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ORIGINAL PAPER

Tempo-Spatial Variability and Health Risks of $PM_{2.5}$ and Associated Metal(loid)s in Greater Cairo, Egypt

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Abstract

Greater Cairo is one of the largest metropolitan areas in the world, yet the tempo-spatial trends of $PM_{2.5}$ and loaded metal(loid)s) in its atmosphere, and their potential health risks, are poorly understood. We investigated the air concentrations of $PM_{2.5}$, and associated Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V and Zn, in one urban and one industrial locations within Greater Cairo for one year in each location. Statistical analysis suggested that $PM_{2.5}$ and its chemical composition in Greater Cairo are more influenced by land-use and local activities rather than meteorological conditions. Both annual and daily levels of $PM_{2.5}$ were well above the WHO air quality guidelines, with annual averages of c. 37 and 56 μg m^{-3}, and daily maximums of 165 and 176 μg m^{-3}, in the urban and industrial areas, respectively. This indicates high probability of $PM_{2.5}$ inflicted short- and long-term health risks to the population of Greater Cairo. Health risk modelling indicated that the residents of Greater Cairo are facing high non-carcinogenic and carcinogenic risks (up to 47 and 28 times the recommended hazard indices, respectively) from the studied 12 metal(loid)s combined. Lead (Pb) was the highest single threat to the health of Greater Cairo residents amounting up to 56% and 83% of the total non-carcinogenic and carcinogenic risks, respectively. Nevertheless, most of the exposure to Pb originated from ingestion rather than inhalation which was marginal. For all elements combined, and for some other individual elements, inhalation was a significant route of exposure but only for non-carcinogenic risks. For carcinogenic risks, the contribution of inhalation to the total risk was negligible.

Keywords Air pollution · Particulate matter · Toxic elements · Mega cities · Arid zone

Introduction

Fine particulate matter with aerodynamic diameter ≤ 2.5 µm ($PM_{2.5}$) has been repeatedly linked to a wide range of adverse health issues and reduced life expectancy (Apte et al. 2018). Short-term rise in $PM_{2.5}$ concentrations during intense pollution episodes has also been associated with sharp increase in hospital admissions due to cardiopulmonary diseases (Qiao et al. 2014). The hazardous effects of $PM_{2.5}$ are mainly due to their ability to penetrate deeper in the lungs and deposit in the internal respiratory tract (Löndahl et al. 2006). In locations with heavy urban and industrial activities, $PM_{2.5}$ is usually loaded with a wide range of potentially toxic substances, e.g. trace metals and metalloids (Espinosa et al. 2002). The health effects of $PM_{2.5}$ is thus further intensified via the release of their content of toxic inorganic and organic substances inside the human body (Godri et al. 2011).

Egypt is the most populous middle eastern country and the third in Africa (United-Nations 2019). Greater Cairo, which is home to more than 20 million inhabitants, is one of the world's megacities and one of the largest urban agglomerations in terms of both geographical area and population (Cheng et al. 2016; Hassan 2018a). The wide scale urban expansion and industrial development of Greater Cairo during the last 70 years, have been inescapably associated with a considerable deterioration in its air quality (Hassan et al. 2018, 2022a; Boraiy et al. 2023). Uncontrolled agriculture and domestic waste incineration on the peripheries of Greater Cairo, the emissions from the industrial complexes encapsulating its urban areas and the extremely heavy traffic in its streets, have all contributed to the alarmingly high concentrations of suspended particulate matter (SPM) of all

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size in Greater Cairo's atmosphere (Hassan 2018b; Pacitto et al. 2021). Moreover, due to the surrounding deserts and the mostly semi-arid nature of Greater Cairo's surface soils the concentrations of $PM_{2.5}$ in its atmosphere frequently reach levels that are almost one order of magnitude greater than the World Health Organization (WHO) recommended safe levels (WHO 2006, 2021). For example, Boman et al. (2013), Cheng et al. (2016) and Shaltout et al. (2020) reported $PM_{2.5}$ concentrations up to 110 μg m^{-3}, in various locations around Greater Cairo during 2010–2015.

Despite the importance of Greater Cairo as one of the largest urban areas in the world and the most rapidly developing cities in the arid zone of the world, studies that investigated the impact of suspended particulate matter (and associated toxic elements) on the health of its residents are scarce. For example, Marchetti et al. (2019) found *'in-vitro'* evidence that both organic and inorganic chemical constituents of $PM_{2.5}$, collected from a heavy traffic location within Greater Cairo, can induce pro-inflammatory response and genotoxic effects in human lung cells. Apte et al. (2018) and Wheida et al. (2018) modelled the impact of $PM_{2.5}$ on the life expectancy in Egypt and suggested that, at an annual average concentration of 75 μg m^{-3}, exposure to $PM_{2.5}$ may reduce the life of the Egyptians by an average of 1.85 years at birth. This is well above the global average life-expectancy reduction of 1.22 years, and the second largest among the 185 studied countries (Apte et al. 2018).

Calculating the carcinogenic and non-carcinogenic risks of toxic elements associated to SPM is one of the most important risk assessment approaches that has recently gained some popularity (Megido et al. 2017; Roy et al. 2019; Alghamdi et al. 2021; Guo et al. 2022; Hassan et al. 2022b; Sah et al. 2022). This approach offers vital information about the severity of pollution with airborne toxic elements and the level of damage they may inflict on the health of the exposed communities. To the best of our knowledge, this approach has not been previously applied to try to quantify the risks of $PM_{2.5}$ associated metal(loid)s in Egypt.

In very large urban congregations such as Greater Cairo, in which pollution control measures and epidemiological strategies could be highly costly, understanding and 'predicting' the health risks of air pollution is indispensable. In addition, although there have been a few previous attempts to study $PM_{2.5}$ in Egypt and Greater Cairo, most of those studies were limited in their tempo-spatial scope, i.e. they either studied $PM_{2.5}$ in one location for relatively long sampling period, or in more than one location but for shorter time spans (Boman et al. 2013; Shaltout et al. 2014, 2018b, 2019a).

Understanding the tempo-spatial behaviour of $PM_{2.5}$ and $PM_{2.5}$ metal(loid)s in Greater Cairo's atmosphere, and the associated health risks, may thus offer valuable knowledge to health and environmental authorities, and to policy makers, both in Egypt and in other countries that have relatively similar meteorological and geographical conditions, or following the same development trend. Therefore, the main aims of this work were: (i) to investigate the temporal and spatial trends of $PM_{2.5}$ and associated metal(loid)s between urban and industrial locations within Greater Cairo for two years, and (ii) to model and evaluate their potential health impact in comparison to the WHO air quality guidelines, and via employing the United States Environmental Protection Agency (USEPA) risk assessment approaches.

Materials and Methods

$PM_{2.5}$ Sampling

$PM_{2.5}$ samples were taken from Dokki urban and Al-Tebbin industrial districts in Greater Cairo, Egypt (Fig. 1), approximately once a week for one year in each location. The sampling seasons were defined here as: Spring (March–May), Summer (June–August), Autumn (September–November) and Winter (December–February). Dokki area is one of the busiest and densely populated areas in Greater Cairo and is characterized by diverse urban activities and heavy traffic all year round. Al-Tebbin industrial area is one of the most important industrial agglomerations on the peripheries of Greater Cairo and is home to various heavy industries, e.g. cement, steel, fertilizers and metallurgical coal (Coke) plants. Ambient air $PM_{2.5}$ sampling was carried out on the rooftops of relatively tall buildings (c. 20 m height) in the sampling areas (30°02′09″N, 31°12′22″E in Dokki and 29°47′03″N, 31°18′11″E in Al-Tebbin) away from any direct emission sources. Samples were collected (24 h each during weekdays) on glass-fibre filters (8″ × 10″) using TISCH TE-6070VX-2.5 high-volume samplers fitted with an automatic mass flow controller, at a fixed flow rate of 1.13 m^3 min^{-1}. The flow rates of the $PM_{2.5}$ samplers were regularly checked (with filter on place) on a monthly basis, and following any maintenance or cleaning events, and adjusted where necessary using a TISCH TE-5030 30″ slack tube water manometer. Glass-fibre filters were conditioned for 24 h in a desiccator before and after sampling. The air concentrations of $PM_{2.5}$ (μg m^{-3}) were calculated from the $PM_{2.5}$ mass and total air volume during each sampling event. Air filters were then stored at 4 °C prior to extraction and chemical analysis of $PM_{2.5}$ associated metal(loid)s.

Extraction and Analysis of $PM_{2.5}$ Metals and Metalloids

Metals and metalloids in $PM_{2.5}$ were extracted from the glass-fibre filters by ultrasound-assisted acid extraction (Krishna and Arunachalam 2004). A known portion of each filter paper was shredded in a conical flask containing

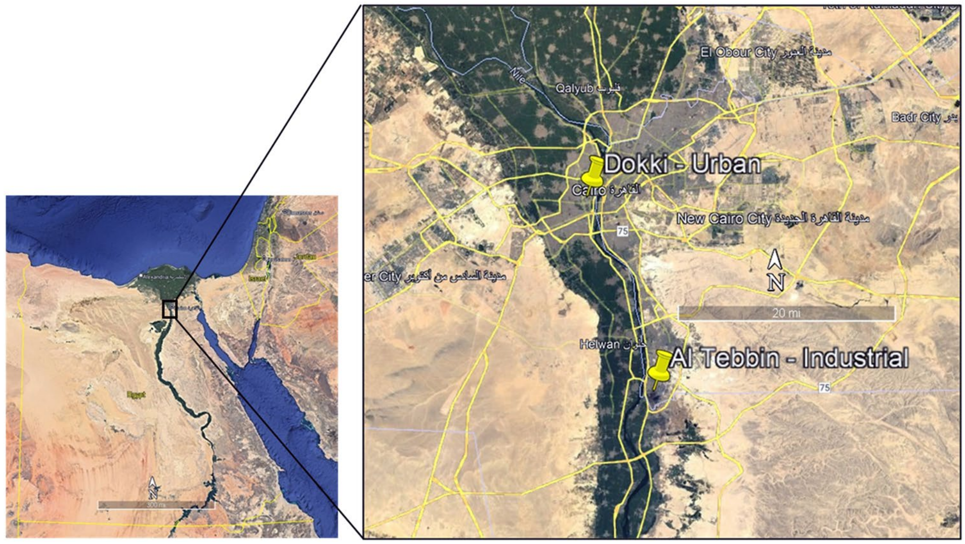


Fig. 1 Map of Egypt showing Greater Cairo and sampling locations. Yellow lines are major roads. Images are obtained from Google Maps (Map data ©2023 Mapa GISrael) and Google Earth (Data SIO, NOAA, U.S. Navy NGA, CBBCO, @ 2023 Google, @ 2023 ORION-ME)

50 mL 1 M HNO_3 (Trace Analysis Grade, TAG). The flasks were then placed in an Eumax ultrasonic bath operating at 40 kHz and 70 °C for 3 h. After cooling down to room temperature, acid extracts were filtered into 250 mL volumetric flasks through Grade 43 Whatman quantitative filter papers, and then made up to the mark with deionised water. Filtered extracts were assayed for the concentrations of Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V and Zn using an Agilent 8800 ICP-QQQ ICP-MS equipped with an Agilent ASX-500 auto-sampler. Internal standards (10 µg L^{-1} Rh and Ir) were introduced via a t-piece directly to the sample loop (Marchetti et al. 2019; Shetaya et al. 2019a). Polyatomic inferences were eliminated by operating the ICP-MS in helium gas collision mode (Shetaya et al. 2017), whereas monoatomic interferences were automatically accounted for by the Mass Hunter ICP-MS operating software. The limits of detection (LOD) were estimated as 3 times the standard deviation between the concentrations of each element in 16 blank samples (Shetaya et al. 2018; Marzouk et al. 2022). Blank glass-fibre filters were treated similarly at each extraction and analysis event and used as sample blanks; the blank values were always below the detection limit for all the 12 investigated metal(liod)s. All ICP-MS analyses were performed in duplicate, and the analysis of any given sample was repeated if the difference between the 2 replicates was > 5% for any element. Analytical recovery was checked using the certified reference material NIST 2711 (powdered Montana soil), which yielded an average recovery of 93 ± 6% for all certified elements (As, Cd, Cu, Pb, Mn, Ni, V and Zn).

Non-Carcinogenic and Carcinogenic Risk Estimation

The potential impact of $PM_{2.5}$ 12 metal(loid)s on the health of urban Cairo residents was assessed using the risk assessment models developed by the USEPA (USEPA 1989, 2004, 2009). These models offer tools and information to calculate the carcinogenic and non-carcinogenic hazard indices of toxic and potentially toxic substances in the terrestrial environment. In this work, the potential carcinogenic and non-carcinogenic risks of Al, As, Cd, Co, Cr (VI), Cu, Fe, Mn, Ni, Pb, V and Zn in $PM_{2.5}$ were estimated for three major exposure routes: 1- ingestion of $PM_{2.5}$, 2- dermal contact with $PM_{2.5}$ and 3- direct inhalation of $PM_{2.5}$. The element concentrations used was the upper confidence limit (95% UCL; Minitab 17 software package) to represent the maximum annual exposure to any given element without counting for any outlier high levels that may have been caused by exceptional and irregular pollution events; the concentrations of Cr(VI) were calculated as 14.3% of total Cr (Megido et al. 2017; Roy et al. 2019).

Quantification of Exposure Doses

The intake of $PM_{2.5}$ associated metal(loid)s were calculated using Eq. 1, 2 and 3 adapted from the models developed by USEPA (1989), USEPA (2004) and USEPA (2009) for ingestion, dermal and inhalation exposure, respectively.

$$\mathrm{CDI_{ing}} = \frac{C\ \mathrm{IngR\ EF\ ED\ CF}}{\mathrm{BW\ AT_{id}}} \tag{1}$$

$$\mathrm{DAD_{drm}} = \frac{\mathrm{C\ SA\ AF\ ABS\ EF\ ED\ CF}}{\mathrm{BW\ AT_{id}}} \tag{2}$$

$$EC_{inh} = \frac{C\ ET\ EF\ ED}{ATn} \quad (3)$$

where CDI_{ing} is the chemical daily intake through ingestion (mg kg^{-1} day^{-1}), DAD_{drm} is the dermal absorbed dose (mg kg^{-1} day^{-1}), EC_{inh} is the exposure concentration through inhalation (µg m^{-3}), C is the $PM_{2.5}$ metal(loid)s concentration (mg kg^{-1} for ingestion and dermal exposure, and µg m^{-3} for inhalation) calculated as 95% upper confidence limit (95% UCL) of the annual mean concentrations, IngR is the ingestion rate (mg day^{-1}), EF is the exposure frequency (days $year^{-1}$), ED is the exposure duration (years), CF is the conversion factor (kg mg^{-1}), BW is the body weight (kg), AT_{id} is the averaging time for ingestion and dermal exposure (equals ED × 365 days for non-carcinogenic risk and 70 × 365 days for carcinogenic risk), SA is the skin surface area (cm^2), AF is the skin adherence factor (mg cm^{-2}), ABS is the dermal absorption factor (unitless), ET is the exposure time (hr day^{-1}), ATn is the inhalation averaging time (equals ED × 365 × ET hrs for non-carcinogenic risks and 70 × 365 × ET hrs for carcinogenic risk). The values of the above terms can be found with their source references in Tables A1 and A2 (Appendix A: Supplementary Material).

Non-Carcinogenic Risk Estimation

The non-carcinogenic health risk from individual $PM_{2.5}$ toxic and potentially toxic metal(loids) through any given exposure route is expressed as a Hazard Quotient (HQ). The HQs from ingestion, dermal, and inhalation exposure pathways were calculated using Eq. 4, 5, and 6, respectively (USEPA 1989, 2004, 2009).

$$HQ_{ing} = \frac{CDI_{ing}}{RFDo} \quad (4)$$

$$HQ_{drm} = \frac{DAD_{drm}}{RFDo\ GIABS} \quad (5)$$

$$HQ_{inh} = \frac{EC_{inh}}{RFCi\ 1000} \quad (6)$$

where HQ_{ing}, HQ_{drm} and HQ_{inh} are the hazard quotients from ingestion, dermal and inhalation exposure, respectively, RFDo is the oral reference dose (mg kg^{-1} day^{-1}) and RFCi is the inhalation reference concentration (mg m^{-3}) recommended for each potential toxin (Table A2; Appendix A). RFCi values were not available for Fe, so non-carcinogenic risks from inhalation exposure of Fe could not be calculated.

The Hazard Index (HI) of any given element or chemical species (e.g. Cr(VI)) is the summation of its HQs from all three routes of exposure (i.e. $HQ_{ing} + HQ_{drm} + HQ_{inh}$). The HI can also be calculated for all toxins combined as the summation of individual elements/species HIs. HI or HQ values ≤ 1 indicates insignificant non-carcinogenic risk form exposure to any particular element(s), whereas HQ or HI > 1 indicates significant non-carcinogenic health risks (USEPA 1989; Megido et al. 2017; Shetaya et al. 2023).

Carcinogenic Risk Estimation

Carcinogenic risk (CR) indicates how probable it is, during 70 years lifetime of exposure, for the exposed population to develop any type of cancer. CR values $< 1 \times 10^{-6}$ indicates negligible risk while values $> 1 \times 10^{-4}$ indicates a probable risk of developing cancer (USEPA 1989; Roberts et al. 2014). The carcinogenic risks of the potentially carcinogenic elements and chemical species (As, Cd, Co, Cr(VI), Ni and Pb) from all three exposure routes (individually and combined) were calculated using Eq. 7, 8, 9 and 10 (USEPA 1989, 2004, 2009).

$$CR_{ing} = CDI_{ing}\ SF_o \quad (7)$$

$$CR_{drm} = \frac{DAD_{drm}\ SF_o}{GIABS} \quad (8)$$

$$CR_{inh} = EC_{inh}\ IUR \quad (9)$$

$$CR_x = CR_{ing} + CR_{drm} + CR_{inh} \quad (10)$$

where CR_{ing}, CR_{drm}, CR_{inh}, CR_x are the carcinogenic risks from any given carcinogen through ingestion, dermal, inhalation and all three exposure routes combined, respectively, GIABS is the gastrointestinal absorption factor (unitless), SFo is the oral slope factor ((mg kg^{-1} day^{-1})$^{-1}$), IUR is the inhalation unit rate ((µg m^{-3})$^{-1}$). The values of SFo, GIABS and IUR are displayed for each carcinogenic element/species with their respective references in Table A2 (Appendix A). SFo and IUR values were only available for As, Cd, Co, Cr(VI), Ni and Pb. The total carcinogenic risk to the residents of urban Cairo from As, Cd, Co, Cr(VI), Ni and Pb combined (CR_{tot}) was calculated as the summation of CR_x of individual carcinogenic elements/chemical species.

Results and Discussion

Temporal and Spatial Variations

$PM_{2.5}$

The average seasonal $PM_{2.5}$ concentrations in Dokki urban and Al-Tebbin industrial areas are displayed in Fig. 2 and Table A3 (Appendix A). Traffic-related emission sources are commonplace in all Greater Cairo urban and industrial areas (Shaltout et al. 2018a). The overall higher $PM_{2.5}$ levels in Al-Tebbin (industrial) than in Dokki (urban) can be attributed to the additional large concentration of cement, steel and power plants which are well known emission sources of $PM_{2.5}$ (Sylvestre et al. 2017; Wu et al. 2020).

The differences in $PM_{2.5}$ concentrations between the 2 locations were statistically significant ($p < 0.05$) (Table A4; Appendix A) in all seasons except in spring which is likely due to the Sahara sandstorms that are common in Egyptian spring (Boman et al. 2013; Hassan and Khoder 2017; Shaltout et al. 2020). These intense and recurrent dust episodes which are naturally loaded with geogenic particles may have masked the apparent difference in $PM_{2.5}$ concentrations between urban and industrial locations of Greater Cairo in spring.

On the other hand, within each location, the differences in $PM_{2.5}$ concentrations between different seasons were (mostly) statistically non-significant ($p > 0.05$) (Table A5; Appendix A). This suggests that, with the exception of temporary pollution episodes (e.g. sandstorms), the $PM_{2.5}$ levels in Greater Cairo are a function of land use and are relatively homogenous between different seasons (within any particular area). The relatively calm weather in Egypt, in general, and Greater Cairo, in particular, may explain the $PM_{2.5}$ temporal homogeneity. Excluding the occasional extreme events, e.g. spring sandstorms and a few rainy days in winter, Greater Cairo is all year round affected by moderate (16 km h^{-1}) north-westerly winds, very low precipitation rates and daily mean temperatures that ranges from 14 to 28 °C (WMO 2019). This prevailing moderate and non-turbulent weather conditions all year round means that $PM_{2.5}$ concentrations are more affected by local geographical nature and emission point sources rather than meteorological conditions and explains the $PM_{2.5}$ 'relative' temporal homogeneity vs spatial heterogeneity in Greater Cairo.

$PM_{2.5}$ metal(loid)s

The seasonal average concentrations (and full statistical summary) of the investigated $PM_{2.5}$ metal(loid)s are displayed in Table 1. For $PM_{2.5}$ associated metal(loid)s, the differences in the annual and seasonal concentrations of the investigated elements between Dokki and Al-Tebbin areas were mostly significant ($p < 0.05$; Table A4; Appendix A). This suggests different elemental profile and relative contribution of metal(loids)s to the $PM_{2.5}$ composition between industrial and urban areas of Greater Cairo, and accordingly different dominant emissions sources. Similar to $PM_{2.5}$, within each location, the differences in the concentrations of $PM_{2.5}$ metal(loid)s between seasons were not very noticeable with the exception of a few cases in the industrial area (Fig. A1 and Fig. A2; Appendix A).

This all 'apparently' suggests an overall temporally homogeneous and spatially heterogeneous $PM_{2.5}$ air concentrations 'and elemental profile' in Greater Cairo, with the exception of occasional pollution events, e.g. sandstorms and upscaling of industrial activities. To investigate this further, the concentrations of all 12 $PM_{2.5}$ metal(loids) (in all collected samples) were dimensionally reduced with principal component analysis (PCA) using Mintiab 17 software package. In both locations the $PM_{2.5}$ meta(loid)s concentrations could not be reduced to 2 major components. In Dokki (urban) the first 5 components showed Eigen values more than 1 and altogether explained 85% of the variance (Fig. A3 A; Appendix A). In Al-Tebbin (industrial) the first 3 components had Eigen values > 1 and explained 73% of the variance (Fig. A3 B; Appendix A). The first 2 components explained only 50% and 61% of the variance in Dokki and Al-Tebbin, respectively.

Unlike larger PM fractions, e.g. PM_{10} and TSP which are dominated by coarse particles (> 1 μm), and hence natural and geogenic sources, $PM_{2.5}$ particles have almost equal contribution of fine (< 1 μm) and coarse particles (Pöschl 2005; Valavanidis et al. 2008). Fine particles are normally produced by chemical process, e.g. fossil fuel combustion and industrial chemical operations, whereas coarse particle are produced by physical process, e.g. soil erosion, industrial physical processes and traffic (WHO 2021). Therefore, $PM_{2.5}$ particles are composed of a very heterogeneous mixture of elements (and metal(loid)s) and are more difficult to be simply represented by two major sources (Espinosa et al. 2002), or in this context by two dominant PCA components as opposed to, e.g. surface soils (Shetaya et al. 2023).

However, assuming that the first 2 components (PC1 and PC2) fairly represent the elemental profile (at least 50% of it), it is obvious from the score plots (Fig. 3A and B) that different seasons can be grouped into discrete clusters relative to PC1 and PC2. This indicates that, despite the apparent homogeneity in the temporal (seasonal) $PM_{2.5}$ elemental profile in each location, there is indeed slight differences between seasons, and that the temporal homogeneity of $PM_{2.5}$ elemental profile may be not absolute. Since the local emission sources are constant, the reason for this potential seasonal-specific $PM_{2.5}$ elemental profile is likely meteorological . For example, the frequent Sahara sandstorms in spring (Boman et al. 2013; Hassan and Khoder 2017; Shaltout et al. 2020), which are loaded with geogenic particles, will normally make the lithogenic elements, e.g. Al, Fe and Mn, dominate the $PM_{2.5}$ elemental profile. On the other hand, the recurrent heat inversion phenomenon in early winter and autumn over Greater Cairo (El-Askary and Kafatos 2008; Mahmoud et al. 2008; Aboel Fetouh et al. 2013; Mostafa et al. 2019) will likely trap the locally emitted pollutants in the tropospheric zone resulting in a prevalence

Table 1 Statistical summary of seasonal air concentrations of $PM_{2.5}$ associated metal(loid)s (ng m^{-3}) in Dokki urban and Al-Tebbin industrial areas of Greater Cairo, Egypt

		Dokki				Al-Tebbin			
		Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Al	Mean	1695	1651	1095	2368	715	3438	4040	7071
	SD	1060	1355	1157	1700	519	1007	3618	975
	Max	3797	3765	4341	5419	1892	6207	8981	8141
	Min	286	420	112	375	178	2603	276	5094
V	Mean	11.1	21.5	6.15	7.99	9.67	13.6	NV	NV
	SD	6.48	9.33	3.52	4.16	5.55	6.75	NA	NA
	Max	24.8	40.9	14.5	17.7	18.5	25.4	NA	NA
	Min	1.8	4.79	1.66	2.25	2.22	4.46	NA	NA
Cr	Mean	NV	9.25	12.1	4.27	4.85	10.4	7.31	6.64
	SD	NA	3.07	4.98	7.03	1.9	1.77	2.78	0.86
	Max	NA	18.5	22.8	20.1	7.91	14.3	13.4	7.77
	Min	NA	6.48	2.23	NA	1.18	7.88	4.7	4.94
Mn	Mean	16.8	19.5	11.4	22.4	31.4	49.2	31	40.1
	SD	12.2	15	3.62	11.6	24.1	39.3	13.1	18.1
	Max	66.7	72.6	20.4	57.7	83	166	53	70.2
	Min	5.9	9.91	6.79	6.8	8.65	25.3	18.4	22.5
Fe	Mean	1318	370	300	754	568	1128	808	540
	SD	932	126	101	478	590	757	443	157
	Max	3457	646	571	1908	1967	3045	1941	930
	Min	242	190	79.4	211	122	425	475	349
Co	Mean	0.36	0.38	0.25	0.35	0.83	1.12	1.22	0.94
	SD	0.29	0.13	0.09	0.19	0.34	0.23	0.29	0.06
	Max	1.49	0.8	0.43	0.91	1.57	1.57	1.79	1.02
	Min	0.12	0.23	0.1	0.17	0.21	0.8	0.98	0.82
Ni	Mean	9.9	17.9	8.41	7.39	4.47	7.04	4.88	3.04
	SD	5.56	7.56	4.07	3.65	1.83	3.27	3.34	0.6
	Max	23	33.6	19.7	15.8	8.07	12.8	13.1	4.15
	Min	1.85	4.35	4.23	3.36	2.07	3.33	2.25	2.41
Cu	Mean	76.7	36.8	26.2	58	52.5	23	38.2	21.9
	SD	48.1	15.6	13.9	34	35.1	6.34	16.4	6.44
	Max	174	67.1	64.3	161	126	35.7	68.6	30.5
	Min	8.6	14.2	10.5	26	14.8	13.5	20.6	12.2
Zn	Mean	5328	4240	3873	2511	2174	13,981	5047	450
	SD	3990	2261	1878	2647	742	2644	10,895	214
	Max	13,200	7846	9544	10,079	3108	18,605	35,924	988
	Min	876	2008	696	324	485	11,230	197	185
As	Mean	10.1	3.09	2.59	10.2	0.97	1.09	2.42	1.99
	SD	7.23	1.8	1.96	6.93	0.63	0.54	2.98	0.88
	Max	35.6	5.71	8.73	28.8	1.95	2.05	8.83	3.81
	Min	3.11	0.41	0.73	1.15	0.21	0.51	0.25	0.55
Cd	Mean	4.04	4.38	2.32	2.92	0.89	5.88	1.64	0.82
	SD	5.2	6.32	2.23	1.95	0.47	2.46	3.03	0.69
	Max	25	24.8	10.9	6.68	1.84	9.99	10.2	2.21
	Min	0.61	0.83	0.68	0.92	0.37	1.86	0.35	0.22
Pb	Mean	104	34.1	37.2	134	148	411	100	166
	SD	108.4	21.7	32.7	112.7	312	238	138	165
	Max	464	93.1	129	411	1035	884	449	501
	Min	17.9	13.3	12	12.2	33.6	132	15.2	9.26

SD standard deviation, *NV* not available (not measured) and *NA* not applicable. Values are approximated to three significant digits

Table 2 Annual average concentrations of $PM_{2.5}$ (μg m^{-3}) and associated metal(loid)s (ng m^{-3}) in this work compared to the corresponding values in 12 other cities (measured in the last 20 years) and the WHO recommended guideline values

Country	City/Area	PM2.5	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb	References
Egypt	Dokki	37.2	1678	11.2	11.3	17.2	713	0.33	10.6	50.3	4052	6.62	3.38	78.4	This Study
Egypt	Al-Tebbin	56.4	3807	6.14	7.36	38.2	770	1.03	4.91	33.6	5622	1.6	2.4	211	This Study
Mexico	Monterrey	8.2	NV	NV	NV	18.1	244	NV	0.69	NV	NV	3.71	NV	43.1	Mancilla et al. (2019)
Taiwan	Taichung	42.8	NV	NV	33.5	19.1	163	NV	11.8	11.5	178	NV	4.3	283	Fang et al. (2003)
India	Agra	105	NV	NV	600	100	1900	NV	300	200	900	NV	NV	1100	Kulshrestha et al. (2009)
	Bhopal	NV	1132	5.3	3.3	18.3	484	2.4	3.2	18.5	246	2.2	NV	66.1	Nirmalkar et al. (2021)
Italy	Venice	16.9	634	14.1	NV	5.22	97.7	0.33	12.2	NV	84.5	3.6	3.5	18.1	Stortini et al. (2009)
Algeria	Algiers	31.6	NV	NV	45.5	3298	7202	NV	NV	2662	NV	93.2	NV	371	Talbi et al. (2018)
China	Shanghai	62.3	2905	NV	31	132	2381	NV	27	29	465	NV	3	133	Wang et al. (2013)
	Hong Kong	NV	NV	NV	1	10	100	NV	4	5	200	NV	NV	NV	Hagler et al. (2007)
	Chifeng	36.2	547	1.8	2.4	16.6	390	0.2	1.2	16.5	83.7	4.6	2.4	51	Hao et al. (2018)
	Ningbo	54.3	457	168	128	38.1	486	1.1	28.2	22.9	265	126	1.4	38.3	Xu et al. (2021)
	Hangzhou	80	716	136	41.2	28.5	523	0.9	8.6	26.5	209	95.3	2.3	47.4	Xu et al. (2021)
Spain	Barcelona	27.7	NV	9	6	14	260	NV	6	52	178	NV	NV	130	Querol et al. (2001)
Finland	Helsinki	11.8	NV	NV	NV	3	100	NV	2	3	10	NV	NV	6	Pakkanen et al. (2001)
Thailand	Bangkok	NV	1316	27	39	201	1441	10	32	136	796	11	113	297	Pongpiachan et al. (2017)
USA	Florida	12.7	NV	2.6	NV	1.9	79	NV	1.3	2.4	13.2	2.2	NV	5.3	Olson et al. (2008)
	New Jersey	NV	27.3	2.84	0.79	1.83	86.6	0.15	7.79	39	14.7	NV	0.1	3.26	Xia and Gao (2011)
	Los Angeles	13.8	60	1	3	12	190	1	3	10	10	NV	6	5	Farahani et al. (2021)
WHO Guideline Values		5, 10	NV	1000	NRS (Cr(VI))	150	NV	NV	NRS	NV	NV	NRS	5	500	(WHO 2000), (WHO 2006), (WHO 2021)

NV not available, *NRS* no recommended safe levels

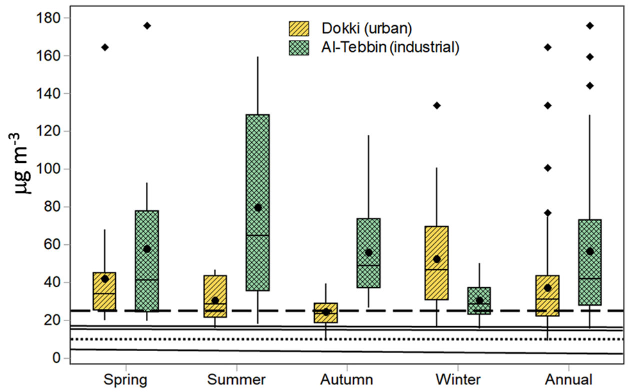


Fig. 2 $PM_{2.5}$ seasonal and annual air concentrations (μg m^{-3}) in Dokki urban and Al-Tebbin industrial areas of Greater Cairo, Egypt, plotted as box and whisker plots where averages are shown as black circles, outliers as black diamonds and medians as horizontal lines. The dashed and dotted lines represent the 2006 WHO annual and 24 h $PM_{2.5}$ ambient air guideline values of 10 and 25 μg m^{-3}, respectively (WHO 2006). The solid single and double lines represent the 2021 WHO annual and 24 h $PM_{2.5}$ ambient air guideline values of 5 and 15 μg m.$^{-3}$, respectively (WHO 2021). Statistical summary of $PM_{2.5}$ data can be found in Table A3 (Appendix A: Supplementary Material)

of the anthropogenic elements, e.g. As, Cd and Pb over the geogenic ones.

Loading plots (Fig. 3C and D) show different metal(loid)s loadings and relative distribution towards PC1 and PC2 between Dokki and Al-Tebbin locations supporting our earlier conclusion of heterogeneous spatial $PM_{2.5}$ elemental profile in Greater Cairo.

Annual Levels and Potential Health Effects

$PM_{2.5}$

The $PM_{2.5}$ levels in Dokki urban and Al-Tebbin industrial areas ranged from 8.93 to 165 and from 15.4 to 176 μg m^{-3}, with annual average concentrations of 37.2 and 56.4, respectively (Fig. 2 and Table A3; Appendix A). The recorded values were substantially (up to tenfolds) greater than the World Health Organisation (WHO) annual guidelines values of 2006 and 2021 (5 and 10 μg m^{-3}, respectively) (WHO 2006, 2021). This suggests that the residents of both areas are at high risk of health effects related to long-term exposure to $PM_{2.5}$, e.g. ischemic heart disease, incident stroke, neurological disorders, lung cancer, diabetes mellitus and

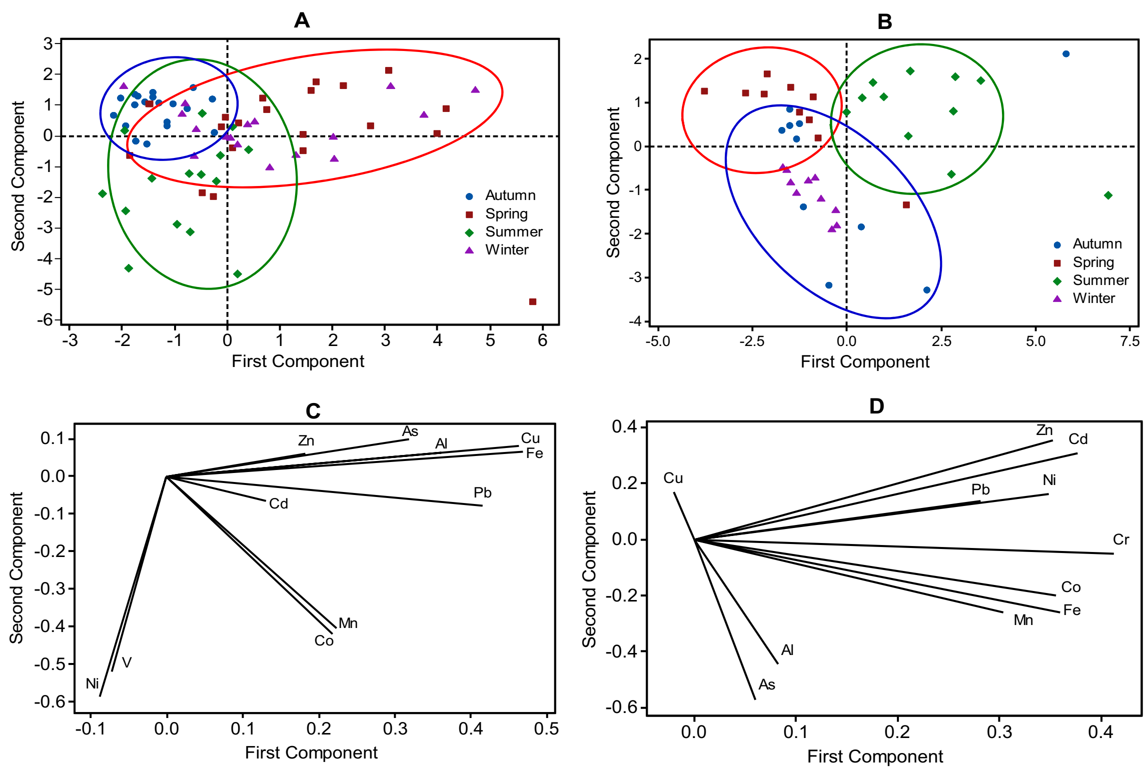


Fig. 3 Principle component analysis (by Mintiab 17 software package) of the ambient air concentrations (ng m^{-3}) of $PM_{2.5}$ Al, As, Cd, Co, Cr (VI), Cu, Fe, Mn, Ni, Pb, V and Zn in Cairo, Egypt. A and B are score plots of the two major PC factors in Dokki urban and Al-Tebbin industrial locations, respectively, showing different seasons in different symbols and colours. C and D are loadings plots of all elements in Dokki and Al-Tebbin, respectively. Discrete clusters in the score plots (A and B) are demarcated with circles of different colours

reproduction issues (Feng et al. 2016; Alexeeff et al. 2021). Similar observations were found for short-term exposure; in both areas the concentration of $PM_{2.5}$ exceeded the WHO 24 h guideline values of 15 µg m^{-3} (WHO 2021) in 100% of the recorded days (Fig. 2), which indicates all year round high risk of $PM_{2.5}$ short-term health effects, e.g. respiratory diseases, hospital admission and daily mortality (Atkinson et al. 2014; Bell et al. 2014). Nevertheless, in comparison to the $PM_{2.5}$ levels in other countries recorded in the last 2 decades, the $PM_{2.5}$ annual average concentrations in both industrial and urban Cairo were not noticeably higher (and were sometimes lower) than the levels recorded in other cities around the world, with the exception of a few cities (Table 2).

The annual $PM_{2.5}$ average concentrations in Al-Tebbin industrial area were significantly ($p<0.05$) higher than those in Dokki urban area (Fig. 2 and Table A4; Appendix A) suggesting that the residents of Al-Tebbin area, as an example of Cairo industrial areas, may be at greater risk of developing $PM_{2.5}$ inflicted long-term and short-term health effects in comparison to the resident of urban areas.

$PM_{2.5}$ Associated Metal(loid)s

The annual average concentrations of the 12 investigated $PM_{2.5}$ metal(loid)s in Dokki and Al-Tebbin areas are displayed in Table 2 in comparison to the corresponding values in other countries and the WHO guideline values (WHO 2000).

There are no WHO guideline values for Al, Fe, Co, Cu and Zn as they are not classified as plain toxins or carcinogens. In fact all of them (except Al) are essential nutrients and would only be toxic or pathogenic to humans at extremely high levels (Jaishankar et al. 2014). Aluminium is very toxic to plants (Roy et al. 1988; Delhaize and Ryan 1995), whereas, the direct exposure of humans to Al is generally not harmful due to the Al elimination capability of the human body (Exley 2013). However, high levels of aluminium in the human body may cause many adverse effects particularly long-term neurotoxicity (Jaishankar et al. 2014). The annual average concentration of $PM_{2.5}$ Al in Al-Tebbin industrial area was noticeably higher than the corresponding values in other cities (Table 2), suggesting that the residents of that area might be at higher risk of Al adverse health effects. The relatively higher Al concentrations in this area may be due to the high concentration of cement and steel industries which are confirmed sources of Al_2O_3 air emissions (Sorenson et al. 1974).

The annual average levels of $PM_{2.5}$ Fe, Co and Cu in Dokki and Al-Tebbin were not particularly high in comparison to other cities. However, Zn levels in both urban and industrial Greater Cairo were extremely higher than the annual average levels in other cities (up to several orders of magnitude). Egyptian soils and sediments are generally not highly enriched in Zn and most of their Zn is locked immobile in residual soil fractions (Shaheen et al. 2020). Therefore, it is highly unlikely that $PM_{2.5}$ Zn (at such elevated levels) is geogenic in origin, e.g. from surface soil resuspension. Some studies reported that anthropogenic Zn in urban and industrial areas may be emitted from traffic related and industrial sources, e.g. fuel combustion, wearing of tires and engines, and steel and cement industries (Boman et al. 2013; Yan et al. 2018; Shaltout et al. 2019b). Both Dokki urban and Al-Tebbin industrial areas, like most of Greater Cairo, are characterized by high intensity traffic and very dense population, which may explain the elevated levels of $PM_{2.5}$ Zn to some extent. The steel, cement and power plants in Al-Tebbin may explain the higher levels of $PM_{2.5}$ Zn than in Dokki. However, this should have been associated with similar sharp increase in other traffic and industry related metal(loid)s which doesn't seem to be the case (Table 2) suggesting only partial contribution of these anthropogenic sources to the elevated $PM_{2.5}$ Zn concentrations. Waste incineration is also an important source of fine Zn PM (Fellner et al. 2015). The wide application of foliar Zn fertilizers to fodder crops in Egypt (Zeidan et al. 2010; Ghoneim 2016), combined with the common practice of open-air agriculture waste incineration on the peripheries of Greater Cairo (Mohamed et al. 2015; Hassan and Khoder 2017; Shetaya et al. 2019b), may be the primary reason for the remarkable levels of $PM_{2.5}$ Zn in Cairo's atmosphere. Excessive levels of Zn exposure may induce Cu deficiency symptoms, e.g. anaemia and immunosuppression in the affected populations (Plum et al. 2010), which may be the case for Greater Cairo's residents.

Annual concentrations of $PM_{2.5}$ V, Mn and Pb were all below the WHO guideline values in both urban and industrial areas (Table 2). Similarly, although there are no recommended safe levels for Cr(VI), Ni and As, but in comparison to other cities, they do not show any remarkable elevation in both areas.

Non-Carcinogenic and Carcinogenic Health Risks

The non-carcinogenic and carcinogenic health risks of all 12 metal(loid)s (individually and combined) to the residents (children and adults) of Dokki urban and Al-Tebbin industrial areas of Greater Cairo were calculated as described in Sect. "Non-carcinogenic and carcinogenic risk estimation". Full analysis and generated data are displayed in Tables A6 and A7; Appendix A, together with elemental and exposure route contributions.

Non-Carcinogenic Hazard Indices

All of Cr(VI), Fe and Cu showed non-carcinogenic hazard indices (HI) < 1 for children and adults in both urban and industrial areas (Fig. 4), indicating insignificant non-carcinogenic risks from these 3 metal(loid)s to the residents of these areas. Aluminium, V, Mn, Co, Ni, Zn and Cd also displayed HI values ≤ 1 in both areas but only for adults. For children, they posed significant non-carcinogenic risks in Dokki urban area (HI of 1.3, 2.7, 1.7, 7.2 and 2.4, respectively), whereas in Al-Tebbin industrial area, the significant non-carcinogenic risks to children originated from Mn, Co, Zn and Cd, with HIs of 2.8, 1.8, 1.4, 6.6 and 1.2, respectively (Fig. 4 and Tables A6 and A7; Appendix A). Despite the extremely high concentrations of $PM_{2.5}$ Zn in both locations (Tables 1 and 2), it seems that Zn does not pose significant non-carcinogenic health risk to adults in Greater Cairo. However, Zn poses very high risk to the health of Greater Cairo children (almost one order of magnitude higher than the HI threshold of 1).

The highest non-carcinogenic risks for adults and children in both urban and industrial areas were posed by As and Pb (Fig. 4). Although, in Al-Tebbin industrial area, As posed insignificant non-carcinogenic risk (HI = 0.4) to the health of the adult population, the risk to children's health was double the HI safe threshold (Tables A6 and A7; Appendix A). In Dokki (urban), As posed very high non-carcinogenic risk to both children and adults with HIs of 1.7 and 13, respectively. Lead (Pb) posed the highest non-carcinogenic risks among all of the 12 studied metal(loid)s in urban and industrial locations alike, and for both children and adults, with HIs that were up to 25 times the safe HI threshold for children (Fig. 4 and Tables A6 and A7; Appendix A).

The combined HI of the 12 investigated $PM_{2.5}$ metal(loid)s ranged from 6.9 (adults in Al-Tebbin industrial area) to 47 (children in Dokki urban area), indicating very high non-carcinogenic risks from these 12 metal(loid)s to the health of Greater Cairo's residents (Fig. 4 and Tables A6 and A7; Appendix A). There was almost no difference in the non-carcinogenic HIs of urban and industrial locations, but the risk to children was up to 7 times greater than that to adults. The higher risk to children's health compared to adults is understandable due to children's lower body mass and undeveloped contaminant elimination mechanisms (Li et al. 2014; Doabi et al. 2018; Alghamdi et al. 2019).

Carcinogenic Risks

Chromium (VI), Co, and Cd all represented negligible to acceptable carcinogenic risks (CR less than or marginally above 1×10^{-4}) to children and adults in both areas (Fig. 5 and Tables A6 and A7; Appendix A). Nickel posed probable carcinogenic risks (CR > 1×10^{-4}) to the children of both urban and industrial areas, and the adults of Al-Tebbin industrial area only. Arsenic showed comparable CR values to that of Ni but only in the urban area, whereas its carcinogenic risks in the industrial district were negligible. Lead (Pb), however, represented a highly probable carcinogenic risk to children and adults of both urban and industrial areas, with CR values up to one order of magnitude the acceptable carcinogenic risk (CR) threshold of 1×10^{-4} (Fig. 5) making it, by far, the highest single carcinogenic threat among the studied elements.

All six elements combined posed highly probable carcinogenic risks (>> 1×10^{-4} and up to 2.4×10^{-3}) to both children and adult residents of the studied urban and industrial locations (Tables A6 and A7; Appendix A). This translates to a probability of 1—24 additional persons per 10,000 to develop cancer due to exposure to these 6 $PM_{2.5}$ metal(loid)s on top of the average number of people expected to be develop cancer during their lifetime without exposure to $PM_{2.5}$ (Megido et al. 2017;

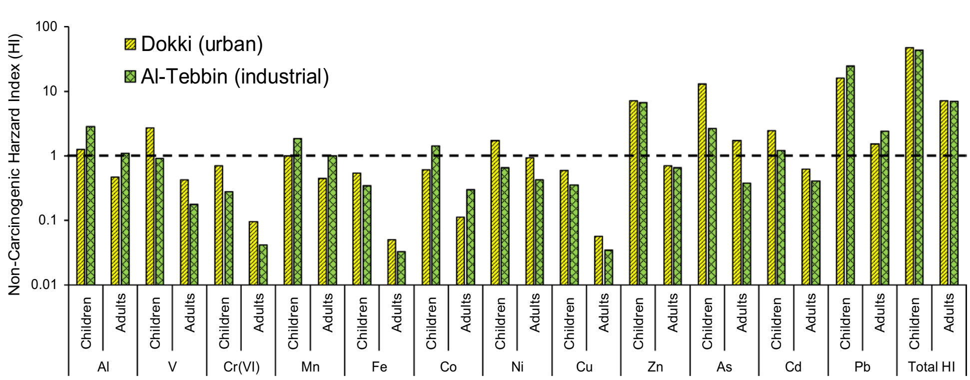


Fig. 4 Projected (logarithmic scaled) non-carcinogenic health indices (HI) for children and adults in Dokki urban and Al-Tebbin industrial areas, from exposure to $PM_{2.5}$ associated metal(loid)s, through ingestion, dermal and inhalation combined. Dashed line (at HI = 1) demarcates the borderline between significant and insignificant non-carcinogenic risks. Full data can be found in Tables A6 and A7 (Appendix A)

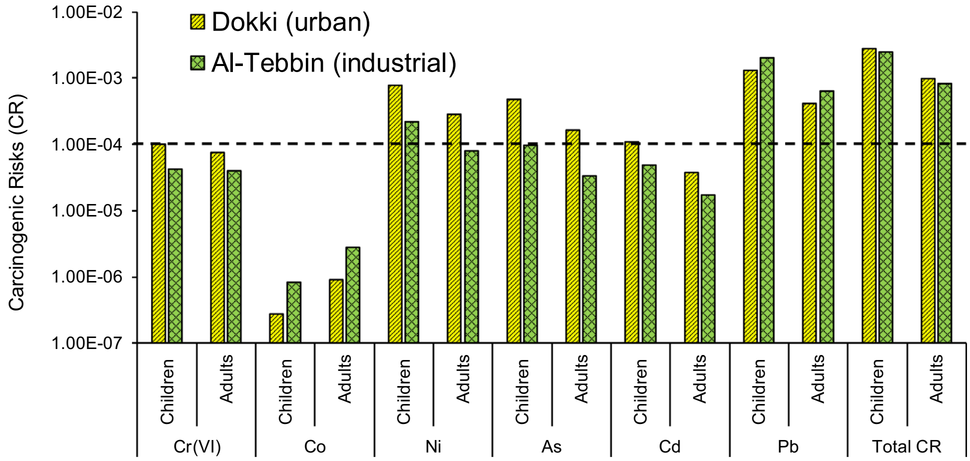


Fig. 5 Modelled (logarithmic scaled) carcinogenic health risks (CR) for children and adults in Dokki urban and Al-Tebbin industrial areas from exposure to $PM_{2.5}$ associated metal(loid)s, through ingestion, dermal and inhalation combined. $CR < 1 \times 10^{-6}$ = negligible risk, $1 \times 10^{-6} < CR < 1 \times 10^{-4}$ = acceptable or tolerable risk and $CR > 1 \times 10^{-4}$ = probable risk of developing cancer (dashed line). Full data can be found in Tables A6 and A7 (Appendix A)

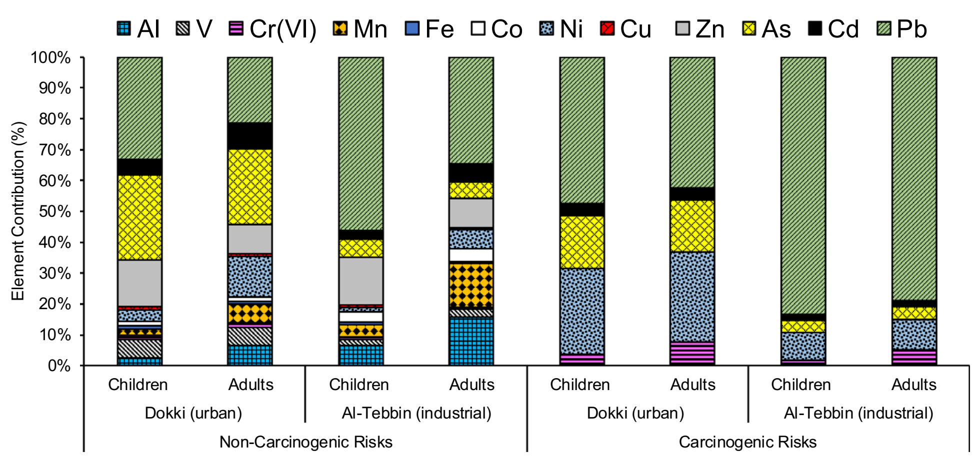
Antoniadis et al. 2019). Likewise non-carcinogenic risks, there was no significant difference in the probability of developing cancer between the residents of urban and industrial Greater Cairo areas, although there was a slightly higher risk for children than that to adults within the same area.

Elemental Contribution

For non-carcinogenic risks, Pb was clearly the highest contributor in both areas with contributions up to 56% for children in Al-Tebbin; the only exception was adults in Dokki to which As marginally superseded Pb with a contribution of 24% (Fig. 6). For Dokki children, As was the second highest contributor (27%) to non-carcinogenic risks after Pb. In Al-Tebbin, Zn and Al were the second major contributors for children and adults with contributions of c. 15 and 16%, respectively. The third major contributor alternated between Zn, Ni, Al and Mn with contributions that ranged from c. 6 to 15%. Cadmium also showed considerable contributions to the total non-carcinogenic risks in urban and industrial Greater Cairo (up to 8%), whereas V contribution was focused in Dokki (c. 6% for children and adults). The contributions of Cr(VI), Fe, Co and Cu, were generally marginal compared to the other metal(loid)s (Fig. 6 and Tables A6 and A7).

For carcinogenic risks, Pb was also the highest contributor for adults and children in both urban and industrial areas with contributions that ranged from c. 43 to 83% (Fig. 6). The contribution of Pb to total carcinogenic risks was much greater in Al-Tebbin than in Dokki. In Dokki (urban), Pb was followed by Ni with contributions of c. 28 and 29% for children and adults, respectively, then As with c. 17% for both age groups. The contribution of Cr(VI) and Cd ranged from c. 4 to 8% and the contribution of Co was almost negligible (<0.1%). In Al-Tebbin (industrial), Ni also came second to

Fig. 6 Contribution (%) of individual $PM_{2.5}$ metalloids to the modelled non-carcinogenic and carcinogenic risks through all exposure routes (ingestion, dermal and inhalation) combined. Data are displayed for children and adults in Dokki urban and Al-Tebbin industrial areas. Full data can be found in Tables A6 and A7 (Appendix A)



Pb but with only c. 9% contribution for children and adults, followed by As, Cr(VI) and Cd (c. 2 – 5% for all of them combined), whereas the contribution of Co was negligible (< 0.5%) (Fig. 6 and Tables A6 and A7).

Exposure Route Contribution

For all metal(loid)s combined, ingestion was the major route of exposure for both non-carcinogenic and carcinogenic risks to children and adults in urban and industrial Greater Cairo with a minimum contribution of c. 52% and a maximum of 92% (Fig. 7 and Tables A6 and A7). Contributions of dermal and inhalation routes were generally insignificant compared to ingestion with the exception of non-carcinogenic risks for adults in both areas, where inhalation showed very considerable contributions of c. 39 and 44%, respectively (Fig. 7).

The considerably higher ingestion contribution to the total carcinogenic and non-carcinogenic risk of $PM_{2.5}$ associated toxins compared to inhalation has been reported in many other studies (Hu et al. 2012; Fang et al. 2013; Izhar et al. 2016; Othman et al. 2019; Guo et al. 2022; Alghamdi et al. 2023). This is likely due to the intrinsic features of the USEPA ingestion vs inhalation models which assume higher exposure rates and bio-accessibility through ingestion than through inhalation for most of the studied metal(loid)s (USEPA 1989). However, the relatively higher contribution of inhalation to adults' non-carcinogenic risks, in comparison to children, is a result of the development of the updated USEPA inhalation exposure equation (Eq. 3) (USEPA 2009) compared to the original one (USEPA 1989). The updated equation was developed in response to general concerns that exposure to toxic elements through inhalation is not a simple matter of inhalation rate versus body weight but is rather a function of the amount of the toxic substance that reaches its specific target site (USEPA 2009). Therefore, inhalation rate and body weight were not included in the updated inhalation equation resulting on equal non-carcinogenic inhalation HQs (hazard quotients) for adults and children (Tables A6 and A7; Appendix A). With lower absolute ingestion and dermal HQs for adults than children, the inhalation contribution (%) became significantly larger for adults (Fig. 7).

For individual metal(loid)s, the relative contribution of each exposure route varied between elements, sampling location and age groups. Almost all (c. 93 – 97%) of Pb non-carcinogenic and carcinogenic risks originated from ingestion; this was the case for children and adults in urban and industrial Greater Cairo. This absolute dominance of ingestion over other routes was also observable for the non-carcinogenic risks of Fe, Cu and Zn (they have no carcinogenic potential) in both areas and for adults and children (Tables A6 and A7; Appendix A). For Al, Co, As and Cd, ingestion was also the highest contributor to non-carcinogenic risks (> 65%), but for children only, whereas for adults, inhalation was also a major contribution route (30 – 84%). However, for carcinogenic risks, ingestion remained the dominant As and Cd exposure route (> 78%) for both age groups and in both locations (Tables A6 and A7; Appendix A). Vanadium and Cr(VI) displayed the highest dermal contribution (up to 52%) to non-carcinogenic risks among all the studied 12 metal(loid)s. The superior contribution of dermal exposure was also true for the carcinogenic risks of Cr(VI), although it was superseded by inhalation for adults in Al-Tebbin industrial area (Tables A6 and A7; Appendix A). On the other hand, inhalation was the major exposure route for the non-carcinogenic risks of Mn and Ni in all scenarios (up to c. 90%), but was almost negligible for the carcinogenic risks of Ni to which ingestion and dermal routes contributed almost equally for both age groups in urban and industrial Greater Cairo (Tables A6 and A7; Appendix A).

This route contribution analysis explains the discrepancies between the health risks as estimated by comparing annual levels of $PM_{2.5}$ metal(loid)s with the WHO

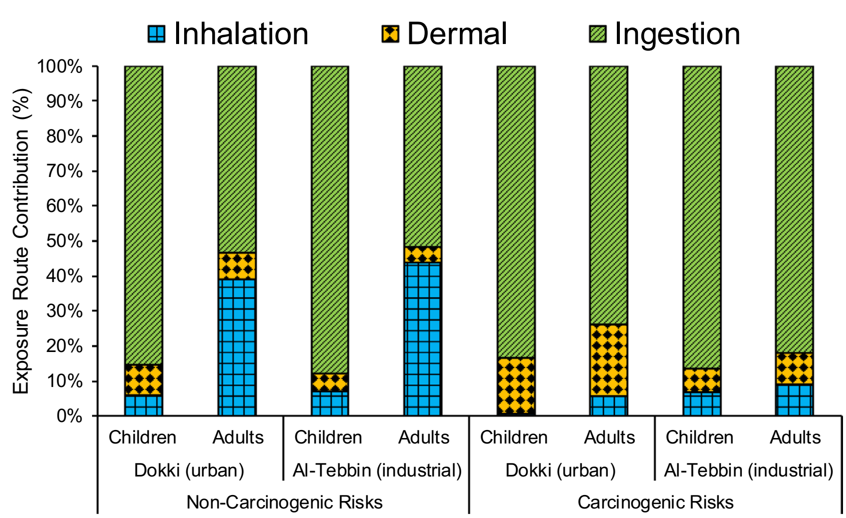


Fig. 7 Contribution (%) of each exposure route (all $PM_{2.5}$ metal(loid)s combined) to the non-carcinogenic and carcinogenic risks for children and adults in Dokki urban and Al-Tebbin industrial areas. Full data can be found in Tables A6 and A7 (Appendix A)

guidelines (Sect. "PM2.5 associated metal(loid)s"), and the projected health risks through non-carcinogenic and carcinogenic USEPA models (Sects. Non-carcinogenic hazard indices and Carcinogenic risks). The most obvious example is Pb; although its annual level in urban and industrial Greater Cairo was lower than the WHO guidelines values (Table 2), but USEPA models showed that it is the single highest non-carcinogenic and carcinogenic threat to the health of Greater Cairo residents. This is mainly due to the fact that the WHO air quality guidelines for toxic metals (WHO 2000) is focused on inhalation as the major exposure route of humans to air pollutants. As we discussed earlier in this section, most of Pb non-carcinogenic and carcinogenic risks originated from ingestion rather than inhalation. The inhalation risks of Pb were actually negligible which agrees with the WHO guidelines. This is also true for the other elements which either have WHO air concentration guidelines values or have no recommended safe levels, e.g. V, Cr(VI), Mn, Ni, As and Cd (Table 2). In fact, the carcinogenic and non-carcinogenic inhalation risks from 'individual' metal(loid)s were insignificant for children and adults in urban and industrial Greater Cairo (Tables A6 and A7; Appendix A). Only the inhalation non-carcinogenic risks from 'all elements combined' were higher than the safe HI threshold of 1. For the 2 elements that had high inhalation contribution to their non-carcinogenic risks (Mn and Ni), their absolute HIs from inhalation (and other routes) were still below 1. This means that they pose no risk at the current levels, but at higher levels, their non-carcinogenic risks will mainly originate from inhalation.

Conclusions and Outlook

Our results suggest that $PM_{2.5}$ and its chemical composition in Greater Cairo are in general temporally homogeneous but spatially heterogeneous, i.e. they are mainly a function of land use and anthropogenic activities rather than being affected by meteorological conditions, which is likely due to the mostly non-turbulent weather of Egypt.

Projected health risks using USEPA models suggested that most of the non-carcinogenic risks originated from Pb and As. For carcinogenic risks, Pb was also the highest carcinogenic threat followed by Ni then As. This may seem contradictory to the fact that $PM_{2.5}$ Pb annual average concentrations in Greater Cairo atmosphere were generally lower than the WHO air quality guideline value of 0.5 μg m^{-3}. However, exposure route analysis showed that most of the Pb risk originated from ingestion rather than inhalation, which was the case for most of the studied elements with the exception of a few scenarios where inhalation or dermal exposure prevailed.

This ingestion exposure dominance means that the overall non-carcinogenic and carcinogenic risks from the investigated elements are likely greater than the values recorded in this work. This is simply because ingestion (and dermal) risks can originate from suspended PM from all sizes and not solely from $PM_{2.5}$. Since the concentration of any toxic element or substance in total suspended particulates (TSP) is normally higher than its corresponding values in $PM_{2.5}$, this will certainly lead to higher health risk potential. It is thus recommended that in future studies both TSP and $PM_{2.5}$ associated toxins should be measured and used for the estimation of ingestion/dermal and inhalation exposure, respectively.

Another point that should be also taken into account is that, in addition to the non-carcinogenic and carcinogenic risks of $PM_{2.5}$ loaded metal(loid)s, $PM_{2.5}$ particles have direct impact on the human body exclusively through inhalation, e.g. respiratory infections, bronchitis, cardiovascular diseases and premature death. So, although the risks from inhalation were found here to be minimal, this is only valid for the carcinogenic and non-carcinogenic risks inflicted by the 12 $PM_{2.5}$ associated metal(loid)s investigated in this work.

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Authors contribution Waleed H. Shetaya constructed the original draft. Salwa K. Hassan arranged the administrative, logistical and financial support. Waleed H. Shetaya, Asmaa El-Mekawy and Salwa K. Hassan contributed to the other aspects of this work including selection of the methodology, laboratory and field work, data curation and analysis, and editing the final version of this manuscript.

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Data Availability Supplementary materials (Appendix A) include most of this work research data that cannot be found in the main article.

Code Availability Not Applicable.

Declarations

Conflict of Interest The authors declare no conflict of interest.

Consent to Participate Not Applicable (No human participants involved).

Animal Research Not Applicable (No animal subjects involved).

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