



Evaluation of air quality and health risks associated with trace elements in respirable particulates (PM_{2.5}) from Islamabad, Pakistan

Rashida Nazir · Munir H. Shah

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Abstract Fine atmospheric particulates are associated with numerous environmental and health issues as they can penetrate deeply in the respiratory tract thereby adversely affecting the human health. This study aimed to investigate the concentrations of trace elements in the respirable (PM_{2.5}) fraction of the atmospheric particulates and to understand their pollution status and health risks. The samples were collected from Islamabad, and the metals were extracted using HNO₃ and HCl based extraction method. Atomic absorption spectroscopy was employed to quantify the concentrations of selected trace elements. PM_{2.5} exhibited considerable variations in their minimum (4.737 µg/m³) and maximum (108.1 µg/m³) levels. The significant contributors among the selected elements bound to PM_{2.5} were Ca (1016 ng/m³), K (759.8 ng/m³), Mg (483.0 ng/m³), Fe (469.7 ng/m³), and Zn (341.1 ng/m³), while Ag (0.578 ng/m³) was found at the lowest levels with an overall descending order: Ca > K > Mg > Fe > Zn

> Cu > Pb > Ni > Cd > Mn > Sr > Cr > Co > Li > Ag. Multivariate PCA and CA identified industrial activities, combustion processes and automobile emissions as the main anthropogenic contributors to particulate pollution. Enrichment factors and geoaccumulation indices were computed to assess the pollution status. The results also revealed that among the trace elements, Cd showed extremely high contamination, followed by Ag, Zn, and Pb, which showed moderate to high contamination in the atmospheric particulates. Carcinogenic health risks from Pb and Ni were found to be within the safe limit (1.0×10^{-6}); however, Cr, Co, and Cd exposure was linked to significant cancer risks. The present elemental levels in PM_{2.5} were also compared with the reported levels from other regions around the world.

Keywords Toxic metal · Pollution index · Health hazard · Ecological risk · AAS · Multivariate analysis

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R. Nazir
Department of Chemistry, Mirpur University of Science and Technology, Mirpur 10250, Pakistan

R. Nazir · M. H. Shah (✉)
Department of Chemistry, Quaid-I-Azam University,
Islamabad 45320, Pakistan
e-mail: mhshahg@qau.edu.pk; munir_qau@yahoo.com

Introduction

Air pollution is a matter of great concern because it can seriously harm both people and the environment. Atmospheric pollution is a serious threat on the global level and has been a persistent problem for decades due to unregulated industrial development and growing urbanisation (Li et al., 2022; Lima et al., 2021; Ramírez et al., 2020). According to a recent finding, one out of every eight people dies due to air pollution

(Vural, 2020). Lung diseases are associated with 23% of the deaths caused by air pollution, as are cardiovascular disease (19%), ischemic disease (24%), and stroke (21%) (Sahu et al., 2021). The World Health Organization (WHO) reported that approximately 91% of the global population lives in the areas where pollutant levels surpass the guideline value (WHO, 2019). Air pollutants such as, nitrogen oxides, sulphur oxides, volatile organics, stratospheric ozone, and atmospheric particulates are the most studied pollutants because they exhibit detrimental effects on humans, deteriorate the environment, and change the climate (Alves et al., 2023; Kalaiarasan et al., 2018; Oliveira et al., 2021; Zhao et al., 2023).

Airborne particulates (including $PM_{2.5}$, PM_{10} , and TSP) are a condensed mixture of microscopic solid particles and liquid droplets in the atmosphere that involve atmospheric progression (Brodny & Tutak, 2021). Amongst these, fine/respirable particulate matter ($PM_{2.5}$) has gained much attention and is regarded as more hazardous in the atmosphere (Ahmad et al., 2021; Liu et al., 2020; Mehmood et al., 2020). According to the state of global air report, most of the world-wide population (>90%) is susceptible to $PM_{2.5}$ concentrations that exceed WHO guidelines, with developing nations particularly more exposed (State of Global Air Report, 2020). The leading anthropogenic sources of airborne particles are forest fires, biofuel combustion, solid waste, and the open burning of municipal/domestic, and farming wastes. Similarly, uncontrolled industrial growth, brick kilns, power plants, crushing and foundries, cement manufacturing, iron/steel industries, and mining are important anthropogenic sources (Liu et al., 2020; Silva et al., 2022). Different photochemical reactions can also produce fine particulates in the atmosphere (Lv et al., 2019). Inhalation of $PM_{2.5}$ has detrimental influence on human health because respirable particulates can easily enter the human respiratory system, accumulate in the inner parts of lungs, and may cause respiration problems (Schwela & Haq, 2020). Exposure to $PM_{2.5}$ is also linked with an increased risk of emphysema, strokes, and chronic obstructive pulmonary disease. Around 90% of the preventive fatalities take place in low-income and overpopulated countries due to the increased prevalence of these diseases, especially in Southeast Asia and the Pacific regions (WHO, 2021a). Previous studies have demonstrated that exposure to elevated $PM_{2.5}$ levels can cause early death and

disruption to the sensory organs, cellular structure, and function (Nair et al., 2020; Tong, 2019). The studies also revealed that $PM_{2.5}$ contents exceeding $10 \mu\text{g}/\text{m}^3$ are linked with a 4% rise in pulmonary fatalities, a 9% rise in respiratory diseases, and a 17% increase in cardiovascular diseases (Bayat et al., 2019). These airborne particulates also result in diminished radiation balance and impaired visibility (Chen et al., 2021; Jain et al., 2020; Wang et al., 2019).

Asian states, particularly developing nations in South Asia, are experiencing extreme particulate pollution from increasing suspended particulate levels. According to the latest survey, the South Asian nations such as, Bangladesh, India, and Pakistan have the worst air quality (Anjum et al., 2021). Some of the Pakistani cities, particularly Lahore has been reported as the world's worst polluted city with very poor air quality index (Anjum et al., 2021). The mean concentration of $PM_{2.5}$ in Lahore and Islamabad were reported as $115 \mu\text{g}/\text{m}^3$ and $47.3 \mu\text{g}/\text{m}^3$, respectively. During winter season, these urban areas are severely affected by elevated levels of $PM_{2.5}$ which may originate from various regions, including the north-western countries (Afghanistan, Iran, and Turkmenistan) and southern countries (India, China, and Nepal). In addition, unplanned urbanization and growing industrial activity have created an unhealthy environment in Pakistan, and anthropogenic emissions are causing the air quality to deteriorate (Lv et al., 2019; Mehmood et al., 2018). Some earlier studies reported from Pakistan showed considerably higher levels of respirable particulates in the local atmosphere, and they also exhibited significant annual and seasonal variations (Lv et al., 2019; Mehmood et al., 2018; Rasheed et al., 2015). However, the comprehensive evaluation related to the characterization of the respirable particulates ($PM_{2.5}$) for toxic trace elements and the discussion of their health risks and toxicity is inadequate. There is a dire need to characterise the prevailing levels of toxic elements and related health risks in the respirable particulate matter in the capital city, Islamabad. The present study aimed to understand the distribution of trace elements and their mutual relationships to estimate their anthropogenic contamination and enrichment in the urban airborne particulates. Association of the pollutant levels with the carcinogenic and non-carcinogenic risks were

also evaluated in this study. The measured levels of trace elements in PM_{2.5} were compared with the reported levels from other regions. The findings of this study will help to identify the sources of trace elements, associated health risks, and their toxicity to both people and the environment, as well as it would help to control the pollution levels.

Experimental methodology

Site description and sample collection

Sampling was performed in the federal capital of Pakistan, Islamabad, which is located about 500 m above sea level (Latitude 33° 49' N; Longitude 72° 24' E). It covers an area of more than 900 km² and has a population of about 2 million. It is flanked on three sides by the Margalla Hills to the north, the Punjab Plains to the east, and water bodies to the west. It lies 14 kms northeast of Rawalpindi (Mehmood et al., 2020). Islamabad has four distinct seasons throughout the year due to its subtropical climate: a hot and wet summer (June to August), a dry autumn (September to November), a cold and rainy winter (December to February), and a pleasant spring (March to May). The Kahuta industrial estate, the industrial sectors (I-9 and I-10), and vehicle exhaust are the main sources of air pollution in the city. The primary industries in the city are pottery, flour mills, paint, dyes, medicines, metallurgy, granite, and oil and ghee plants.

To perform detailed chemical analysis, fine atmospheric particulates (PM_{2.5}) were collected on quartz fibre filter papers using a sequential air sampler (DPM5, AMS Analytica, Italy) which was installed on a rooftop about 30 feet from the ground and distant from other nearby buildings. The air sampler was equipped with an automatic flow rate controller, and samples were collected following the EU standard method (CEN, 2005). The sampling was performed in a typical urban area of Islamabad (Quaid-i-Azam University campus). The particulate samples were collected for 12–24 h. Before and after the sample collection, the mass of filter papers was determined gravimetrically using standard methodology (CEN, 2005).

Sample preparation

The particulate samples were further processed to prepare the solutions for trace elemental analysis following the USEPA methodology (Method IO-3.1, 1999). The acid extraction method was used to extract the elements on a hot plate. The filters containing particulates were folded in half along the length with the sample material facing inward and cut into 1"×8" strips. The filter pieces were placed at the bottom of a labelled 100-mL bottle to make sure that acid should completely cover the filter paper. Then 50 mL of the extraction mixture (5.6% nitric acid and 16.8% hydrochloric acid, (v/v)) was added to the vessel and placed on the hot plate in a fume hood. The mixture was refluxed smoothly for 60 min. The flasks were then removed from the hot plate and allowed to cool. The digestate thus formed was filtered using Whatman filter paper (No. 42). Each solution was filtered in a volumetric flask (50 mL) and diluted up to the mark with a 0.1 N nitric acid solution. The blanks (which contained only a filter and reagents) was also prepared using the same method. The glassware was carefully cleaned by immersing it in a 5% HNO₃ solution (v/v) for 24 h, then washed with distilled water and dried in an oven (70 °C) overnight. The filter papers were placed in a humidity-controlled desiccator (containing silica gel) for 24 h before and after the sample collection. The mass of the particulates was determined with an electronic balance and stored in an airtight Ziplock plastic bag. Each batch also included a reagent blank, which passed through the same process as the samples.

Quantification of the trace elements

In the present study, an atomic absorption spectrometer (Shimadzu AA-670, Japan) was employed for the quantification of selected trace elements (Fe, Ca, Co, Mg, Cu, Mn, Zn, K, Li, Sr, Cd, Ag, Cr, Ni, and Pb) in the atmospheric particulate samples (Method IO-3.2, 1999). Using the calibration line, which demonstrated a strong correlation coefficient (>0.990), the trace elements in the samples were quantified under the optimum analytical conditions which are given in Table S1 (supplementary material). Using stock solutions (1000 mg/L), freshly prepared working standards were used for each element. To justify the

validity of the quantitative results, standard reference material (NIST SRM-2711) was evaluated which showed excellent recovery as given in Table S2 (supplementary material). An interlaboratory comparison of the results was also performed, and it was found that there was less than a 2% divergence between them. It was also recorded that the blank contribution for each element was less than 5% of the measured values. Similar analytical procedures were reported by several authors (Jain et al., 2020; Ramírez et al., 2019; Rojas et al., 2019).

Statistical analysis

The quantified data were then subjected to statistical analysis comprising of minimum, maximum, mean, median, standard deviation (SD), standard error (SE), kurtosis, and skewness. The analysis revealed relative distribution, variations, and dispersion of the individual variables. The mutual relationships between the variables in the particulate matter were investigated using correlation coefficients. Furthermore, the data were subjected to multivariate statistical techniques, including cluster analysis and principal component analysis which defined the pollution profile of the contaminants in the particulates (Alves et al., 2023). Multivariate methods enhance the worth of the extensive data by consolidating it into smaller, easy, and relatively simple groups. Additionally, pollution assessment, ecological risk measurement, and health risk evaluation for trace elements in the atmospheric particulates were accomplished as described in results and discussion section.

Pollution assessment

The pollution index was assessed by evaluating the elemental levels in airborne particles by computing the enrichment factor (EF) and geoaccumulation index (I_{geo}).

Enrichment factor

The enrichment factor (EF) of the trace elements was computed to objectively evaluate how human activities affected the levels of the elements present in the particulate samples. It usually illustrates the extent of environmental contamination and the pollution level of the elements in the particulates. It is

regarded as a valuable tool for separating components from human activities from those of natural sources (Alves et al., 2023). The following relationship is used to calculate it:

$$EF = \frac{[X/M_{ref}]_{sample}}{[X/M_{ref}]_{crust}}$$

X represents the mean level of the target element and M_{ref} indicates the average level of the reference element in the analysed particulates/sample (ng/m^3) and background soil/crust (mg/kg). Although various elements can be employed as reference elements; Fe was selected in this study.

Geoaccumulation index

Geoaccumulation index (I_{geo}) is a geochemical criterion for assessing particulates' environmental contamination and pollution levels and it was computed by following relationship:

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5B_n} \right)$$

" C_n " denotes the element's measured concentration in the particles, and " B_n " is the geochemical background value in the soil. Factor (1.5) is employed to minimise the anthropogenic influences and probability of pre-industrial levels varying due to lithogenic factors.

Ecological risk assessment

Significant enrichment of trace elements in the atmosphere can disturb the equilibrium of natural environment and thus may exhibit lethal effects on microbes, animals, plants, and people. The degree of particle-bound contamination of trace elements has been assessed using the ecological risk index (RI). This variable determines the levels of the trace elements and their toxic impacts. The following expression was used for the calculation of trace metals' toxic responses:

$$RI = \sum_{i=1}^m E_r^i$$

' E_r ' represents the ecotoxicological threat factor of the elements, and ' T_r ' represents the element's toxic reaction factor, which is linked with its ability for

emission and the relative amounts in various mediums, including igneous rock, soil, freshwater, terrestrial plants, terrestrial animals, etc.

Human health risk assessment

Generally, the people are exposed to trace elements through direct oral consumption, dermal contact, and inhalation (Jayarathne et al., 2018; Zhang et al., 2018). The contribution of different materials varies widely through these routes; however, for inhalable atmospheric particulates, inhalation is considered as the primary exposure route (Alves et al., 2023; Zhang et al., 2018). Therefore, the health risk was computed for inhalation exposure in this study. Exposure concentration through inhalation (EC_{inh} , $\mu\text{g}/\text{m}^3$) can be calculated as per USEPA methodology (USEPA, 2016a):

$$EC_{inh} = C \times \frac{ET \times EF \times ED}{AT_n}$$

Here, C is the average concentration, ET, EF, and ED refer to the exposure time (days), exposure frequency (days/years), and exposure duration (years), respectively, while AT_n is the average lifetime (years). The non-carcinogenic risk was assessed by computing the hazard quotient (HQ) applying the USEPA methodology (Behrooz et al., 2021; USEPA, 2016a):

$$HQ_{inh} = \frac{EC_{inh}}{RfCi \times 1000}$$

' $RfCi$ ' is the inhalation reference concentration ($\mu\text{g}/\text{m}^3$). A hazard quotient value less than one is generally considered safe or non-hazardous. The hazard index (HI) was calculated in terms of the arithmetic sum of all elements' HQs, to determine the total non-carcinogenic risks. If HI is less than unity, there is no noticeable potential risk to the people.

The lifetime cancer risk (CR), which illustrates the gradual probability that people may develop cancer throughout their lives because of exposure to toxic elements by inhalation was calculated to determine the cancer risk. It was estimated by the following relationship (USEPA, 2016a; Zhang et al., 2018):

$$CR_{inh} = EC_{inh} \times IUR$$

'IUR' refers to the inhalation unit risk. The CR of Pb, Ni, Cd, Cr, and Co (via inhalation) was evaluated in this investigation because the CSF values for

these hazardous elements are only available through inhalation. It is an indicative parameter of the lifelong carcinogenic threat to the local people. The carcinogenic risk is generally perceived as significant if the CR value is greater than 1.0×10^{-6} , and people may develop cancer because of the lifetime exposure to harmful substances.

Results and discussion

Appraisal of $PM_{2.5}$

Basic statistical parameters related to the distribution of respirable particulates ($PM_{2.5}$) and selected trace elements in the atmosphere of Islamabad are shown in Table 1. $PM_{2.5}$ showed significant variations in the local atmosphere, ranging from a minimal of $4.737 \mu\text{g}/\text{m}^3$ to a highest of $108.1 \mu\text{g}/\text{m}^3$. The average and median levels of $PM_{2.5}$ were found at 44.09 and $41.69 \mu\text{g}/\text{m}^3$, respectively. Appreciable dispersion was found in $PM_{2.5}$, as shown by reasonably higher standard deviation and standard error values, while skewness and kurtosis indicated the moderately random distribution of the particulates. A substantial decrease in the concentrations of fine particulate matter ($44.09 \mu\text{g}/\text{m}^3$) was noticed in this investigation because the present mean contents were relatively lower than majority of the earlier reported concentrations. For instance, Rasheed et al. (2015) stated that the annual mean contents of $PM_{2.5}$ in the atmosphere of Islamabad were 79.0 and $66.1 \mu\text{g}/\text{m}^3$ in 2010 and 2011, respectively. Likewise, another study reported that in 2016 and 2017, the annual levels of $PM_{2.5}$ were 70 and $44.5 \mu\text{g}/\text{m}^3$, respectively (Lv et al., 2019). Similarly, Mehmood et al. (2018) showed four separate sets of temporal data with respirable particulate matter levels of 69.97 (winter), 51.40 (fall), 44.54 (summer), and $40.45 \mu\text{g}/\text{m}^3$ (spring) during 2017 for Islamabad. However, the current average $PM_{2.5}$ levels ($44.09 \mu\text{g}/\text{m}^3$) exceeded the recommended limits set by both WHO ($15 \mu\text{g}/\text{m}^3$) and Pakistan ($25 \mu\text{g}/\text{m}^3$). Elevated levels of $PM_{2.5}$ in Islamabad may result from multiple factors, such as, an increase in vehicular traffic, outdated automobiles, reliance on filthy fuels (petrol and diesel), and unrestrained emissions sources. The higher concentration of $PM_{2.5}$ can lead to severe health problems including difficulty breathing, skin allergies, cardiovascular issues, and even

Table 1 Statistical distribution parameters for PM_{2.5} (µg/m³) and concentrations of trace elements (ng/m³) in the atmospheric particulates of Islamabad

	PM _{2.5}	Cd	Cr	Ni	Pb	Mn	Cu	Co	Ag	Li	Sr	Ca	Mg	K	Zn	Fe
Min	4.737	1.218	0.616	0.203	1.129	2.012	7.229	0.041	0.041	0.103	1.109	214.1	42.71	34.91	25.87	57.91
Max	108.1	18.50	7.831	19.56	80.90	56.41	175.3	11.97	2.826	4.764	14.90	3303	1081	1426	795.8	1382
Mean	44.09	8.696	3.648	6.810	27.69	14.75	40.99	2.814	0.578	1.237	7.015	1061	483.0	759.8	341.1	469.7
Median	41.69	8.728	3.491	6.417	22.06	13.04	18.69	1.925	0.411	1.109	7.270	937.6	453.6	820.9	292.4	393.9
SD	26.18	4.794	1.500	5.087	20.51	9.738	42.24	2.991	0.639	0.837	3.067	652.5	219.4	317.0	235.9	303.7
SE	3.595	0.749	0.206	0.776	2.844	1.338	5.801	0.485	0.121	0.115	0.425	90.48	30.14	46.74	36.84	41.72
Kurtosis	0.198	-0.863	0.080	-0.071	-0.110	6.734	2.612	1.756	6.273	4.913	0.230	2.264	0.255	0.333	-0.915	0.893
Skewness	0.745	0.180	0.429	0.716	0.794	2.198	1.695	1.496	2.474	1.625	0.370	1.318	0.598	-0.372	0.395	1.025

hospitalization. Additionally, poor air quality can result in loss of workdays, which can significantly impact the financial sector. The increased healthcare costs and reduced working efficiency due to poor air quality can severely affect the economy. Moreover, elevated concentrations of the atmospheric particles can cause a hazy appearance in the city that can obscure the visibility. Nonetheless, the mean concentration of PM_{2.5} demonstrated a gradual decline in preceding years, which indicated that the particulate concentration has noticeably decreased. It may be attributed to the improvement in the infrastructure and transport system by introducing the improved metro system.

Distribution of trace elements in PM_{2.5}

The mean concentration of the selected trace elements (Table 1) revealed that Ca (1016 ng/m³), K (759.8 ng/m³), Mg (483.0 ng/m³), Fe (469.7 ng/m³), and Zn (341.1 ng/m³) showed relatively higher contributions, while Cu (40.99 ng/m³) exhibited relatively lower levels, followed by Pb (27.69 ng/m³), Mn (14.75 ng/m³), and Cd (8.696 ng/m³). The lowest average levels were observed for Li (1.237 ng/m³) and Ag (0.578 ng/m³) in the respirable particulates, as shown in Table 1. The variability in elemental concentration was examined in terms of range and standard deviation/standard error values, which revealed appreciable variations in their levels in the local atmosphere. Overall, most of the elements showed significant dispersion and random distribution, as indicated by large variations in their maximum and minimum levels and diverse mean and median levels. Significant lopsidedness in the distribution was observed for Pb, Ag, Cu, Li, Co, and Ca in the respirable particulates, as demonstrated by higher kurtosis and skewness values.

Average concentrations of trace elements in the respirable particulates revealed following ascending trend: Ag < Li < Co < Cr < Ni < Sr < Cd < Mn < Pb < Cu < Zn < Fe < Mg < Ca < K. The quartile distribution of PM_{2.5} and atmospheric trace elements is shown in Fig. S1 (supplementary material). A widespread and sporadic distribution was noticed for particulate metals, including Co, Ag, Pb, Ni, Li, K, Zn, Cu, and Mg. In contrast, relatively narrow and symmetrical distribution was shown for Ca, Cr, Cd, Sr, and PM_{2.5}. Overall, most of the elements exhibited random and significantly distorted distribution in the fine

Table 2 Correlation coefficient (*r*)* matrix for PM_{2.5} and selected elemental levels in the atmospheric particulates

	PM _{2.5}	Cd	Cr	Ni	Pb	Mn	Cu	Co	Ag	Li	Sr	Ca	Mg	K	Zn	Fe
PM _{2.5}	1.000															
Cd	0.063	1.000														
Cr	0.177	0.085	1.000													
Ni	0.490	0.010	0.097	1.000												
Pb	0.090	0.109	0.223	0.051	1.000											
Mn	0.642	0.043	0.463	0.302	0.282	1.000										
Cu	-0.151	0.072	0.371	-0.032	0.226	-0.017	1.000									
Co	0.103	-0.093	-0.147	0.139	0.094	0.111	0.079	1.000								
Ag	-0.043	-0.107	0.068	-0.103	-0.102	-0.199	-0.051	0.471	1.000							
Li	0.141	0.146	0.716	0.194	0.256	0.599	0.349	-0.068	-0.236	1.000						
Sr	0.514	0.155	0.038	0.171	0.106	0.656	-0.151	-0.155	-0.487	0.280	1.000					
Ca	0.324	-0.103	-0.135	-0.125	0.131	0.321	-0.384	-0.028	-0.023	-0.271	0.336	1.000				
Mg	0.525	0.095	0.467	0.160	0.246	0.824	-0.020	0.211	-0.129	0.453	0.593	0.489	1.000			
K	-0.287	-0.255	-0.014	-0.288	0.086	-0.191	-0.060	0.062	0.363	-0.129	-0.297	0.123	-0.177	1.000		
Zn	-0.180	0.207	0.367	0.040	0.310	0.100	0.624	0.053	-0.097	0.647	0.109	-0.437	0.044	0.134	1.000	
Fe	0.698	0.014	0.354	0.228	0.162	0.942	-0.147	0.126	-0.190	0.415	0.641	0.472	0.842	-0.168	-0.185	1.000

* *r*-values shown in bold are significant at *p* < 0.05

particulates, indicating considerable anthropogenic influence or impact on the level of trace elements in the local atmosphere.

Correlation of PM_{2.5} and trace elements

The correlation coefficients among the selected trace elements and PM_{2.5} are demonstrated in Table 2, where the statistically significant coefficient (*r*) values are indicated in bold. PM_{2.5} showed strong and significant direct relationships with Fe (*r*=0.698), Mn (*r*=0.642), Mg (*r*=0.525), Sr (*r*=0.514), Ni (*r*=0.490), and Ca (*r*=0.324). Among the trace elements, strong correlations (*r*>0.700) were observed among Fe–Mn (*r*=0.942), Fe–Mg (*r*=0.842), Mg–Mn (*r*=0.824), and Cr–Li (*r*=0.716), followed by some strong associations between Sr–Mn (*r*=0.656), Zn–Li (*r*=0.647), Fe–Sr (*r*=0.641), Zn–Cu (*r*=0.624), Mn–Li (*r*=0.599), and Mg–Sr (*r*=0.593). Some statistically significant correlations were also observed among Cr–Mn, Cr–Cu, Mg–Cr, Zn–Cr, Fe–Cr, Mn–Ni, Pb–Zn, Ca–Mn, Cu–Li, Co–Ag, K–Ag, Mg–Li, Fe–Li, Ca–Sr, Ca–Mg, and Ca–Fe (Table 2).

The correlation study, therefore, revealed mutual associations and probably similar source of Fe, Mn, Mg, Sr, and Ca in the atmospheric particulates. Similarly, Cr, Li, Zn, Cu, and Pb revealed strong or significant mutual associations in the fine particulates. The first set of elements was primarily derived from lithogenic sources, whereas the second set was largely considered anthropogenic. Conversely, a few pairs exhibited significant inverse relationships: Sr–Ag (*r*=-0.487), Ca–Zn (*r*=-0.437), and Ca–Cu (*r*=-0.384), thereby implying opposite variations in the atmospheric particulates. It was interesting to note that Cd exhibited statistically insignificant correlations with all other elements; it may be ascribed to its multiple source origin and diverse variations in the inhalable atmospheric particulates.

Pollution assessment

Evaluation of the anthropogenic influence on trace elemental burden in the atmospheric particulates was an essential part of the present investigation. It was evaluated by computing the enrichment factors and geoaccumulation indices, as shown in Fig. 1. The *EF* is usually utilized to establish trace elements'

anthropogenic pollution level. It is mainly interpreted in the following categories: *EF*<10 shows the crustal source of the metals, while *EF*>10 proposes the primary anthropogenic source of the element. An *EF* of 10–100 implies that the metals are moderately enriched, while *EF*>100 signifies anomalous enrichment of the elements in the particulates. As shown in Fig. 1a, among the selected trace elements, the highest *EF* in the atmospheric particulates was observed for Cd, followed by Ag, Zn, Cu, and Pb; all these elements were enormously enriched in the atmospheric particulates. Nonetheless, moderate enrichment was noted for Ni and Co in the local atmosphere, while the rest of the elements were mainly derived from lithogenic sources or crustal materials.

The average geoaccumulation index (*I*_{geo}) of various trace elements is shown in Fig. 1b for comparative assessment. Generally, *I*_{geo} is taken as follows: *I*_{geo}≤0 unpolluted, 0<*I*_{geo}≤1 shows unpolluted to moderately polluted, 1<*I*_{geo}≤2 shows moderately polluted, 2<*I*_{geo}≤3 shows moderately to deeply polluted, 3<*I*_{geo}≤4 shows severely polluted, 4<*I*_{geo}≤5 shows severely to extremely polluted, and *I*_{geo}≥5 shows extremely contaminated. Accordingly, among the trace elements, Cd revealed extreme contamination, followed by Ag, which showed moderate to heavy contamination, while Zn and Pb exhibited moderate contamination in the atmospheric particulates. The *I*_{geo} values for the rest of the elements were <0, indicating the uncontaminated status of these elements in the atmospheric particulates. Overall, the pollution assessment revealed considerable anthropogenic impacts of Cd, Ag, Pb, and Zn in the local atmosphere.

Source apportionment

Source apportionment and identification of the elements in the atmospheric particulates was another important part of this investigation. It was accomplished using principal component analysis (PCA) and cluster analysis (CA). PC loadings of PM_{2.5} and trace elements are shown in Table 3, and the corresponding CA is shown in Fig. S2 (supplementary material). Five significant PCs with eigen values exceeding unity were obtained by varimax normalized rotation on the dataset, explaining about 71% of the cumulative variance. PC 1

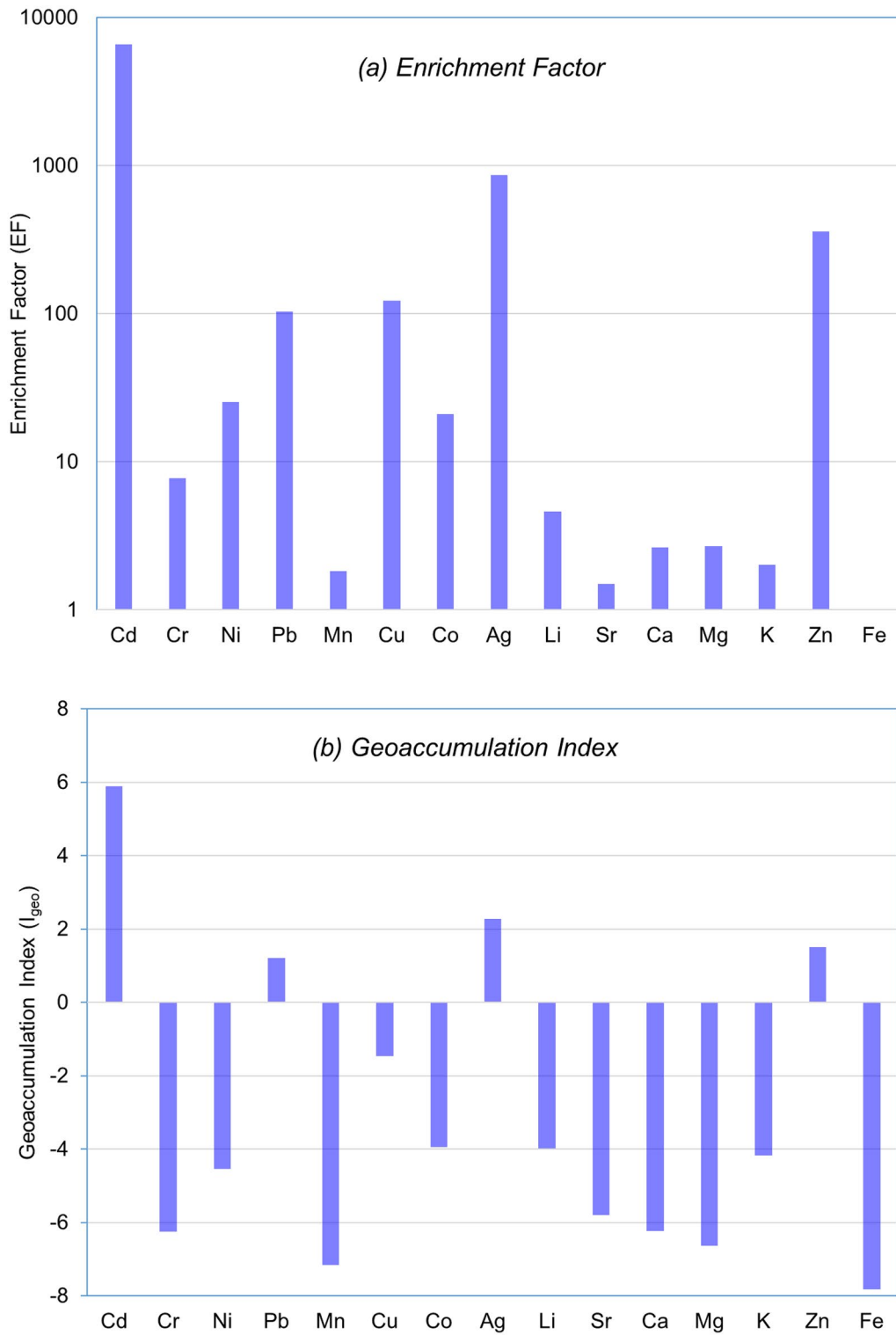


Fig. 1 Comparison of average **a** enrichment factors and **b** geoaccumulation indices of selected elements in the atmospheric particulates

Table 3 Principal component analysis of PM_{2.5} and selected elemental levels in the atmospheric particulates

	PC 1	PC 2	PC 3	PC 4	PC 5
Eigen value	4.673	2.686	1.644	1.370	1.060
Total Variance (%)	29.21	16.79	10.27	8.565	6.625
Cumulative Variance (%)	29.21	46.00	56.27	64.83	71.46
PM2.5	0.714	-0.128	0.122	-0.415	0.010
Cd	0.002	0.074	-0.117	-0.184	0.659
Cr	0.376	0.746	-0.052	0.019	-0.274
Ni	-0.223	-0.084	-0.180	0.702	0.050
Pb	0.285	0.303	0.167	0.331	0.489
Mn	0.926	0.232	-0.027	-0.129	-0.003
Cu	-0.186	0.737	0.085	0.010	0.219
Co	0.082	-0.014	0.836	-0.098	0.149
Ag	-0.128	-0.026	0.730	0.113	-0.273
Li	0.403	0.792	-0.179	-0.130	-0.032
Sr	0.694	-0.087	-0.336	-0.145	0.293
Ca	0.584	-0.529	0.007	0.408	0.046
Mg	0.897	0.154	0.040	0.019	0.054
K	-0.102	0.045	0.237	0.694	-0.260
Zn	-0.096	0.715	0.039	0.094	0.375
Fe	0.955	0.018	-0.015	-0.097	-0.061

revealed dominant loadings for PM_{2.5}, Mn, Fe, Mn, Mg, Ca, and Sr which were mainly derived from lithogenic sources or crustal materials. These variables also showed a strong mutual cluster in CA, thus supporting the PCA results. PC 2 showed elevated loadings for Cr, Cu, Li, and Zn that were predominantly influenced by industrial emissions, and cluster analysis is supporting these results. PC 3 and PC 4 showed higher loadings in favour of Co, Ag, and Ni, K, respectively. These elements were primarily emanated from incinerators and combustion processes. The last PC showed higher loadings in favour of Pb and Cd, along with some considerable input of Zn. These elements were largely released from transportation activities and vehicular emissions in the local atmosphere. The CA and PCA results were in excellent agreement with each other. Overall, the multivariate methods showed significant anthropogenic contributions of the trace elements (mainly emanating from industrial emissions, incineration/combustion processes, and automobile emissions) in the atmospheric particulates.

Ecological risk assessment

The ecological risk caused by trace elements in the atmosphere was evaluated using an ecological risk index (*RI*) and environmental risk coefficients (*Er*). *RI* is a cumulative index, and generally, it is classified into four categories:

- (i) low ecological risk ($RI < 150$)
- (ii) moderate ecological risk ($150 \leq RI < 300$)
- (iii) considerable ecological risk ($300 \leq RI < 600$)
- (iv) very high ecological risk ($RI \geq 600$)

Generally, for each metal, the possible ecological risk coefficient can be classified into five categories depending on the *Er* values: low risk when $Er < 40$, moderate risk when $40 \leq Er < 80$, significant risk when $80 \leq Er < 160$, high risk when $160 \leq Er < 320$, and extremely high risk when $Er \geq 320$. The ecological risk coefficients of the trace elements in the present investigation were less than 40, indicating a low risk to the organisms and the ecosystem, as shown in Fig. 2. Overall, low ecological risk due to respirable was noted in this study.

Health risk assessment

Assessing the health risks associate with the trace elements in atmospheric particulates was the most significant aspect of the current investigation. The average exposure concentrations of trace elements through inhalation of the atmospheric particulates are shown in Fig. 3a. Relatively higher exposure amounts were observed for Ca, K, Mg, Fe, and Zn. The elevated exposure to these elements is not typically considered toxic because they are mostly essential without having detrimental health effects. Moderately higher exposure levels were noticed for Cu, Pb, Mn, Cd, Sr, Ni, Cr, and Co. The elevated and prolonged exposure to these elements may result in serious health effects, which would be further explored in succeeding section.

The non-carcinogenic health risk associated with the prevailing elemental levels was assessed in terms of the hazard quotient/index. The average hazard quotients of the trace elements are shown in Fig. 3b. Typically, an HQ value of less than one is regarded

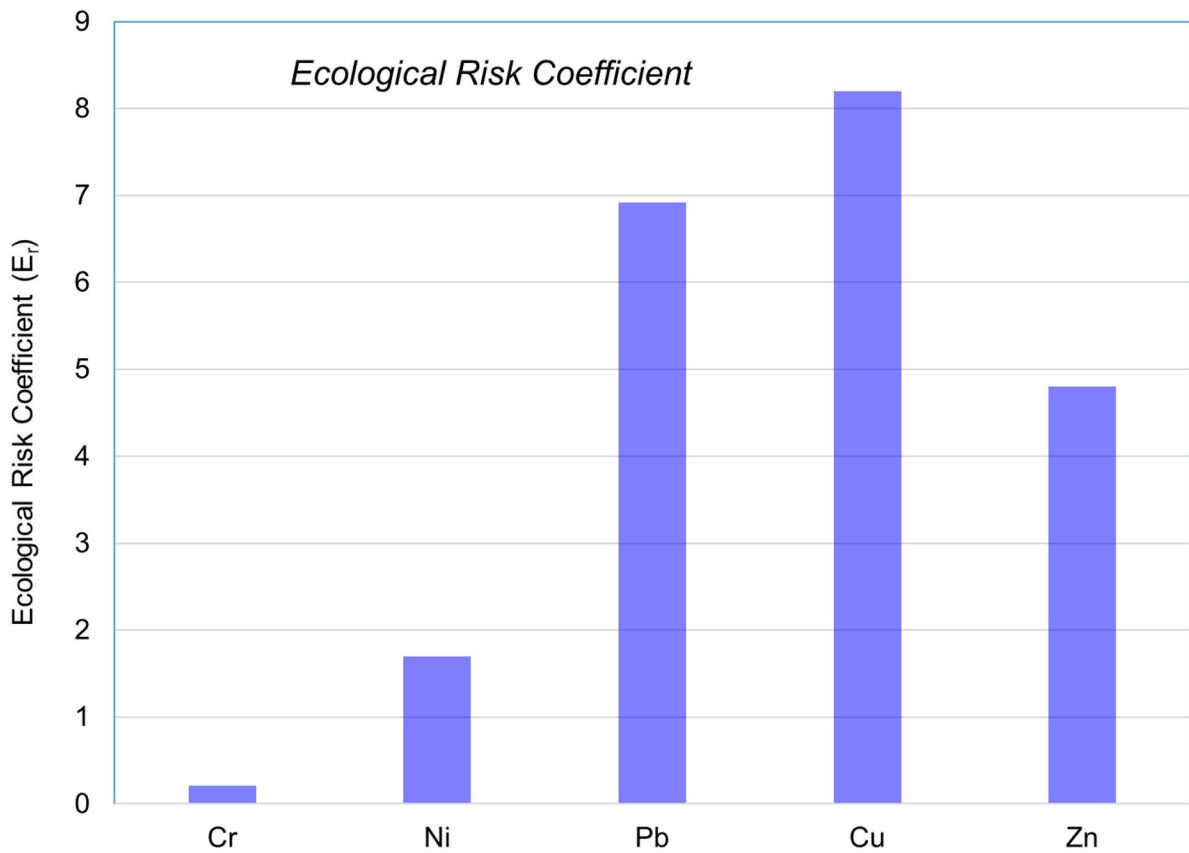


Fig. 2 Average values of ecological risk coefficients (E_i) of trace elements in the atmospheric particulates

as safe. The HQ values computed for all trace elements in the present study were less than 1.0, and the HI value (0.753) was also within the safe limit; consequently, no significant non-carcinogenic risks were associated with the elemental contact through inhalation or breathing of the atmospheric particulates. However, on a comparative basis, the highest HQ value was noted for Cd, followed by Co, Mn, Ni, Cr, and Pb, while it was almost negligible for Cu and Zn, as shown in Fig. 3b.

Additionally, the carcinogenic risk related to the inhalation of the particulate matter containing toxic trace metals was assessed, as shown in Fig. 3c. Generally, a calculated cancer risk less than 1×10^{-6} is considered as safe for the local population; a risk value of 1×10^{-4} is considered significant, and a calculated cancer risk higher than 1×10^{-4} is considered unacceptable. In the present investigation, the calculated CR for Pb and Ni were found to be within the safe limit ($< 1 \times 10^{-6}$); however, significant CR was

found to be associated with Cr, Co, and Cd exposure through inhalation of the particulates (Fig. 3c). Among the toxic elements, the maximum CR was observed for Cr, followed by Co and Cd, while considerably lower values were noted for Pb and Ni. Overall, the present study revealed significant carcinogenic risks associated with the exposure to toxic metals by inhalation of the fine atmospheric particulates. Therefore, immediate attention should be focused on controlling or reducing the emission sources of toxic metals into the local atmosphere.

Comparison with the reported levels

A comparison of the current average levels of PM_{2.5} and trace elements was also made with the reported levels globally (Table 4). The mean PM_{2.5} concentration in this study (44.09 g/m³) was found to be significantly exceeding than the 24-h guideline values recommended by WHO (15 g/m³), USEPA (35 g/m³), and Pak-EPA (25 g/

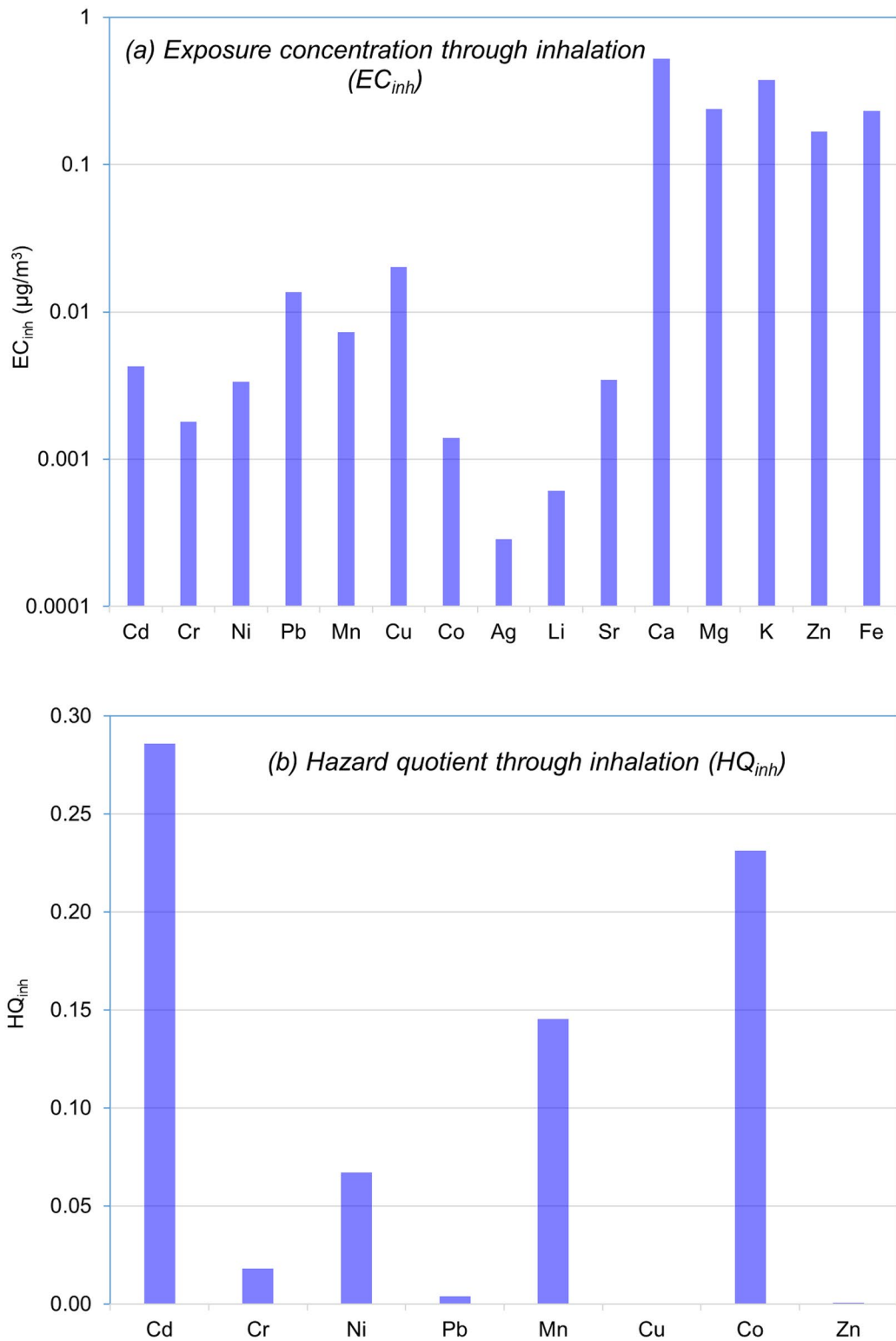


Fig. 3 Average levels of **a** exposure concentrations ($\mu\text{g}/\text{m}^3$), **b** hazard quotients and **c** carcinogenic risks of trace elements through inhalation of $\text{PM}_{2.5}$

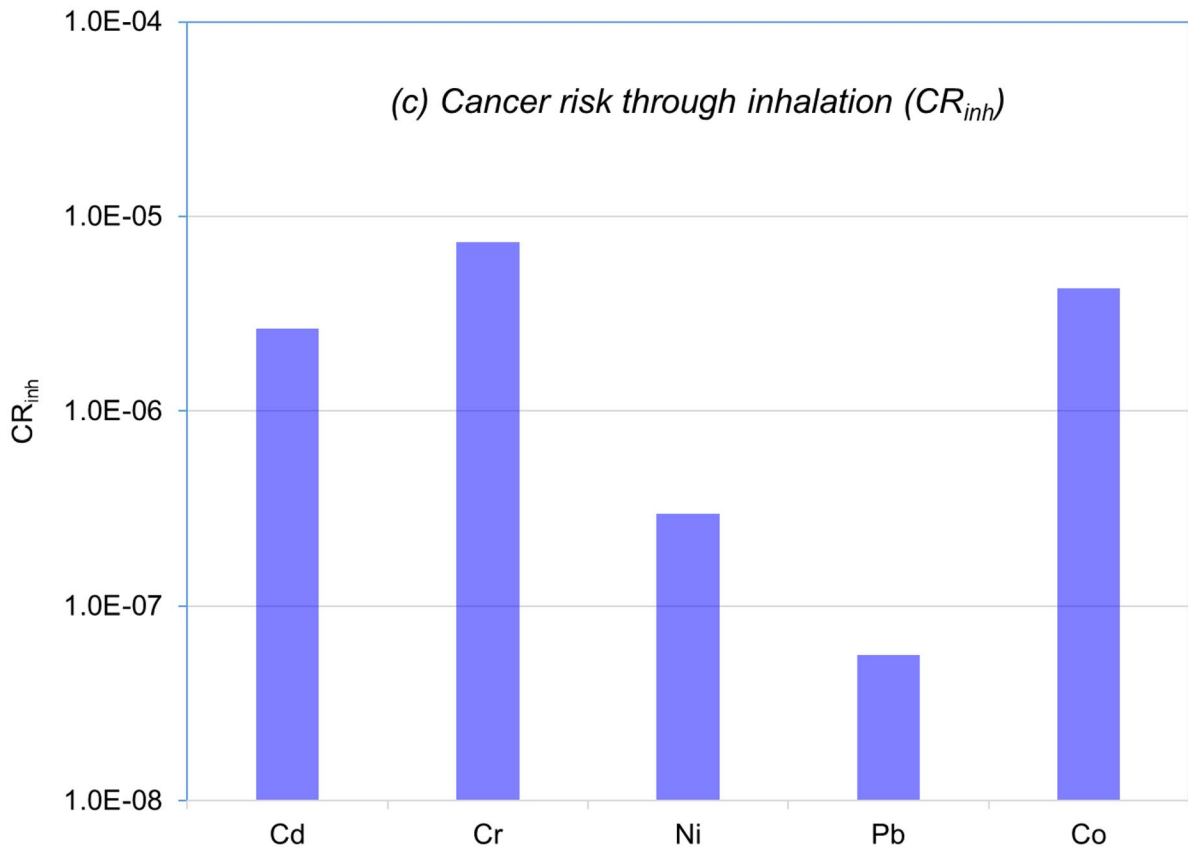


Fig. 3 (continued)

m^3), as well as those of the annual average standards of WHO ($5 \text{ g}/m^3$), USEPA ($12 \text{ g}/m^3$), and Pak-EPA ($15 \text{ g}/m^3$) (Pak-EPA, 2010; USEPA, 2016b; WHO, 2021b). Similarly, the present $PM_{2.5}$ levels were also higher than those reported from Karaj (Kermani et al., 2021), Colombo (Dhammapala et al., 2022), Batu Pahat, Johor Bahru (Alias et al., 2020), Southern California (Habre et al., 2021), and Las Angeles (Farahani et al., 2021). However, the current average contents of $PM_{2.5}$ were relatively lower than those reported from other South Asian cities, including Lahore, Peshawar (Ahmad et al., 2021), Delhi (Jain et al., 2020; Sharma et al., 2016), Dhaka (Rahman et al., 2020), Chiang Rai, Bangkok (Kayee et al., 2020), and Ho Chi Minh City and Beijing (Guo et al., 2021; Phan et al., 2020).

The comparison of the average elemental levels in the particulates revealed that the present concentrations of most of the elements were considerably lower than the reported levels from Lahore, Peshawar, Isfahan (Soleimani et al., 2018), Delhi, Shandong

(Zhang et al., 2018), and Ho Chi Minh City. Conversely, the present average contents of the airborne elements were significantly higher than the reported levels from Singapore (George et al., 2020), Chiang Rai, Bangkok, Batu Pahat, Johor Bahru, Southern California, and Las Angeles. The average contents of $PM_{2.5}$, Cr, Mn, and Cd were somewhat comparable to the reported levels from Guiya (Zheng et al., 2014), whereas Pb was significantly lower than the reported levels. Similarly, compared with the reported concentrations from Shenzhen (Qin et al., 2020), the current levels of Ni, Co, Pb, Ca, and Cu were almost comparable, while the mean levels of Cr and Mn were less than the reported levels. Overall, the comparative study revealed that the present average levels of particulate elemental levels were less than those reported from Pakistan, India, Bangladesh, China, and Vietnam but considerably higher than those reported from the USA, Singapore, Malaysia, Iran, Sri Lanka, and Thailand (Table 4).

Table 4 Comparison of the present average levels of PM_{2.5} (µg/m³) and trace elements (ng/m³) with the reported levels around the world

Site	PM _{2.5}	Cd	Cr	Ni	Pb	Mn	Cu	Co	Ag	Li	Sr	Ca	Mg	K	Zn	Fe	Reference
Islamabad (Pakistan)	44.09	8.69	6.48	6.81	27.69	14.75	40.99	2.81	0.57	1.23	7.01	1061	483.0	759.8	341.1	469.7	Present study
Lahore (Pakistan)	522	64.0	66.5	28.7	3810	170	174		2.40	37.7			1170		7290	4490	Ahmad et al. (2021)
Peshawar (Pakistan)	370	22.7	155	72.0	563	125	26.7		2.80	78.5			2080		4720	4380	Ahmad et al. (2021)
Isfahan (Iran)		7	70	35	41	31	49										Soleimani et al. (2018)
Karaj (Iran)	40.65	83.97	49.51	60.83	133.1	84.67	203.2								241.8	336.8	Kermani et al. (2021)
Dhaka (Bangladesh)	87.8																Rahman et al. (2020)
Delhi (India)	121.9		40		20	20	40					2840	940		120	260	Sharma et al. (2016)
Delhi (India)	131		180		300	10	100								380	780	Jain et al. (2020)
Colombo (Sri Lanka)	31.9																Dhammapala et al. (2022)
Guiyu (China)	49.9	5.7	4.5		160	17											Zheng et al. (2014)
Shandong (China)		20			300	80	30		20			190	190	5370	630	1180	Zhang et al. (2018)
Shenzhen (China)		1.19	28.99	6.82	33.28	42.53	28.98	3.45				1070					Qin et al. (2020)
Beijing (China)	72.34																Guo et al. (2021)
Singapore		0.004	0.464		0.283							17.9		13.1	0.718	5.17	George et al. (2020)
Chiang Rai (Thailand)	170		3.0	1.4	6.4	6.6	2.6		1.0			113	44		15	142	Kayee et al. (2020)
Bangkok (Thailand)	91		1.8	1.6	9.7	7.3	4.4		0.76			79	49		34	123	Kayee et al. (2020)
Batu Pahat (Malaysia)	27.45			1.38	11.50		27.39	0.04							33.33		Alias et al. (2020)
Johor Bahru (Malaysia)	26.28			3.23	4.26		5.90	0.05							7.69		Alias et al. (2020)
Ho Chi Minh (Vietnam)	97.79		128	32.0	225	112	391								128	4041	Phan et al. (2020)
California (USA)	14.01		0.3		1.5	1.6	3.8		0.8			55.5	36.4	46.1	6.4	85.8	Habre et al. (2021)
Los Angeles (USA)	13.75				12	10						70	50	60	10	190	Farahani et al. (2021)

Conclusions

The present study revealed significant variations in the PM_{2.5} and trace elemental levels in the local atmosphere of Islamabad. Most of the elements showed large dispersion and random distribution in the atmospheric particulates. The correlation analysis exhibited several strong mutual relations among the trace elements. The enrichment factor and geo-accumulation index revealed significantly elevated contamination of Cd, Ag, Zn, Pb, and Cu in the particulates. Multivariate methods showed considerable anthropogenic emissions of the trace elements, mainly emanating from industrial emissions, automobile exhaust, combustion, and incineration processes. Health risk assessment demonstrated insignificant non-carcinogenic risks; however, considerable cancer risk was associated with the Cd, Cr, and Co levels in the atmospheric particulates. Finally, the average levels were compared with the guideline values and the reported levels from other regions around the world. It revealed that PM_{2.5} levels were above the guidelines set by the WHO, USEPA, and Pakistan EPA.

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Authors' contributions Rashida Nazir: *Data curation; Investigation; Methodology; Validation; Formal analysis; Writing—original draft.* Munir H. Shah: *Conceptualization; Validation; Visualization; Funding acquisition; Project administration; Resources; Software; Supervision; Writing—review & editing.* All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors".

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Availability of data and material The datasets used for this study are available upon reasonable request to the corresponding author.

Code availability Not applicable.

Declarations

Conflicting interests The authors have no relevant financial or non-financial interests to disclose.

References

- Ahmad, M., Yu, Q., Chen, J., Cheng, S., Qin, W., & Zhang, Y. (2021). Chemical characteristics, oxidative potential, and sources of PM_{2.5} in wintertime in Lahore and Peshawar, Pakistan. *Journal of Environmental Sciences*, *102*, 148–158.
- Alias, N. F., Khan, M. F., Sairi, N. A., Zain, S. M., Suradi, H., Rahim, H. A., Banerjee, T., Bari, M. A., Othman, M., & Latif, M. T. (2020). Characteristics, emission sources, and risk factors of heavy metals in PM_{2.5} from Southern Malaysia. *ACS Earth and Space Chemistry*, *14*, 1309–1323.
- Alves, C., Evtuygina, M., Vicente, E., Vicente, A., Rienda, I. C., de la Campa, A. S., Tomé, M., & Duarte, I. (2023). PM_{2.5} chemical composition and health risks by inhalation near a chemical complex. *Journal of Environmental Sciences*, *124*, 860–874.
- Anjum, M. S., Ali, S. M., Subhani, M. A., Anwar, M. N., Nizami, A. S., Ashraf, U., & Khokhar, M. F. (2021). An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan; a critical review. *Journal of Hazardous Materials*, *402*, 123943.
- Bayat, R., Ashrafi, K., Motlagh, M. S., Hassanvand, M. S., Daroudi, R., Fink, G., & Künzli, N. (2019). Health impact and related cost of ambient air pollution in Tehran. *Environmental Research*, *176*, 108547.
- Behrooz, R. D., Kaskaoutis, D. G., Grivas, G., & Mihalopoulos, N. (2021). Human health risk assessment for toxic elements in the extreme ambient dust conditions observed in Sistan, Iran. *Chemosphere*, *262*, 127835.
- Brodny, J., & Tutak, M. (2021). The analysis of similarities between the European Union countries in terms of the level and structure of the emissions of selected gases and air pollutants into the atmosphere. *Journal of Cleaner Production*, *279*, 123641.
- CEN. (2005). Ambient air quality - Standard gravimetric measurement method for the determination of the PM_{2.5} mass fraction of suspended particulate matter. EN 14907:2005. Brussels, Belgium: Comité Européen de Normalisation (CEN; European Committee for Standardization).
- Chen, S. L., Chang, S. W., Chen, Y. J., & Chen, H. L. (2021). The possible warming effect of fine particulate matter in the atmosphere. *Communications Earth & Environment*, *2*, 1–9.
- Dhammapala, R., Basnayake, A., Premasiri, S., Chathuranga, L., & Mera, K. (2022). PM_{2.5} in Sri Lanka: Trend analysis, low-cost sensor correlations and spatial distribution. *Aerosol and Air Quality Research*, *22*, 210266.
- Farahani, V. J., Soleimani, E., Pirhadi, M., & Sioutas, C. (2021). Long-term trends in concentrations and sources of PM_{2.5}-bound metals and elements in central Los Angeles. *Atmospheric Environment*, *15*, 118361.
- George, S., Chua, M. L., ZheWei, D. Z., Das, R., Bijin, V. A., Connolly, J. E., Lee, K. P., Yung, C. F., Teoh, O. H., & Thomas, B. (2020). Personal level exposure and hazard potential of particulate matter during haze and non-haze periods in Singapore. *Chemosphere*, *243*, 125401.
- Guo, W., Zhang, B., Wei, Q., Guo, Y., Yin, X., Li, F., Wang, L., & Wang, W. (2021). Estimating ground-level PM_{2.5}

- concentrations using the two-stage model in Beijing-Tianjin-Hebei, China. *Atmospheric Pollution Research*, *12*, 101154.
- Habre, R., Girguis, M., Urman, R., Fruin, S., Lurmann, F., Shafer, M., Gorski, P., Franklin, M., McConnell, R., Avol, E., & Gilliland, F. (2021). Contribution of the tailpipe and non-tailpipe traffic sources to quasi-ultrafine, fine and coarse particulate matter in Southern California. *Journal of the Air & Waste Management Association*, *71*, 209–230.
- Jain, S., Sharma, S. K., Vijayan, N., & Mandal, T. K. (2020). Seasonal characteristics of aerosols (PM_{2.5} and PM₁₀) and their source apportionment using PMF, a four-year study over Delhi, India. *Environmental Pollution*, *262*, 114337. 32.
- Jayarathne, A., Egodawatta, P., Ayoko, G. A., & Goonetilleke, A. (2018). Assessment of ecological and human health risks of metals in urban road dust based on geochemical fractionation and potential bioavailability. *Science of the Total Environment*, *635*, 1609–1619.
- Kalaiarasan, G., Balakrishnan, R. M., Sethunath, N. A., & Manoharan, S. (2018). Source apportionment studies on particulate matter (PM₁₀ and PM_{2.5}) in ambient air of urban Mangalore, India. *Journal of Environmental Management*, *217*, 815–824.
- Kayee, J., Sompongchaiyakul, P., Sanwlani, N., Bureekul, S., Wang, X., & Das, R. (2020). Metal concentrations and source apportionment of PM_{2.5} in Chiang Rai and Bangkok, Thailand during a biomass burning season. *ACS Earth and Space Chemistry*, *19*, 1213–1226. 21.
- Kermani, M., Jafari, A. J., Gholami, M., Arfaeinia, H., Shahsavani, A., & Fanaei, F. (2021). Characterization, possible sources and health risk assessment of PM_{2.5}-bound Heavy Metals in the most industrial city of Iran. *Journal of Environmental Health Science and Engineering*, *19*, 151–163.
- Li, W., Shao, L., Li, Z., Li, H., Gao, J., Li, J., Zhang, H., Zhang, Z., Silva, L. F. O., Zhang, M., Chen, Y., & Oliveira, M. L. S. (2022). Surface chemistry of atmospheric nanoparticles during a haze episode in Beijing by TOF-SIMS. *Gondwana Research*, *110*, 305–318.
- Lima, B. D., Teixeira, E. C., Hower, J. C., Civeira, M. S., Ramírez, O., Yang, C., Oliveira, M. L. S., & Silva, L. F. O. (2021). Metal-enriched nanoparticles and black carbon: A perspective from the Brazil railway system air pollution. *Geoscience Frontiers*, *12*(3), 101129.
- Liu, Y., Li, C., Zhang, C., Liu, X., Qu, Y., An, J., Ma, D., Feng, M., & Tan, Q. (2020). Chemical characteristics, source apportionment, and regional contribution of PM_{2.5} in Zhangjiakou, Northern China: a multiple sampling sites observation and modelling perspective. *Environmental Advances*, *3*, 100034.
- Lv, D., Chen, Y., Zhu, T., Li, T., Shen, F., Li, X., & Mehmood, T. (2019). The pollution characteristics of PM₁₀ and PM_{2.5} during summer and winter in Beijing, Suning and Islamabad. *Atmospheric Pollution Research*, *10*, 1159–1164.
- Mehmood, T., Ahmad, I., Bibi, S., Mustafa, B., & Ali, I. (2020). Insight into monsoon for shaping the air quality of Islamabad, Pakistan, Comparing the magnitude of health risk associated with PM₁₀ and PM_{2.5} exposures. *Journal of the Air & Waste Management Association*, *70*, 1340–1355.
- Mehmood, T., Tianle, Z., Ahmad, I., Li, X., Shen, F., Akram, W., & Dong, L. (2018). Variations of PM_{2.5}, PM₁₀ mass concentration and health assessment in Islamabad, Pakistan. *Earth and Environmental Science*, *133*, 012031.
- Method IO-3.1. (1999). Selection, Preparation and Extraction of Filter Material. EPA/625/R-96/010a. Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air. US-Environmental Protection Agency, Cincinnati, OH.
- Method IO-3.2. (1999). Determination of Metals in Ambient Particulate Matter Using Atomic Absorption (AA) Spectroscopy. EPA/625/R-96/010a. Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air. US-Environmental Protection Agency, Cincinnati, OH.
- Nair, M., Bherwani, H., Kumar, S., Gulia, S., Goyal, S. K., & Kumar, R. (2020). Assessment of the contribution of agricultural residue burning on air quality of Delhi using remote sensing and modelling tools. *Atmospheric Environment*, *230*, 117504.
- Oliveira, M. L., Neckel, A., Pinto, D., Maculan, L. S., Zanchett, M. R., & Silva, L. F. (2021). Air pollutants and their degradation of a historic building in the largest metropolitan area in Latin America. *Chemosphere*, *277*, 130286.
- Pak-EPA. (2010). *National Environmental Quality Standards for Ambient Air*. Environment Protection Department, The Ministry of Environment, Islamabad, Pakistan.
- Phan, C. C., Nguyen, T. Q., Nguyen, M. K., Park, K. H., Bae, G. N., Seung-bok, L., & Bach, Q. V. (2020). Aerosol mass and major composition characterization of ambient air in Ho Chi Minh City, Vietnam. *International Journal of Environmental Science and Technology*, *17*, 3189–3198.
- Qin, S., Li, B., Wang, X., Huang, H., Zeng, M., Xiao, F., & Xu, X. (2020). Metal element detection and carcinogenicity risk assessment of PM_{2.5} samples. *Environmental Toxicology and Chemistry*, *39*, 1273–1276.
- Rahman, M. M., Begum, B. A., Hopke, P. K., Nahar, K., & Thurston, G. D. (2020). Assessing the PM_{2.5} impacts of biomass combustion in megacity Dhaka, Bangladesh. *Environmental Pollution*, *264*, 14798.
- Ramírez, O., da Boit, K., Blanco, E., & Silva, L. F. O. (2020). Hazardous thoracic and ultrafine particles from road dust in a Caribbean industrial city. *Urban Climate*, *33*, 100655.
- Ramírez, O., Sánchez de la Campa, A. M., Amato, F., Moreno, T., Silva, L. F., & de la Rosa, J. D. (2019). Physicochemical characterization and sources of the thoracic fraction of road dust in a Latin American megacity. *Science of the Total Environment*, *652*, 434–446.
- Rasheed, A., Aneja, V. P., Ayyer, A., & Rafique, U. (2015). Measurement and analysis of fine particulate matter (PM_{2.5}) in urban areas of Pakistan. *Aerosol and Air Quality Research*, *15*, 426–439.
- Rojas, J. C., Sánchez, N. E., Schneider, I., Oliveira, M. L. S., Teixeira, E. C., & Silva, L. F. O. (2019). Exposure to nanometric pollutants in primary schools: Environmental implications. *Urban Climate*, *27*, 412–419.
- Sahu, S. K., Mangaraj, P., Beig, G., Tyagi, B., Tikle, S., & Vinoj, V. (2021). Establishing a link between fine particulate matter (PM_{2.5}) zones and COVID-19 over India based on anthropogenic emission sources and air quality data. *Urban Climate*, *38*, 100883.
- Schwela, D. H., & Haq, G. (2020). Strengths and weaknesses of the WHO urban air pollutant database. *Aerosol and Air Quality Research*, *20*, 1026–1037.

- Sharma, S. K., Mandal, T. K., Jain, S., Sharma, A., & Saxena, M. (2016). Source apportionment of PM_{2.5} in Delhi, India using PMF model. *Bulletin of Environmental Contamination and Toxicology*, 97, 286–293.
- Silva, L. F., Schneider, I. L., Artaxo, P., Nunez-Blanco, Y., Pinto, D., Flores, E. M., Gomez-Plata, L., Ramirez, O., & Dotto, G. L. (2022). Particulate matter geochemistry of a highly industrialized region in the Caribbean: Basis for future toxicological studies. *Geoscience Frontiers*, 13, 101115.
- Soleimani, M., Amini, N., Sadeghian, B., Wang, D., & Fang, L. (2018). Heavy metals and their source identification in particulate matter (PM_{2.5}) in Isfahan City, Iran. *Journal of Environmental Sciences*, 72, 166–175.
- State of Global Air Report. (2020). Retrieved November 11, 2020, from <https://www.stateofglobalair.org/>
- Tong, S. (2019). Air pollution and disease burden. *Lancet Planetary Health*, 3, 49–50.
- USEPA. (2016a). *Regional Screening Levels (RSLs) - Generic Tables*. Retrieved December 21, 2020, from <https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables-may-2016>
- USEPA. (2016b). *Technical Assistance Document for the Reporting of Daily Air Quality-the Air Quality Index (AQI)*. Office of Air Quality Planning and Standards, US-Environmental Protection Agency, Cincinnati, OH.
- Vural, E. (2020). Investigation of experienced air pollution on selected pollutants scale in Kırıkkale City (2018–2019), Kastamonu University. *Journal of Engineering and Sciences*, 6, 41–50.
- Wang, Q., Luo, K., Fan, J., Gao, X., & Cen, K. (2019). Spatial distribution and multiscale transport characteristics of PM_{2.5} in China. *Aerosol and Air Quality Research*, 19, 1993–2007.
- WHO. (2019). *Mortality and Burden of Disease from Ambient Air Pollution*. World Health Organization. Retrieved April 17, 2019, from <https://www.who.int/airpollution/ambient/en/>
- WHO. (2021a). *Ambient (Outdoor) Air Quality and Health*. World Health Organization. Retrieved November 12, 2021, from <https://www.who.int/news-room/fact-sheets/detail/>
- WHO. (2021b). *New WHO Global Air Quality Guidelines Aim to Save Millions of Lives from Air Pollution*, World Health Organization. Retrieved September 25, 2022, from <https://www.int/news/item/>
- Zhang, J., Zhou, X., Wang, Z., Yang, L., Wang, J., & Wang, W. (2018). Trace elements in PM_{2.5} in Shandong Province: Source identification and health risk assessment. *Science of the Total Environment*, 15, 558–577.
- Zhao, K., Zhang, Y., Shang, J., Schauer, J. J., Huang, W., Tian, J., Yang, S., Fang, D., & Zhang, D. (2023). Impact of Beijing’s “Coal to Electricity” program on ambient PM_{2.5} and the associated reactive oxygen species (ROS). *Journal of Environmental Sciences*, 133, 93–106.
- Zheng, X., Xu, X., Yekeen, T. A., Zhang, Y., Chen, A., Kim, S. S., Dietrich, K. N., Ho, S. M., Lee, S. A., Reponen, T., & Huo, X. (2014). Ambient air heavy metals in PM_{2.5} and potential human health risk assessment in an informal electronic-waste recycling site of China. *Aerosol and Air Quality Research*, 16, 388–397.

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