 2006), the $PM_{2.5}$ samples were categorized into five different particle mass ranges: ≤ 25 μg m^{-3}, 25–37.5 μg m^{-3}, 37.5–50 μg m^{-3}, 50–75 μg m^{-3}, and > 75 μg m^{-3} (Fig. 4). A 41% of the $PM_{2.5}$ mass concentrations (Fig. 4) were lower than the air quality guidelines (AQG) levels for 24 h for $PM_{2.5}$ (WHO 2006), whereas 59% of the $PM_{2.5}$ mass concentrations were higher with 28% of the $PM_{2.5}$ mass concentrations above WHO's interim level I: 75 μg m^{-3}. At this level, the short-term mortality is increased by 5% compared with concentrations below the WHO AQG (WHO 2006).

The average concentrations of $PM_{2.5}$ (Table 2) do not deviate from the concentrations found in most studies in Cairo, Egypt, except the 2001 study of Abu-Allaban (Abu-Allaban et al. 2002), where the mass concentrations of $PM_{2.5}$ is approximately 50% higher compared with the current study. The previous studies (Boman et al. 2013; Shaltout et al. 2018b) reporting $PM_{2.5}$ concentrations of 51 and 55 μg m^{-3} respectively at residential (Dokki) and industrial (Helwan) areas in Cairo. These concentrations are lower than the present study but still higher than the WHO AQG limit. This tells us that the $PM_{2.5}$ pollution problem is not only linked to the industrial area of Shubra El-Kheima, but it is a problem on a more regional scale, which is confirmed by Index Mundi (2018), based on Brauer et al. (2016) showing that 100% of Egypt's population is exposed to $PM_{2.5}$ levels exceeding WHO AQG levels. Compared with the studies in other cities in Table 2, the $PM_{2.5}$ concentrations in GC are

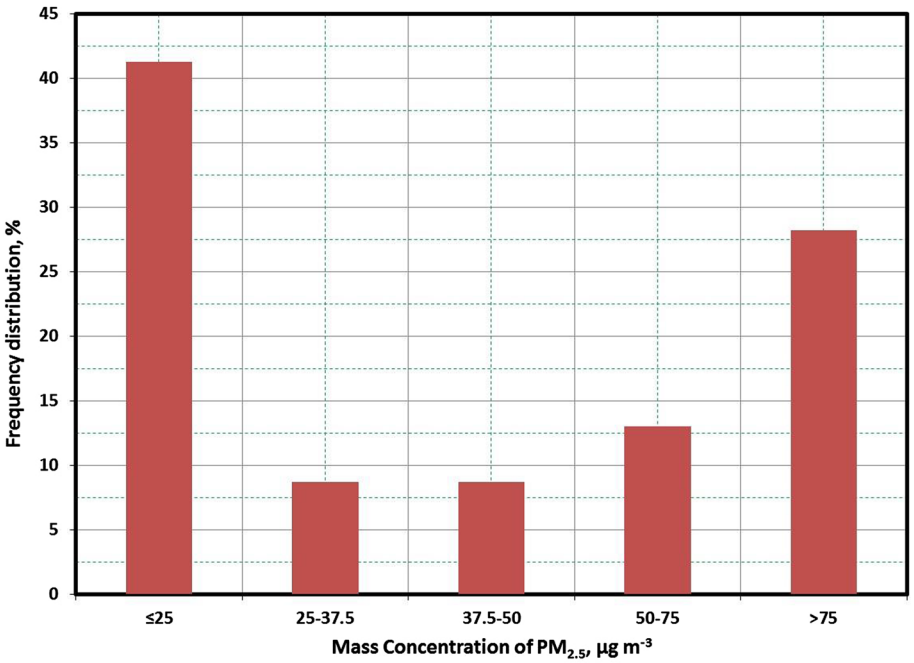

Fig. 4 Percentages of the individual $PM_{2.5}$ concentrations in each particle mass range

Table 2 Mass concentration (μg m^{-3}) of $PM_{2.5}$ at the present location (Shubra El-Kheima) and other different studies in Egypt, Saudi Arabia, Lebanon, and Kenya

Country	City/location	Year	$PM_{2.5}$ mass, μg/m^3	Reference
Egypt	Cairo/Shubra El-Kheima	2010 (Fall)	22 ± 7	Present study
		2011 (Winter)	88 ± 18	
		2011 (Spring)	70 ± 11	
Egypt	Cairo/Shubra El-Kheima	1999	269	Safar and Labib (2010)
		2000	225	
		2001	236	
		2002	198	
		2003	223	
Egypt	Cairo/Shubra El-Kheima	1999 (Winter)	216 ± 11	Abu-Allaban et al. (2007)
		1999 (Fall)	174 ± 9	
		1999 (Summer)	61 ± 3	
Egypt	Cairo/Shubra El-Kheima	2001–2002	103 ± 60	Zakey et al. (2008)
Egypt	Cairo/Dokki	2010 (Fall)	39 ± 4	Boman et al. (2013)
		2011 (Winter)	65 ± 27	
		2011 (Spring)	49 ± 25	
Egypt	Cairo/Helwan	2014 (Fall)	48 ± 22	Shaltout et al. (2018b)
		2015 (Winter)	62 ± 16	
Saudi Arabia	Taif/Industrial area	2011 (Summer)	47 ± 15	Shaltout et al. (2013b)
Lebanon	Beirut	2006–2007	27.6	Saliba et al. (2010)
		2004–2005	38.86	
		2003	40.95	
Kenya	Nairobi	2001	30	Gatari et al. (2009)

higher, indicating the severity of the situation in the Shubra El-Kheima area of Cairo, which can be attributed to a mixture of local emission from the industrial processes, meteorological conditions, and particles from natural sources.

Enrichment Factors of Measured Elements

The detected mineral and trace elements in the present $PM_{2.5}$ aerosols could be originated from natural and anthropogenic sources. To differentiate between anthropogenic and natural sources, the enrichment factors (EFs) were calculated. The degree of anthropogenic contribution was determined (Han et al. 2006). For an element X and reference crustal element Y, the enrichment factor for the element X equals:

$$\mathrm{EF}_X = \frac{(X/Y)_{\mathrm{air}}}{(X/Y)_{\mathrm{crust}}} \quad (1)$$

where (X/Y) is the concentration ratio of X and Y elements in the $PM_{2.5}$ aerosols or in the earth crust, respectively. In this work, Fe was selected as the reference crustal element Y as recommended earlier, because iron is stable in the soil and it is originated mainly from natural sources (Barbieri 2016; Ackerman 1980). The upper continental crust chemical composition was supplied from Wedepohl (1995). The estimation of EFs was performed while assuming that the contribution of anthropogenic sources to Fe is insignificant in Shubra El-Kheima compared with the contribution from natural sources. If the EF values are < 10, the element of interest has a significant crustal source. Because the EF values are > 10, the element of interest ascribed to the noncrustal origin as well as the anthropogenic sources (Nayebare et al. 2018). As illustrated in Fig. 5, the values of EF are lower than 10 for K, Ca, Ti, Mn, Rb, Sr, and Ni, indicating crustal sources (e.g., resuspended dust and soil), whereas EF values > 10 were found for C, S, Cl, Cu, Zn, Br, and Pb, suggesting anthropogenic or noncrustal sources (Han et al. 2006; Xu et al. 2012). The high EFs for Zn, Pb, Cl, and Br suggest the influence of traffic emissions, tire wear, incinerator emissions, fossil fuel combustion, and marine sources (Khoder et al. 2012; Alghamdi et al. 2015). The presence of S is usually attributed to the combustion of heavy fuel oil or diesel (Asaoka et al. 2019). The presence of a high EF for Cu also can be related to anthropogenic activities, such as nonferrous metal industries and chromium plating, but also may come from the wear of asbestos-free brake linings.

Source Apportionment Using Principle Component Analysis

Intra-element relationships can supply useful information about the sources of the detected elements and their pathway (Manta et al. 2002). Because the elemental content of the samples only makes up 23% of the sample mass on average,

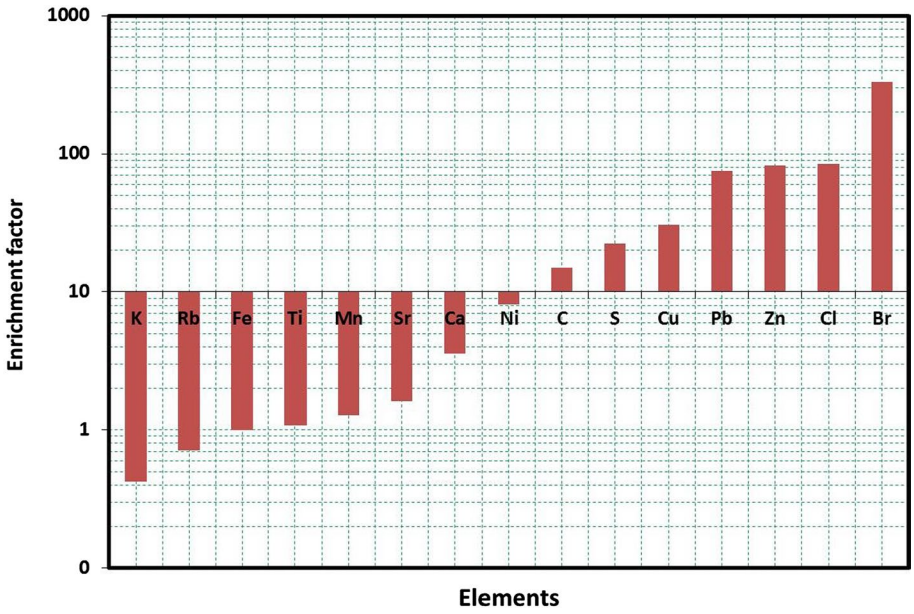

Fig. 5 Enrichment factors of the measured elements in fine aerosol samples collected form Industrial area, Greater Cairo, Egypt

the source apportionment in this study only related to possible sources for the elements and no mass closure calculations are done. As a first step to identify intra-element relationships Pearson's correlation coefficients (Table 3) were calculated for the analyzed elements in the $PM_{2.5}$ samples. As the correlation coefficients approach to 1, it indicates a strong positive correlation (Shaltout et al. 2011). We have defined high positive correlation coefficients as ranging from 0.75 to 0.99 (highlighted in bold), whereas moderately high correlation coefficients are ranging from 0.50 to 0.74 (highlighted in italic). Four extremes can be noted in Table 3. First, $PM_{2.5}$ masses have a high correlation with Ca, Mn, Fe, Ni, Cu, Br, Sr, Pb, and BC and a moderate correlation with the other elements. This could be attributed to a well-mixed aerosol at the sampling location with a similar variation of all elements and $PM_{2.5}$ mass. Second, Cl has a low positive correlation with most of the detected elements except Br and BC. This indicates that Cl is probably originating from a marine source. Third, a high correlation can be found between the mainly crustal elements K, Ca, Ti, Mn, Fe, and Sr, and this could be an indication of a major contribution of mineral dust mixed with resuspended road dust from the nearby roads (Loyola et al. 2006). Fourth, Pb has a strong correlation with S, Ca, Mn, Ni, and Br, and a moderately high correlation with Cl, K, Ti, Fe, Rb, and Sr, which indicates the complex nature of Pb-containing particles. Pb is

Table 3 Pearson's correlation coefficients for the concentration of detected element in $PM_{2.5}$ collected from the Industrial area (Shubra El-Kheima), GC, Egypt

	$PM_{2.5}$	S	Cl	K	Ca	Ti	Mn	Fe	Ni	Cu	Zn	Br	Rb	Sr	Pb	C
$PM_{2.5}$	**1.00**															
S	*0.73*	**1.00**														
Cl	*0.72*	0.34	**1.00**													
K	*0.67*	**0.94**	0.21	**1.00**												
Ca	**0.91**	**0.86**	0.48	**0.86**	**1.00**											
Ti	*0.70*	**0.89**	0.23	**0.99**	**0.87**	**1.00**										
Mn	**0.91**	**0.89**	0.48	**0.89**	**0.96**	**0.90**	**1.00**									
Fe	**0.87**	**0.88**	0.39	**0.92**	**0.95**	**0.92**	**0.99**	**1.00**								
Ni	**0.81**	*0.59*	*0.63*	0.38	*0.67*	0.34	*0.65*	*0.61*	**1.00**							
Cu	**0.82**	*0.59*	*0.74*	*0.56*	*0.64*	*0.61*	**0.77**	*0.73*	*0.53*	**1.00**						
Zn	*0.66*	*0.66*	0.46	*0.64*	*0.54*	*0.63*	*0.71*	*0.74*	*0.55*	**0.83**	**1.00**					
Br	**0.75**	0.44	**0.84**	0.27	*0.65*	0.26	*0.53*	0.43	**0.76**	0.45	0.17	**1.00**				
Rb	*0.64*	**0.77**	0.34	*0.65*	*0.56*	*0.62*	*0.66*	*0.69*	*0.67*	*0.62*	**0.86**	0.26	**1.00**			
Sr	**0.94**	**0.76**	*0.56*	**0.81**	**0.97**	**0.84**	**0.94**	**0.93**	*0.63*	*0.72*	*0.59*	*0.64*	*0.54*	**1.00**		
Pb	**0.77**	**0.81**	*0.57*	*0.66*	**0.85**	*0.60*	**0.77**	*0.71*	**0.78**	0.43	0.34	**0.82**	*0.49*	*0.74*	**1.00**	
BC	**0.85**	*0.71*	**0.84**	*0.65*	*0.73*	*0.67*	**0.81**	**0.75**	*0.58*	**0.94**	**0.75**	*0.64*	*0.61*	**0.78**	*0.63*	**1.00**

used in industrial processes, was extensively used for leaded gasoline before the ban in 2001, and is known to stay in the environment for long periods making source apportionment of Pb containing particles troublesome (Rizk and Khoder 2001).

To possibly obtain a better source apportionment, principal component analysis (PCA) was used. Four components, explaining 96% of the total variance of the analysis, were extracted after Varimax rotation with Kaiser Normalization to enhance the separation of the components (Table 4). The first component represented 76% of the total variation, and it is dominated by the elements found in natural sources with mainly mineral dust elements (Ca, Ti, Mn, Fe, Cu, and Sr). This is underlined by the high loading of $PM_{2.5}$ mass as well. Cu is the only element that previously was shown to have a high EF, indicating a possible anthropogenic contribution to this component. Probably it is particles from wear of brake linings that have been mixed with natural dust particles and that are resuspended by wind and traffic. The second component represents 10% of the variation, and it is a mixture between natural and anthropogenic sources represented by high loadings of K, Zn, and Rb with moderate loadings of Ca, Ti, Mn, Fe, Ni, Sr, and Pb. The mixture is hard to characterize but can be an indication of particles from different combustion processes, both biomass-based and industrially based combustion and is thus assorted Combustion in Table 4. The third component represents 5.7% of the variation, and it represents mainly the combustion of heavy fuel oils probably due to the present industrial location, represented by the high loading of S, although the influence of traffic with diesel-fuelled vehicles cannot be ruled out. The moderate loadings of Pb can be representing the emission from industries and resuspension of dust. Finally, the fourth component explains 4.3% of the variation with high loadings of Cl indicating that the Cl particles are originating from a marine source like sea salt. The high loading of Cl to this component can thus be an indication of the long-distance transport of the $PM_{2.5}$. With the relatively small number of samples and the high PM concentrations in the spring months due to possible Khamsin winds, these high concentrations influence the PCA might hide other possible PCA components. Compared with the study by (Boman et al. 2013) conducted in the center of Cairo, the main difference is the lack of a traffic component at the industrial site in this study.

Table 4 The extracted four components of the PCA after using Varimax rotation with Kaiser normalization as well as their associated sources

	Component			
	1	2	3	4
	Mineral dust	Combustion	Industry/diesel	Industry/sea salt/LDT
S	0.074	0.038	0.106	0.959
Cl	0.269	0.089	0.911	0.066
K	0.571	0.738	0.198	0.195
Ca	0.847	0.421	0.286	−0.010
Ti	0.824	0.492	0.096	0.204
Mn	0.796	0.542	0.250	0.006
Fe	0.790	0.571	0.201	0.027
Ni	0.296	0.793	0.306	−0.213
Cu	0.838	0.093	0.267	0.128
Zn	0.391	0.860	0.239	0.070
Br	0.174	0.249	0.903	0.005
Rb	0.340	0.906	0.124	0.106
Sr	0.844	0.385	0.320	−0.038
Pb	0.433	0.444	0.550	0.260
C	0.305	0.584	0.602	0.284

LDT long distance transport particles

In an attempt to get a better understanding of possible sources, the HYSPLIT model was run for part of the measurement period (Draxler and Rolph 2013). In Fig. 6, back trajectory frequency plots are drawn for the first 2 weeks of December 2010 and the last 2 weeks of February 2011. The colors in the figure represent in percentage the number of trajectories in passing a grid cell divides by the total number of trajectories. These periods had the highest S content, and it is illustrated by the trajectories passing over the Mediterranean Sea. In the same periods, the air mass also is passing over desert areas in northern Africa and on the Arabic peninsula, explaining the high content of mineral dust related elements.

Conclusions

From this study, we can conclude that the residential-industrial area Shubra El-Kheima in the north of Greater Cairo, Egypt, is a polluted location when it comes to $PM_{2.5}$ aerosols. This is especially true for the winter and spring months, which have higher $PM_{2.5}$ mass concentrations. At the same time, this pollution situation is not unique for Shubra El-Kheima, although this study indicates differences in sources for elemental containing particles between this and other areas in Cairo. It also can be concluded that, based on the elemental analysis of the particles, the composition of the particles is relatively homogeneous, making it impossible to extract clear anthropogenic sources from the analyzed material. From the results, we can conclude that in the future longer measurement campaigns and a better characterization of the content of the particles are needed to determine more accurately the anthropogenic contribution to the air pollution in Cairo.

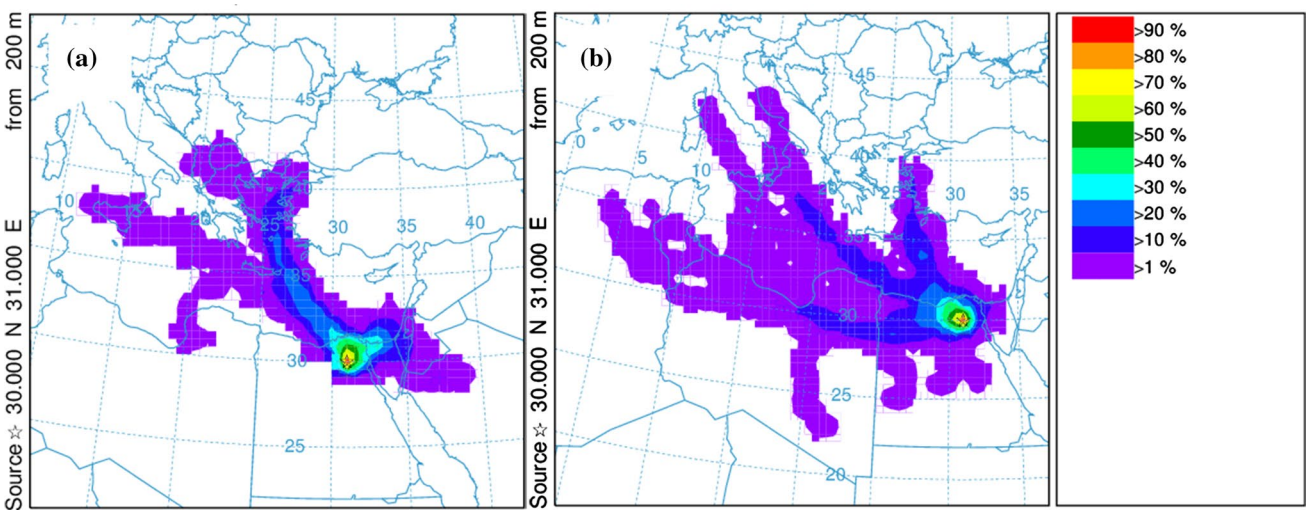

Fig. 6 HYSPLIT frequency plots for the first 2 weeks of December 2010 (**a**) and the last 2 weeks of February 2011 (**b**)

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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