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Research article

Source and respiratory deposition of trace elements in $PM_{2.5}$ at an urban location in Dhaka city

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ABSTRACT

Air pollution has been creating severe environmental crises in Dhaka. This city ranks at the top among the major cities of the world. A multidimensional study is needed to assess the severity of this crisis. This study aims to determine the sources of trace elements in $PM_{2.5}$ and their effects on health. We measured concentrations of 15 trace elements in $PM_{2.5}$ every hour for eight days using a well-equipped mobile air quality monitoring system integrated with an automatic sampling system (AQMS, Horiba, Japan). We analyzed the concentrations of the trace elements to identify their potential sources and diurnal variation and to compute the respiratory deposition dose of the trace elements to estimate the health risks they pose. The daily average concentration of $PM_{2.5}$ was higher than the allowable limit set by the World Health Organization (WHO). Among the trace elements, sulfur had the highest concentration and vanadium was the lowest. We found out that concentrations of the elements were the highest during the middle of the day and the lowest during midnight. Four source profiles of $PM_{2.5}$ were identified by positive matrix factorization (PMF). Soil dust with sulfur-rich petroleum contributed about 65 %, industrial and non-exhaust emissions about 5 % each, and heavy engine oil combustion about 25 % to air pollution. Air mass backward trajectory analysis indicated that Dhaka's air contains both local and transboundary pollution. According to the determined respiratory deposition dose of the elements, males had higher deposition than females during heavy exercise. Sulfur and vanadium have the highest and lowest respiratory deposition dose, respectively. The highest amount of deposition occurred in the upper airways. We expect that this study will help professionals develop effective strategies to prevent and mitigate the emission of air pollutants.

1. Introduction

Air pollution has been creating severe environmental crises since the development of human civilization, particularly since the industrial revolution. Among the cities with the most polluted air, Dhaka has been at the top almost every year. The anthropogenic contribution has increased due to human activity and industrial development [1]. According to Wang & Hao, high levels of atmospheric pollution have been occurring in the south- and southeast Asian cities due to the rapid rise in fossil fuel use required for fast urbanization and industrialization [2]. Sources of high $PM_{2.5}$ concentration are vehicular emissions including those from two-stroke

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List of Abbreviations

(IARC) International Agency for Research on Cancer
(RDD) Respiratory deposition dose
(PMF) Positive matrix factorization
(BCSIR) Bangladesh Council of Scientific and Industrial Research
(HYSPLIT) Hybrid Single-Particle Lagrangian Integrated Trajectory
(NOAA) National Oceanic and Atmospheric Administration
(ARL) Air Resources Laboratory
(US EPA) United States Environmental Protection Agency
(ICRP) International Commission on Radiological Protection
(DF) Deposition fraction
(UA) Upper airway
(TB) Tracheobronchial region
(AL) Alveolar region
(IF) Inhalable fraction
(WHO) World Health Organization
(NAAQS) National Ambient Air Quality Standard
(GrADS) Grid Analysis and Display System
(ECMWF) European Center for Medium-Range Weather Forecasts
(IGP) Indo Gangetic Plain

engines, industrial emissions, brick kilns, coal combustion, biomass burning, and construction activities [3]. In Dhaka, motor vehicles and brick kilns contribute an average of 22 % and 36 %, respectively, to the city's fine particles [4].

Air pollutants pose major risks to public health. These effects can be both acute and chronic. According to Manisalidis et al. chronic obstructive pulmonary disease, shortness of breath, asthma, cough, and respiratory diseases are some of the health effects of short-term exposure to air pollutants, whereas chronic asthma, cardiovascular diseases, and pulmonary insufficiency are among the health hazards from long term exposure to air pollutants [5]. Particulate matter with an aerodynamic diameter of 10 μm or less can penetrate our lungs, affecting the entire respiratory system. Asthma attacks, acute respiratory inflammation, and death from cardiorespiratory disorders have all been attributed to prolonged exposure to air pollution. The leading environmental health risk factor, $PM_{2.5}$, is thought to be responsible for several million of annual global fatalities [6]. It can penetrate the lungs and impair lung function by damaging the alveolar wall [7]. Some trace elements in the air are also carcinogenic. The most toxic trace elements include arsenic, chromium, cadmium, mercury, and lead, which are known to damage multiple organs even at low exposure levels [8]. Chromium, cadmium, nickel, and lead were classified as potentially carcinogenic to humans [9]. While Pb is regarded as a class 2A carcinogen, the trace elements As, Cd, Cr, and Ni are class 1 carcinogens [10]. Moreover, Cd impairs kidney function, whereas high concentrations of Pb can cause severe neurological and hematological issues in those exposed, primarily children. Cd and Pb have several sources, such as industrial emissions, burning of leaded gasoline, coal and lubricating oil, wearing of tire and break, and mining [11]. Leaded gasoline is still the primary source of airborne lead in the countries that are continuing its use as a fuel for motorized vehicles or only recently banned its use [12]. As stated by Chung et al. sources of arsenic in the air are medicine, electronics, industrial manufacturing, wood preservatives, and smoking [13]. Due to its germicidal properties and resistance to rotting and decay, arsenic is typically utilized as a pesticide, herbicide, or wood preservative. It may travel great distances, bind to small airborne particles, and persist in the atmosphere for longer days. Manganese, aluminum, copper, and barium are the elements that contribute the most to the non-cancer risk posed by prolonged inhalation exposure [14]. Also, according to Woodruff et al. infant mortality has been linked to high levels of air pollution [15]. Within a given metropolitan city, there is variation in both temporal and spatial exposure to urban air pollutants [16]. People who either live or work close to busy, congested roads in urban areas suffer the health impacts of poor air quality because increased concentrations of pollutants tend to occur close to highways and streets [17].

Health risk assessments for inhalation of toxic substances are essential because the rapid rise in industrialization causes a steady increase in emissions, and human health depends primarily on the quality of the air we breathe [14]. The contaminated air of Dhaka has been the subject of numerous research articles and newspaper reports. However, most of these studies do not mention any health effects related to the observed quantities of trace metals.

Source apportionment modeling as a basis for mitigating air pollution has been well-established since the last decade. Among several source apportionment methods, positive matrix factorization (PMF) is a robust one as a receptor model. It has been widely applied in the literature to identify and quantify the sources of air pollution. PMF has been widely used for source characterization of airborne particulate matters [3]. The PMF theory was introduced by Paatero & Tapper [18]. According to the authors, PMF has strict non-negativity restrictions for the factors and uses error estimates for elements of the measured data matrix. The contribution of each source to the mass concentration of trace elements in particulate matter of different size fractions is calculated using PMF. A clear picture of Dhaka's polluted air and how it affects the city's residents is needed. We have used respiratory deposition dose to estimate the health impact of trace elements on the human respiratory system. In Bangladesh, this method was applied by Moniruzzaman et al. who analyzed the health impact of 15 elements in PM_{10} and $PM_{2.5}$ and showed the seasonal variation using the single average concentration of each element sampled over 24 h [10]. To obtain an in-depth scenario of the concentration and deposition trend, we analyzed the diurnal pattern of elemental concentrations and calculated the hourly respiratory deposition dose (RDD) of each trace element for seven days. The diurnal data enabled us to observe the highest and lowest concentrations throughout the day and their impact on human health.

This research aimed to identify the potential source of the trace elements in $PM_{2.5}$ and to determine the health effects of trace elements in $PM_{2.5}$. To achieve the aim of this research, we fulfilled the following objectives: measuring the concentration of 15 trace elements from $PM_{2.5}$ real-time air sampling, carrying out source apportionment of trace elements in $PM_{2.5}$ to determine the potential sources of those elements, analyzing air mass back trajectories, visualizing wind circulation pattern and estimating the respiratory deposition dose (RDD) of the elements to assess the health effects of those elements in the human respiratory system.

2. Methods

2.1. Site description

Bangladesh is located in the eastern region of South Asia, bordered by Myanmar on the southeast, India on the west, north, and northeast, and the Bay of Bengal to the south. The capital of Bangladesh is Dhaka. With an estimated population of over 22 million and a population density of 23,234 people per square kilometer over a total area of 300 square kilometers, the megacity of Dhaka ranks as the sixth-largest city in the world [19]. Being the center of trade and industry of Bangladesh, it is growing rapidly [20]. The modes of transportation in the city include rickshaws, cycles, vans, petrol-run cars, CNG-run vehicles, motorcycles, buses, pick-up trucks, and diesel-run trucks [21]. According to the Bangladesh Road Transport Authority (BRTA), 158,417 new vehicles were registered in Dhaka in 2019 [22]. Some common industries in Bangladesh are those manufacturing bricks, sugar, pulp and paper, tanneries, pharmaceuticals, textiles, garments, chemicals, tobacco, and food and beverage [23], where petrol, diesel, octane, biomass, and natural gases are commonly used as fuel. This information gives us a general idea about the kind of air pollutants and their potential sources. A map of the sampling site with its surroundings is shown in Fig. 1.

2.2. Sampling and analysis

Concentrations of 15 elements were retrieved from the Bangladesh Council of Scientific and Industrial Research (BCSIR). With the help of the X-ray fluorescence technique, real-time data were collected every hour for eight days (March 21, 2022–March 28, 2022) in a mobile van known as Mobile Ambient Air Quality with Elemental Monitoring station by HORIBA Japan located inside the campus of the BCSIR near Elephant road; the van was located 100 m away from the main road. $PM_{2.5}$ samples were collected using a well-

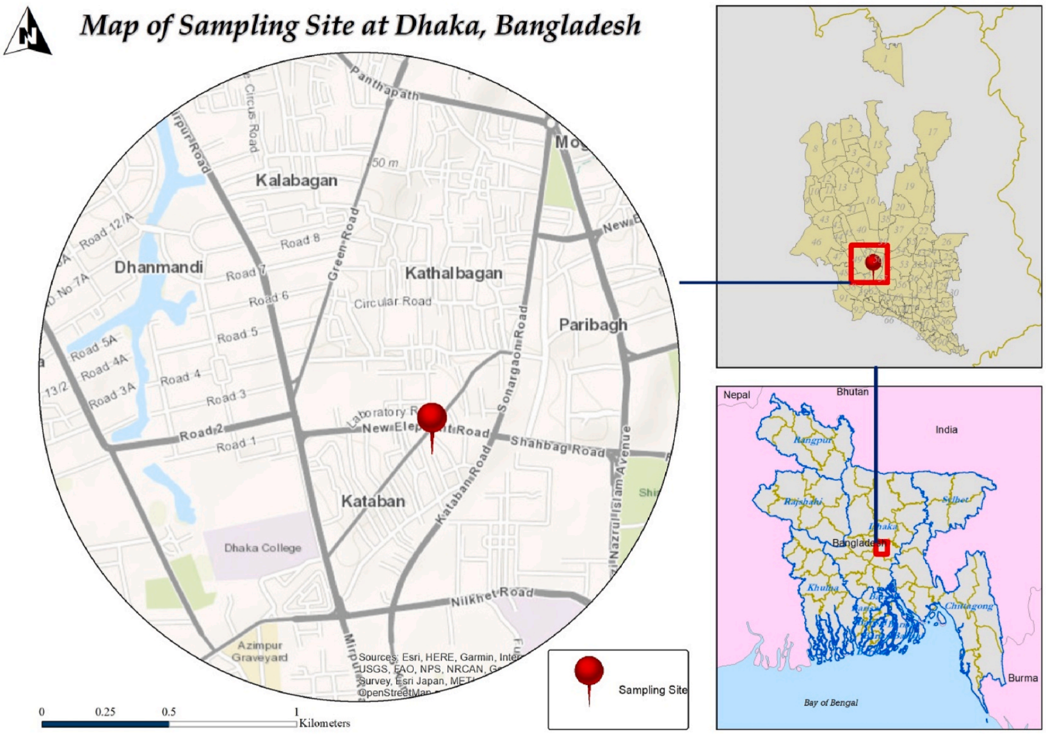


Fig. 1. Map of sampling site

equipped mobile air quality monitoring system integrated with an automatic sampling system (AQMS, Horiba, Japan). The air sampling inlet is well-protected to function in different weather conditions. An automatic temperature control unit has been connected to the inlet to remove moisture from the samples. Every hour for 24 h, at a flow rate of 16.7 L/min, $PM_{2.5}$ samples were taken from an air sampling inlet onto a 2-layer non-woven PTFE fabric filter tape for this study. The device automatically measured the sample volume and calculated the mass concentration of particulate matter and elements at the sampling location. An adjacent X-ray fluorescence spectroscopy was used to conduct an in-situ analysis of all the elements in filter tape (PX-375 analyzer, Horiba, Japan). This instrument was used for quantitative analysis of the elements in the collected samples by beaming the X-rays released by the X-ray tube to the sample and then detecting the characteristic X-rays, which were emitted from the sample and had element-specific energy, with the silicon drift detector (SDD) [10]. The exact geographical location of the sampling site is 23°44′20.87″ N latitude and 90°23′18.99″ E longitude. The concentration of the following elements was measured: Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Pb, Al, Si, S, K, and Ca, where 168 data points were obtained for each element. The instruments in the van collected air samples every hour and automatically monitored the concentration in the computer dataset. The sampling started on March 21, 2022 at 9:00 a.m. and ended on March 28, 2022 at 9:00 a.m.

2.3. *Local meteorology*

The climate of Bangladesh is characterized by consistent high temperatures, high levels of humidity, and notable seasonal fluctuations in precipitation [4]. Depending on the meteorological condition, the climate of Bangladesh has four seasons a year, including pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February) [24]. According to Begum & Hopke, there is a rise in relative humidity, moderately strong winds, and rainfall during the pre-monsoon season, which is dominated by southwestern (marine) winds [25]. During post-monsoon, the wind speed decreases, and the direction shifts to the northeast. Dry soil, low relative humidity, little precipitation, and weak northwest wind conditions are characteristics of the winter season. During the monsoon, the chemical composition of $PM_{2.5}$ is affected by moist air and marine sea salt delivered by the air mass from the Bay of Bengal [22].

2.4. *Data analysis*

The potential sources of the trace elements were determined using PMF modeling. Respiratory deposition dose was calculated to estimate the health risk posed by those elements in the human respiratory system. Air mass back trajectories were computed using the Hybrid Single-Particle Lagrangian Integrated Trajectory web version (HYSPLIT). Wind components were visualized using reanalysis data obtained from the ECMWF website [26].

2.4.1. *Air mass trajectory analysis using HYSPLIT modeling*

Backward trajectories were analyzed to determine the routes taken by air masses to reach the sample site using the HYSPLIT model developed by the National Oceanic and Atmospheric Administration/Air Resources Laboratory [27]. HYSPLIT is a computer program that computes air parcel trajectories, i.e., how far and in which direction a parcel of air, and consequently air pollutants, will move. The backward trajectories were started from the BCSIR Elephant Road entrance (23°44′20.87″ N and 90°23′18.99″ E). To determine the possible transport pathways of $PM_{2.5}$ from its potential sources in Dhaka, a 48 h/2 days backward trajectory above ground level was measured with 500 m as the starting height and at a 6-h interval using the HYSPLIT model. The trajectory time was chosen 48-h because the aim was to know how the local sources and processes contributed to the changes in $PM_{2.5}$ concentration. The starting height was chosen at 500 m to avoid interrupting the backward trajectories at lower altitudes [22]. It is also approximately the height of the mixing layer [4]. The starting time was local time 11:00 p.m. (UTC 17:00), except for the last day, which was local time 9:00 a.m. (UTC 3:00). Also, to visualize the wind component, the reanalysis data were obtained from the ECMWF website [26]. The gridded data were then plotted using the GrADS (Grid Analysis and Display System) platform.

2.4.2. *PMF source apportionment model*

Source apportionment of the elements was conducted with the help of EPA PMF 5.0 software. EPA PMF is a model of the United States Environmental Protection Agency (US EPA) to determine the sources of the pollutants [28]. It is a mathematical factor-based receptor model that illustrates source types with a robust uncertainty estimate [29]. One hourly measurement of 15 elements for continuous 8-day sampling has been performed. There were a total of 168 samples and 15 variables that were applied to PMF modelling. Concentration and uncertainty data were run through EPA PMF 5.0 software [29]. The uncertainty value of each sample of each variable was calculated with the help of the empirical formula Eq. (1):

$$\sigma_{ij} = 0.03(X_{ij} + X_j) \tag{1}$$

where,

σ_{ij} = the estimated measurement error for jth species in the ith sample.
X_{ij} = the observed concentration of elements.
X_j = the mean value.

The factor 0.03 was determined through trial and error procedures [30].

The estimation of uncertainty was calculated with the help of Eq. (2) [31,32]:

$$S_{ij} = \sigma_{ij} + CX_{ij} \tag{2}$$

where,

S_{ij} = uncertainty

σ_{ij} = the estimation of measurement error.

X_{ij} = the observed concentration of elements.

C = constant, a value of 0.2 was used for this project [32] because it generated the highest Q value since the results are mostly in line with theory and are physically interpretable [29].

After running the concentration and uncertainty data of 15 elements on EPA PMF, the determined factor value of 4 helped us to explain the sources of the elements.

2.4.3. Estimation of respiratory deposition dose

The respiratory deposition dose (RDD) approach is used to assess the effects of any air pollutant on human respiratory health. It is the mass of a given particle size deposited in the respiratory system [33]. Hinds developed a method for estimating the mass deposition of heavy metals in the respiratory system [34]:

$$M_{dep} = PM * V_m * (DF) \tag{3}$$

where,

M_{dep} = the mass of a given particle size deposited in the respiratory system per unit time (ng/h).

PM = concentration of trace elements (ng/m^3).

V_m = the inhalation rate; according to the International Commission on Radiological Protection (ICRP) deposition model, the inhalation rate for males is 1.5 m^3/h, and for females is 1.25 m^3/h during light exercise. The inhalation rate for males is 3.0 m^3/h, and for females is 2.70 m^3/h during heavy exercise. And for infants of 1-year-old, the rate is 0.35 m^3/h [35].

DF = the deposition fraction of particles (ICRP model only considers diffusional, gravitational, and inertial depositions).

According to the airways of the particles, there are three depositional areas, such as upper airway (UA), tracheobronchial region (TB), and alveolar region (AL). So, DF for three airways was estimated for trace elements found in $PM_{2.5}$ using equations (4), (6) and (7) [34].

2.4.3.1. Upper airway

$$DF_{UA} = IF \text{ x } \left(\frac{1}{1 + exp\ (6.84 + 1.183\ In\ d_p)} + \frac{1}{1 + exp\ (0.924 - 1.885\ In\ d_p)} \right) \tag{4}$$

where IF is the inhalable fraction, estimated by ref. [34]:

$$IF = 1\text{-}0.5 \left(1\text{-}\frac{1}{1 + 0.00076 d_p^{2.8}} \right) \tag{5}$$

2.4.3.2. Tracheobronchial region

Table 1
Statistical parameters of concentration of trace elements in $PM_{2.5}$ (SD: standard deviation)

Elements	Mean	Maximum	Minimum	SD	Median
Ti (ng/m^3)	12.5	48.8	0.980	9.64	10.2
V (ng/m^3)	0.637	4.14	0.0100	0.735	0.420
Cr (ng/m^3)	2.01	15.8	0.0200	2.56	0.935
Mn (ng/m^3)	26.3	106	8.84	15.6	21.3
Fe (ng/m^3)	360	874	152	142	332
Ni (ng/m^3)	3.92	32.4	0.160	5.51	1.79
Cu (ng/m^3)	13.2	140	0.100	21.9	4.80
Zn (ng/m^3)	899	12,900	46.7	1890	187
As (ng/m^3)	603	3620	124	620	372
Pb (ng/m^3)	143	2060	12.1	253	68.6
Al (ng/m^3)	1540	3600	679	538	1390
Si (ng/m^3)	2540	7540	1020	1060	2340
S (ng/m^3)	11,300	28,400	3880	3970	10,600
K (ng/m^3)	852	1940	225	357	770
Ca (ng/m^3)	513	1350	152	210	451

$$DF_{TB} = \left(\frac{0.00352}{d_p}\right)\left[\exp\left(-0.234(\ln d_p + 3.40)^2\right) + 63.9\exp\left(-0.819(\ln d_p - 1.61)^2\right)\right] \quad (6)$$

2.4.3.3. Alveolar region

$$DF_{AL} = \left(\frac{0.0155}{d_p}\right)\left[\exp\left(-0.416(\ln d_p + 2.84)^2\right) + 19.11\exp\left(-0.482(\ln d_p - 1.362)^2\right)\right] \quad (7)$$

where,

d_p = particle size is 2.5 μm since we are dealing with trace elements in $PM_{2.5}$

The sum of DF_{UA}, DF_{TB}, and DF_{AL} for one full breath for the entire respiratory tract is the total deposition fraction (DF).

3. Results and discussions

3.1. Data variability and trajectory modeling

Concentrations of 15 elements (Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Pb, Al, Si, S, K, and Ca) were obtained from BCSIR. Details of the elemental concentration are shown in Table 1.

The maximum concentration of the elements (ng/m^3) were: Ti (48.8), V (4.14), Cr (15.8), Mn (106), Fe (874), Ni (32.4), Cu (140), Zn (12,900), As (3620), Pb (2060), Al (3600), Si (7540), S (28,400), K (1940), and Ca (1350). The minimum concentration of the elements (ng/m^3) were Ti (0.980), V (0.0100), Cr (0.0200), Mn (8.84), Fe (152), Ni (0.160), Cu (0.100), Zn (46.7), As (124), Pb (12.1), Al (679), Si (1020), S (3880), K (225), and Ca (152). Sulfur had the highest concentration of all, which was 28,428 ng/m^3. Vanadium had the lowest concentration of all, which was 0.01 ng/m^3. All these data are given in three significant figures. A mathematical calculation may give a long answer, with too many digits, in such cases all the values are expressed with fixed number of significant figures [36].

The concentration of $PM_{2.5}$ is shown in Table 2. The 24-h average concentrations of $PM_{2.5}$ varied from 77 μg/m^3 to 153 μg/m^3, which were alarmingly higher than that of the WHO 24-h guideline (25 μg/m^3) and 24-h US EPA National Ambient Air Quality Standard (NAAQS) (35 μg/m^3) [37]. It would be relevant to mention that the average concentrations of $PM_{2.5}$ measured in some other urban locations of Asia, such as Bangkok, Beijing, Chennai, Manila, Hanoi, and Bandung were, respectively, 34, 136, 44, 43.5, 78.5 and 45.5 μg/m^3 [38]. Concentrations of the elements were found high during the middle of the day, specifically from 11 a.m. to 2 p.m., and low during midnight, specifically from 11 p.m. to 4 a.m. Most of the elements showed this trend for highs and lows in their concentrations. However, some exceptions were also seen, such as V, Ni, and S showing higher concentrations throughout the day. This difference is shown in Fig. 2(a–f). Fig. 2 (a) shows the high concentration of Pb during the mid-day, whereas in Fig. 2 (b), the concentration of S is seen to be elevated throughout the day in a scattered manner. We assume that the very high frequency of transport and intense construction and demolition activities are responsible for largest emission load of pollutants during the daytime. Emissions from both these sources substantially reduce by midnight, which is reflected in the low concentration of trace elements from 11 p.m. to 4 a.m.

According to Begum et al. the reason behind the high concentration of sulfur is likely to be the sulfur sources available in Dhaka [4]. Dhaka is a heavily congested city, where emissions from diesel- or petrol-run vehicles, especially two-wheel motorcycles and heavy trucks, contribute significantly to air pollution. Diesel fuel contains around 3000 ppm of sulfur. So, the amount of particulate sulfur emissions is also rather large. Also, the coal burnt in brick kilns includes 4–6% sulfur, which is abundant around the city. Brick kilns are responsible for 38% of the total $PM_{2.5}$ levels in the Dhaka Metropolitan Area [39] and contribute to 84% of the sulfur [25]. The brick kilns are located all around the city, for instance, on the banks of Dhaleshwari, Buriganga, Shitalakshya, and Turag rivers, and also on the northern side of Dhaka [40]. Based on the data obtained from backward trajectory analysis, the brick kilns located on the banks of Dhaleshwari and Buriganga rivers is likely to be a major contributing factor to the air pollution of the sampling site. Sulfur emitted from various sources causes the formation of acid rain and decreases atmospheric visibility. Breathing in too much sulfur can irritate airways and cause coughing. Irritation in the respiratory tract (nose, throat, and lungs), skin, and eyes portray some major effects of sulfur on the human body.

Table 2
Statistical parameters of concentration of $PM_{2.5}$.

$PM_{2.5}$ (μg/m^3)					
Date	Mean	Max	Min	SD	Median
March 21, 2022	153	212	79.0	39.8	153
March 22, 2022	145	262	87.0	59.4	118
March 23, 2022	108	152	79.0	18.0	106
March 24, 2022	87.2	107	69.0	12.4	90.5
March 25, 2022	81.0	122	52.0	20.9	79.0
March 26, 2022	77.0	103	51.0	15.0	73.5
March 27, 2022	96.9	132	58.0	21.8	97.0
March 28, 2022	93.1	108	83.0	7.98	92.0

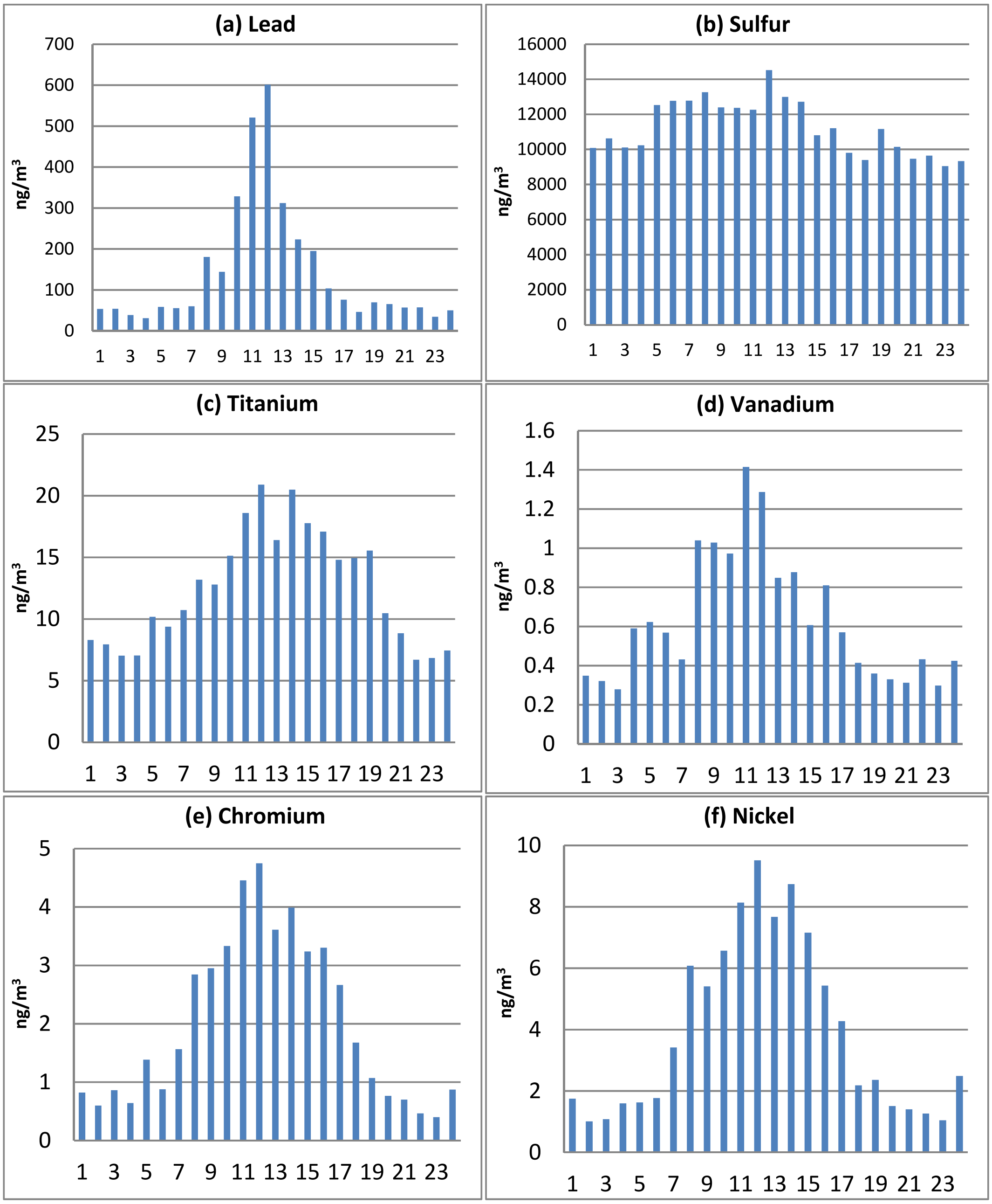


Fig. 2. Diurnal variation in mean concentration of select elements.

The air mass transport pathways of $PM_{2.5}$ are shown in Fig. 3(a–c). HYSPLIT backward trajectory (BT) models were used to determine air mass transportation in Dhaka. In Fig. 3, the computed air parcel trajectories show how far and in what direction a parcel of air, and subsequently air pollutants, traveled each day. The result shows that most of the air mass (78%) came from the eastern, western, and northern parts of India. This finding aligns with other research, which also found that most of the air mass transported to Dhaka during February and March originated in northern and eastern India, including Kolkata [22]. This indicates that the composition of $PM_{2.5}$ is significantly impacted by transboundary urban emission sources. Also, some air mass originated from Pakistan and Afghanistan and then traveled over India. Some common industries in Pakistan are light engineering and electrical industries, steel industries, thermal power plants, petroleum refineries, fertilizer manufacturing plants, and so on [3]. Depending on the air mass transport pathways, we can state that the air of Dhaka has transboundary impacts. As stated by Begum et al. before reaching out to the study site in Dhaka, a significant part of the pollutants travels over India, which heavily depends on coal for energy [4]. Also, biofuel consumption is vast in India, which could account for about one-half of the total fuel consumption in India.

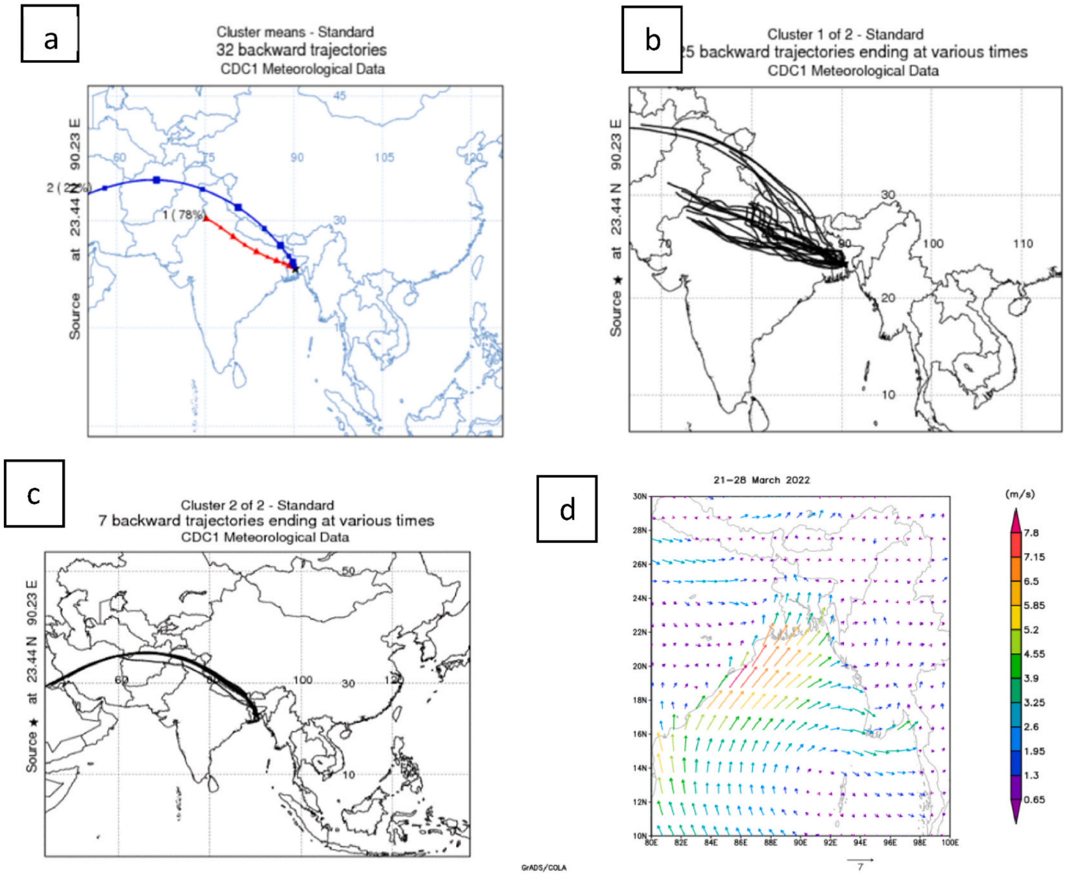


Fig. 3. Air mass circulation and wind vector using HYSPLIT and GRADS, respectively

A wind field has been presented in Fig. 3(d), which is retrieved from the ECMWF reanalysis data repository. The plot demonstrates the wind circulation during the end of March in 2022. It circulates both from the western as well as the southwestern region. However, the magnitude of the wind was stronger in the southwestern Bay of Bengal region than in the western Indian part. The regional synoptic wind circulation pattern around IGP (Indo Gangetic Plain) region shows that the wind vector is dominated by southwestern winds during the pre-monsoon season, which aligns with previously published articles [25].

3.2. Source apportionment

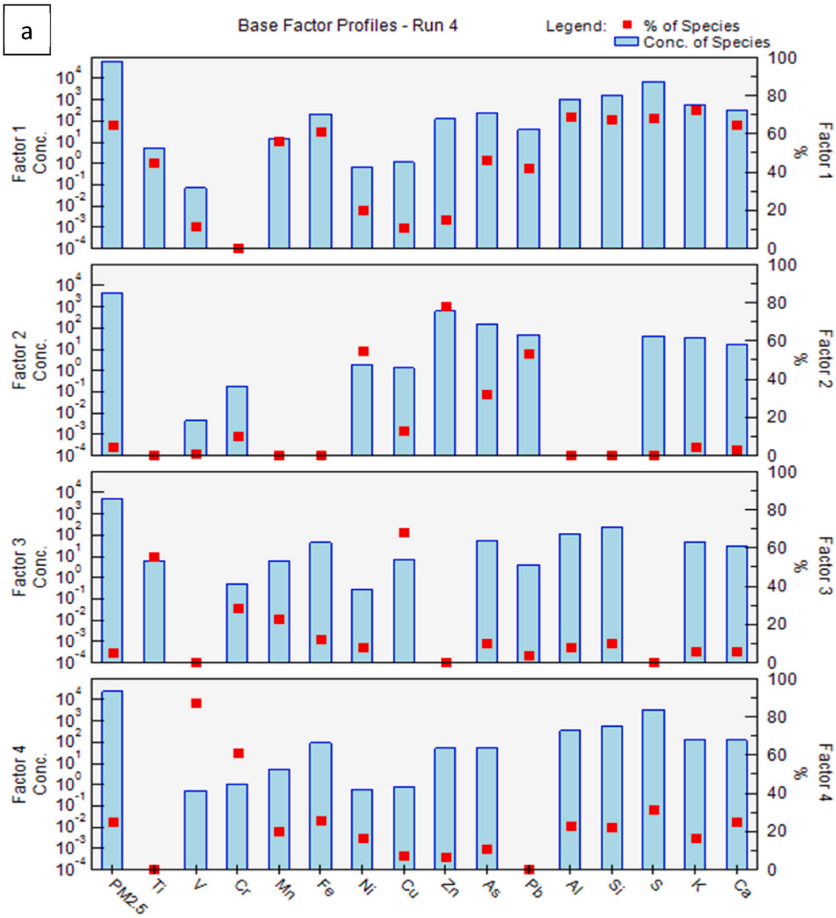
Concentrations of the 15 trace elements were analyzed using the EPA PMF 5.0 software to identify the potential dominant sources. EPA PMF modeling determined four factors for the trace elements in $PM_{2.5}$. The four sources of trace elements identified in $PM_{2.5}$ are soil dust with S-rich petroleum oil, industrial emission, non-exhaust emission, and heavy engine oil combustion. The determined source profiles are shown in Fig. 4 (a).

3.2.1. Factor profile 1 (soil dust)

The first source profile includes a high amount of Al, Si, S, K, and Ca and a small amount of Ti, Fe, Ni, As, and Pb, representing soil dust with S-rich petroleum oil. Si, Al, Fe, K, Ti, and Ca are crustal tracer elements since they are part of the elements that make up the Earth's crust [41]. A complex mixture of organic and inorganic substances that are transported, deposited, and then resuspended makes up road/soil dust [42]. According to Begum & Hopke, soil dust has seasonal variation and contributes significantly more in the winter [25]. Agricultural lands near the city and construction projects may contribute to this profile. Sulfur may be released from diesel used in trucks; around 3000 ppm of sulfur can be found in diesel. However, these trucks are allowed in the streets of Dhaka only from 10 p.m. to 6 a.m. [4].

3.2.2. Factor profile 2 (industrial emission)

The second source profile consists of Ni, Zn, Pb, and As, which represents industrial emission source. As stated by Islam et al. Ni is used to manufacture stainless steel and other nickel alloys [43]. In the metallurgical, chemical, and food processing industries, nickel metal and its alloys are widely used, particularly as catalysts and pigments. Some other sources of nickel are dye, paints and varnishes,



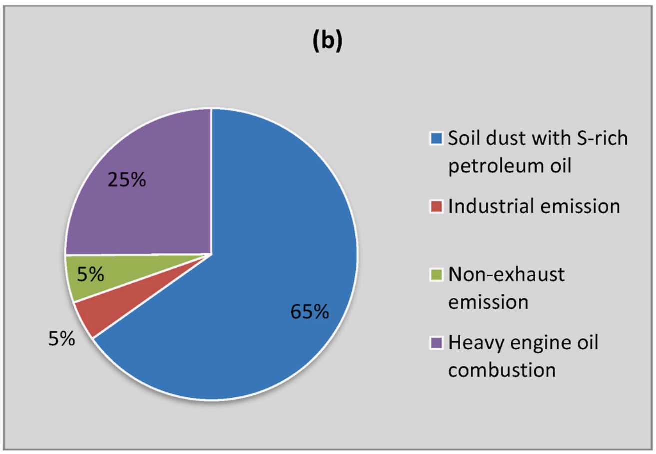


Fig. 4. (a) Source profiles of trace elements in $PM_{2.5}$; (b) Source contribution of $PM_{2.5}$; (c–h) Source contribution of some health concern elements.

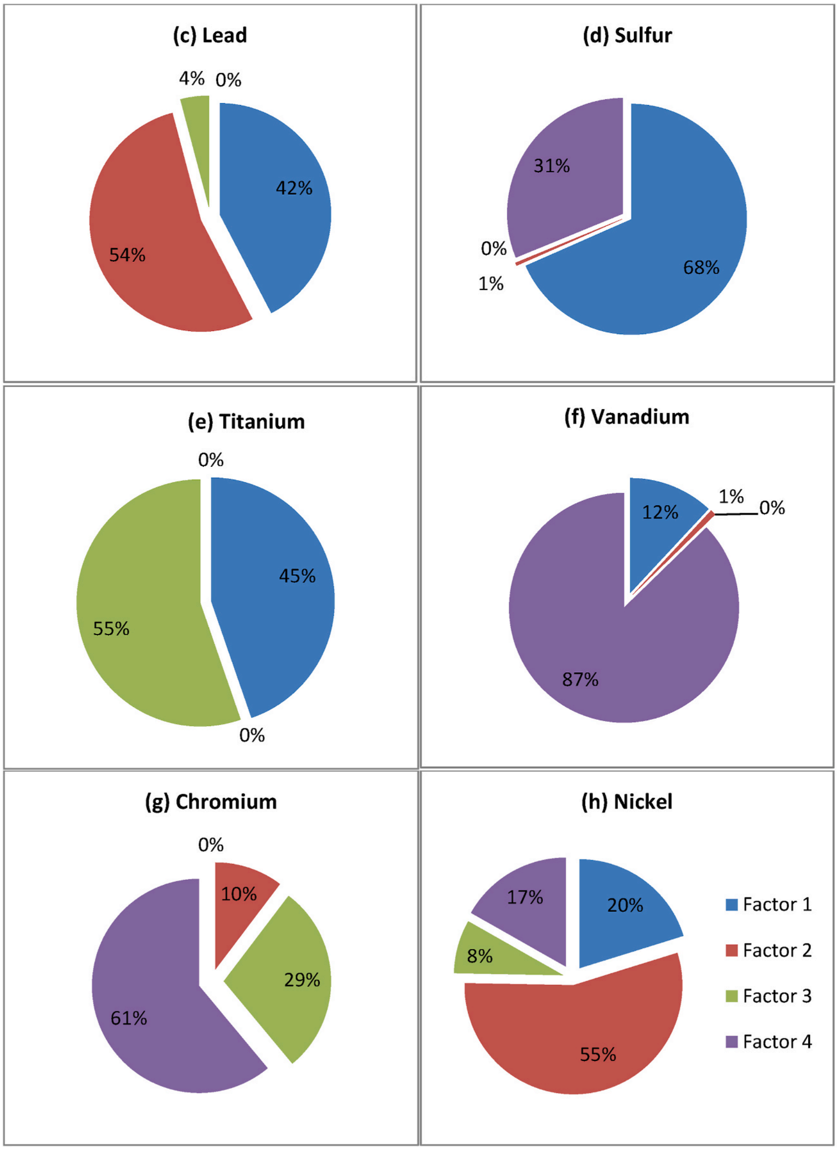


Fig. 4. (*continued*).

electrical equipment, telephone cables, and building materials. The principal sources of airborne zinc are emissions from industrial processes and condensed traffic [44]. According to Hao et al. the steel industry was identified as a significant source of Zn, and copper smelting plants emit Pb and As [45]. Also, burning coal contributes to the higher Ni, Zn, Pb, and As emission ratios from coal-fired power plants [46,47]. A major source of As, Pb, and Zn in China is coal combustion from coal-fired power plants, residential sectors, and industrial boilers [48]. Zn can be emitted from steel manufacturing industries as well [46].

3.2.3. Factor profile 3 (non-exhaust emission)

The third source profile consists of a non-exhaust emission source with a high amount of Ti, Cu, Cr, Mn, and Fe. Non-exhaust emissions occur from wearing brakes, tires, and roads and re-suspension of road dust [49]. Non-exhaust emission contributes to air pollution as much as exhaust emission. As of 2021, about 1.6 million motor vehicles were registered in Dhaka [50]. According to Thorpe & Harrison, numerous metals are widely utilized in brake lining components, such as Fe, Cu, Ti, Cr, Mn, and Zn [51]. Thorpe and Harrison found the presence of K (1.4–4.1 %), Ti (4.6–9.5 %), Cu (13.0–17.6 %), and Ba (7.3–13.2 %) during a bulk material analysis of three types of brake pads used frequently in Japan [51]. Potassium titanate, a substance frequently added to brake pads to increase wear characteristics and heat resistance, is where K and Ti are derived from. Al, Ca, Cu, Fe, Ti, and Zn are used in the manufacturing of tires as well. Cu is identified as a tracer for brake and tire wear because it is most abundant in brake linings [52]. The metals which are most likely to be released from brake and tire wear is usefully indicated by the chemical makeup of the brake lining material and tire, which is why we can conclude that Ti, Cu, Cr, Mn, and Fe are emitted from non-exhaust sources.

3.2.4. Factor profile 4 (heavy engine oil combustion)

The fourth profile consists of a heavy oil combustion source with a high amount of V, Cr, and Fe and a tiny amount of Al, Si, S, K, and Ca. Vanadium is emitted from heavy lubricating oil and coal combustion [53]. It is produced by the burning of fuel and lubricating oil in tailpipe emissions [54]. Cr and Fe are produced from non-exhaust emissions, such as the wearing of brakes and tires [51]. As cited in Lin et al. in addition to road dust, the principal sources of Fe in locations near traffic emissions include worn debris from brake linings and tires as well as diesel engine emissions [54]. Also, Cu is one of the main lubricating oil additives [55].

The percentage of source contribution was obtained from PMF analysis. Factor 1 is related to soil dust with S-rich petroleum oil, which contributes to 65 % of the pollution. The second source is industrial emission which contributes to 5 % of the pollution. The third factor is non-exhaust emission, which contributes to 5 %, and factor 4 is heavy engine oil combustion, which contributes to 25 % of pollution. The source contribution is shown in a pie chart in Fig. 4 (b). Also, source contributions in each factor profile of some health concern elements are shown in Fig. 4(c–h).

3.3. Respiratory deposition dose

Respiratory deposition doses are determined for males and females during light exercise, males and females during heavy exercise, and infants. RDD for three layers of the human respiratory system was determined: upper airway (UA), tracheobronchial region (TB), and alveolar region (AL). The sum of the three layers RDD is determined as the total RDD. The respiratory deposition dose varies with the capacity of the lungs, which depends on the age, gender, and intensity of physical activity of the individual. The amount of respiratory deposition also depends on the amount of pollution and the duration of exposure. Here, light exercise means the subject is mostly standing or walking at a normal pace, i.e., the inhalation rate for a male is 1.5 m^3/h, and for a female is 1.25 m^3/h. During heavy exercise, the inhalation rate for a male is 3.0 m^3/h, and for a female is 2.70 m^3/h. In the context of Dhaka, heavy exercise may include but is not limited to manual labor, for example-pulling rickshaws, vans, and carts, construction and demolition works, manual transportation of heavy weight, and even working out for fitness. Doing heavy exercise increases the rate of respiration, thereby increasing the respiratory deposition dose of the pollutants. Also, they are exposed to polluted air for a longer amount of time.

The highest deposition dose of the elements is seen in the respiratory system of a male during heavy exercise. The second highest deposition dose is seen in a female during heavy exercise. These are followed by a male during light exercise, a female during light exercise, and a 1-year-old infant. So the deposition dose among different groups shows the trend: male (heavy exercise) > female (heavy exercise) > male (light exercise) > female (light exercise) > infant. The adult population is exposed to pollution more than infants and has a higher inhalation rate, which is why the amount of deposition is greater among adults than infants.

The deposition dose of the trace elements in $PM_{2.5}$ in upper airways, the tracheobronchial and alveolar region shows a trend: S > Si > Al > Zn > K > As > Ca > Fe > Pb > Mn > Cu > Ti > Ni > Cr > V. From Fig. 5, we can state that sulfur has the highest amount of deposition in our respiratory system with the mean total deposition of 28,913 ng/h for males during heavy exercise, 26,021 ng/h for females during heavy exercise, 14,456 ng/h for males during light exercise, 12,047 ng/h for females during light exercise and 3373 ng/h for infants. Vanadium has the lowest deposition with a mean total deposition of 1.63 ng/h for males during heavy exercise, 1.47 ng/h for females during heavy exercise, 0.817 ng/h for males during light exercise, 0.681 ng/h for females during light exercise and 0.191 ng/h for infants.

In the three layers of the respiratory system, the highest amount of deposition has occurred in the upper airway (UA). The mean deposition of sulfur in the UA region is 11,613 ng/h for males during light exercise, 9677 ng/h for females during light exercise, 2709 ng/h for infants, 23,226 ng/h for males during heavy exercise, and 20,903 ng/h for females during heavy exercise. The tracheobronchial region (TB) has the lowest amount of deposition. The mean deposition of sulfur in the TB region is 1024 ng/h for males during light exercise, 854 ng/h for females during light exercise, 239 ng/h for infants, 2049 ng/h for males during heavy exercise, and 1844 ng/h for females during heavy exercise. Moderate deposition has occurred in the alveolar region (AL). The mean deposition of sulfur in the AL region is 1818 ng/h for males during light exercise, 1515 ng/h for females during light exercise, 424 ng/h for infants, 3637 ng/h for males during heavy exercise and 3273 ng/h for females during heavy exercise. The mean deposition of vanadium in the

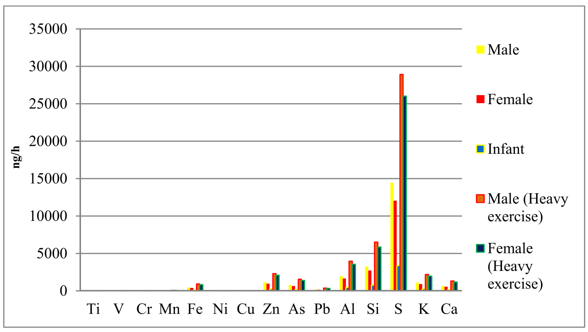


Fig. 5. Total respiratory deposition dose in male and female (light exercise), male and female (heavy exercise) and infant.

UA region is 0.657 ng/h for males during light exercise, 0.547 ng/h for females during light exercise, 0.153 ng/h for infants, 1.313 ng/h for males during heavy exercise and 1.182 ng/h for females during heavy exercise. The mean deposition of vanadium in the TB region is 0.058 ng/h for males during light exercise, 0.048 ng/h for females during light exercise, 0.014 ng/h for infants, 0.116 ng/h for males during heavy exercise and 0.104 ng/h for females during heavy exercise. The mean deposition of vanadium in the AL region is 0.103 ng/h for males during light exercise, 0.086 ng/h for females during light exercise, 0.024 ng/h for infants, 0.206 ng/h for males during heavy exercise and 0.185 ng/h for females during heavy exercise. Fig. 6(a–e) shows the mean RDD for different groups in three airways of the human respiratory system. In a recent study in Dhaka, it was observed that the highest deposition was seen in UA [10]. One of the primary mechanisms causing the high deposition at the mouth-throat and upper airways is inertial impaction, which is caused due to short residence time and increased velocity [56]. The upper airways trap most of the elements with the help of its natural filtration system. They trap relatively bigger particles that go to our stomach through mucus and are excreted. Smaller particles are deposited in TB and AL regions. Prolonged contact with carcinogenic elements is associated with serious health risks. Long-term exposure to certain elements may result in disorders of the heart, blood vessels, liver, kidneys and brain. The medical professionals will be able to address the problem associated with respiratory issues according to the findings of this study.

The highest deposition occurred from 11 a.m. to 2 p.m. The lowest amount of deposition occurred from 11 p.m. to 4 a.m. However, elements like sulfur showed high deposition throughout the day. Fig. 7(a–b) shows the difference between lead and sulfur deposition throughout the day. Pb follows the trend of high deposition from 11 a.m. to 2 p.m., but S does not follow that trend. Hourly deposition of Ti, V, Cr, and Ni is also shown in Fig. 7 (c). Trace elements will have both long-term and short-term health effects on an exposed individual. This data can help in determining safe schedules for the population. For example, to avoid higher RDD during daily exercise

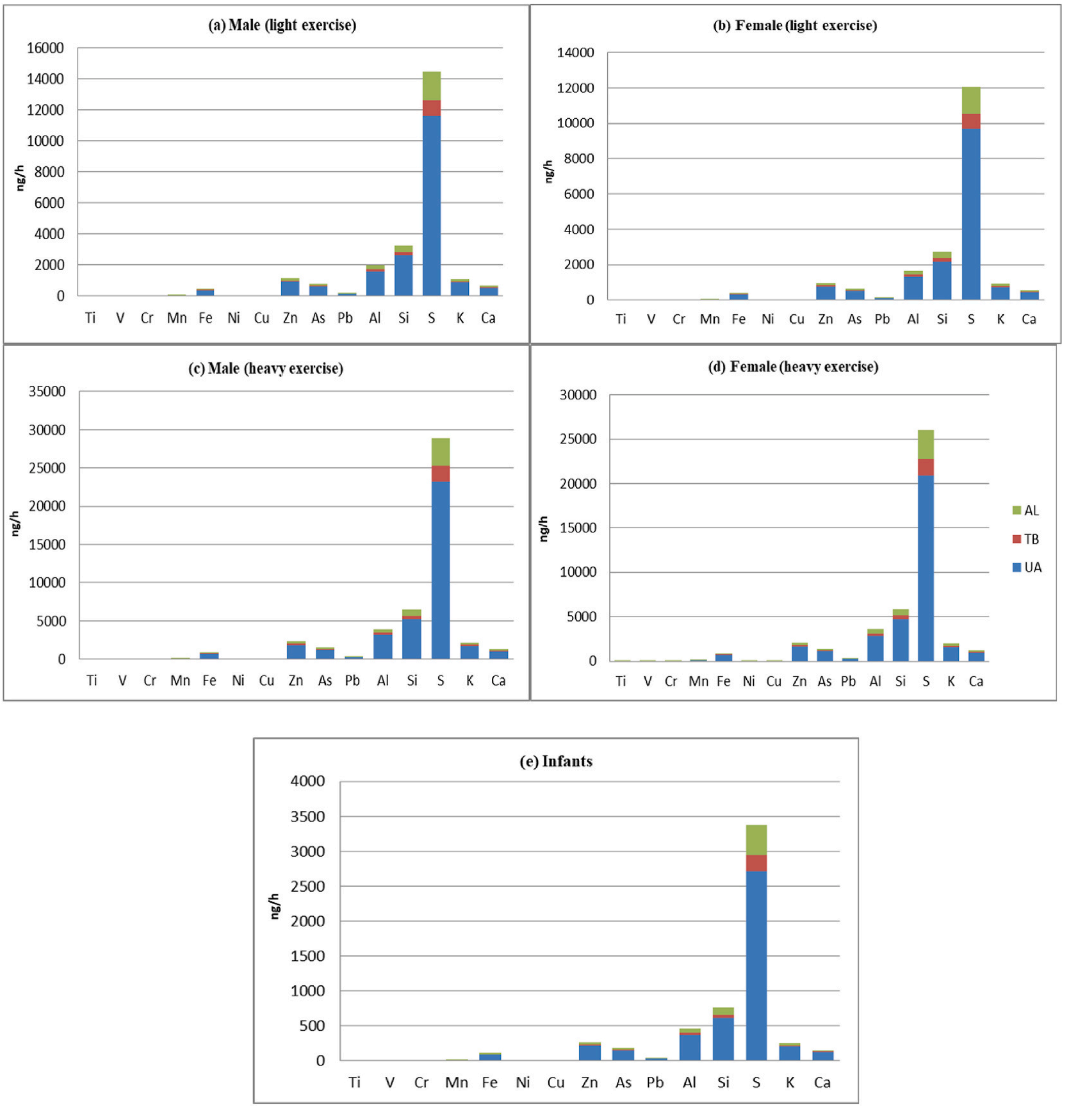


Fig. 6. (a–e) Mean RDD for different groups in three airways of the human respiratory system.

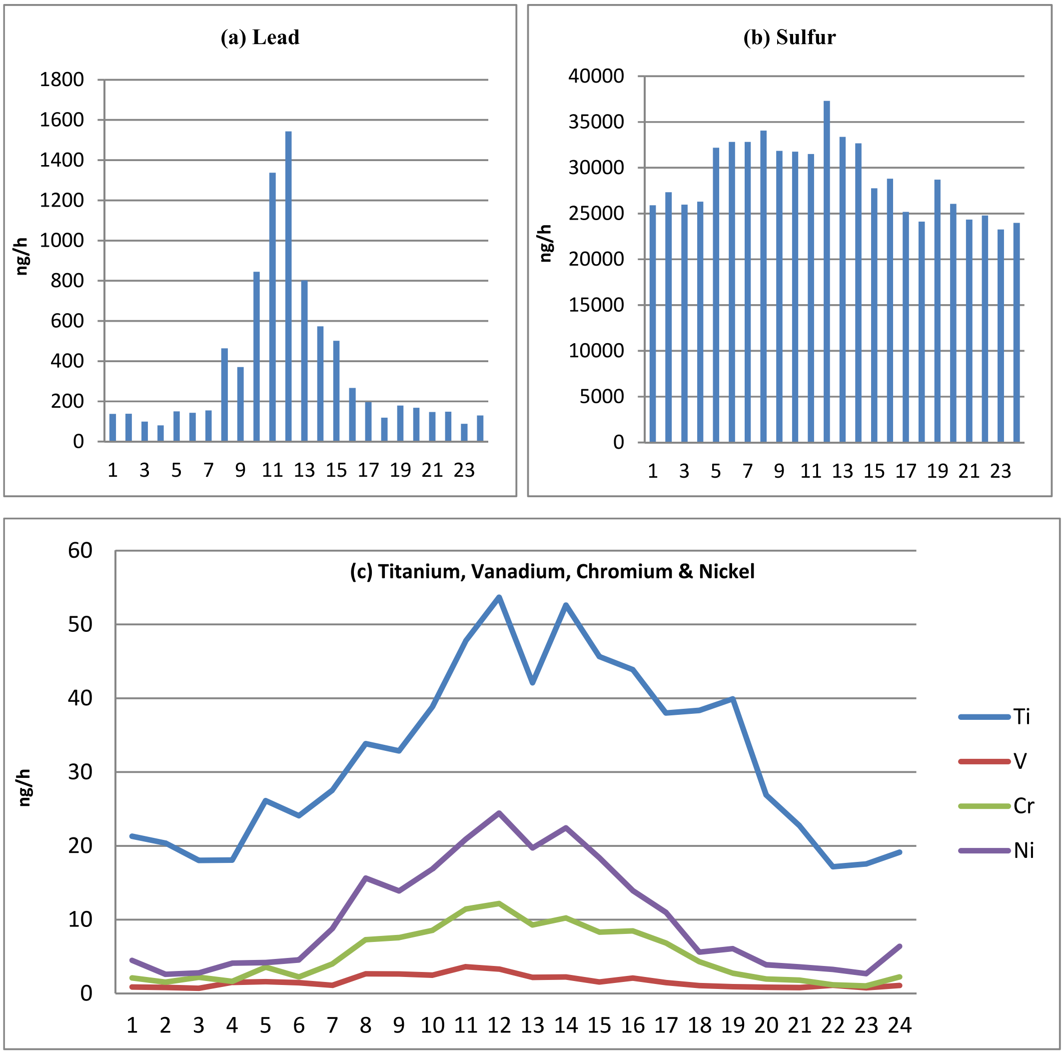


Fig. 7. Hourly total deposition dose of (a) lead, (b) sulfur, and (c) titanium, vanadium, chromium and nickel in the respiratory system of males during heavy exercise.

if one wants to know what a safer time is, we can establish that early morning can be a suitable time to exercise. From the results identified, it can be concluded that preventive measures to reduce trace elements in air are necessary at the moment.

4. Conclusion

This study determined the concentration and sources of 15 trace elements in $PM_{2.5}$ in Dhaka's air. Sulfur was found to be the dominant trace element. Direct sulfur emissions from motor vehicles and coal burning in brick kilns might be the causes of its abundance in the air. Sulfur causes acid rain and decreases atmospheric visibility. Four pollution sources of these elements were identified: soil dust with S-rich petroleum oil, industrial emission, non-exhaust emission, and heavy engine oil combustion. Based on the air mass backward trajectory analysis, we can conclude that sources of $PM_{2.5}$ are not only localized but are also impacted by transboundary air pollution. The diurnal patterns of elemental concentrations and respiratory deposition dose gave us an in-depth scenario of the concentration and deposition trends. The RDD of each element was determined for the respiratory system of subjects grouped by gender and the intensity of exercise. RDD varies with the capacity of the lungs, which depends on the age, gender, and intensity of physical activity of the individual. RDD also depends on the amount of pollution and the duration of exposure. RDD was the highest for males during heavy exercise, which indicates that this group has a higher inhalation rate, greater intensity of physical activity, and is exposed to more pollution for a longer duration of time. From the diurnal pattern, it was observed that the highest amount of deposition occurred from 11 a.m. to 2 p.m., and the lowest amount of deposition occurred from 11 p.m. to 4 a.m. Sulfur has the most elevated deposition among all the other elements in $PM_{2.5}$. Irritation in the respiratory tract, skin, and eyes is one of the significant impacts of sulfur on the human body. Measures to reduce sulfur in the air are therefore very much needed. Fuel with less sulfur content and improved technologies in brick kilns are necessary. One notable step the government has taken is measures to reduce sulfur emissions by replacing diesel/petrol with CNG and by allowing heavy-duty diesel vehicles on the road in Dhaka from only 10 p.m. until 6 a.m. This study demonstrates these measures are far from being enough. If genuinely effective measures are not taken soon to mitigate the emission of $PM_{2.5,}$ significant damage to public health will continue and exacerbate over time. The increasing risk to public health from the alarmingly high concentration of trace elements in $PM_{2.5}$ and their respiratory deposition dose underscores the urgent need for government authorities to formulate effective policies for pollution control and fast-track their implementation.

Additional information

No additional information is available for this paper.

Data availability

The data associated with our study has not been deposited into any publicly available repository. It will however be made available upon request.

CRediT authorship contribution statement

Zarin Tasneem Jawaa: Writing – review & editing, Writing – original draft, Formal analysis. **Karabi Farhana Biswas:** Writing – review & editing, Validation, Supervision. **Md Firoz Khan:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Mohammad Moniruzzaman:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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