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RESEARCH ARTICLE

Source identification and health risk assessment of $PM_{2.5}$ in urban districts of Hanoi using PCA/APCS and UNMIX

Thi Hieu Bui[1] · **Thi Phuong Mai Nguyen**[2]

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Abstract

Comparing results obtained by different models with different physical assumptions and constraints for source apportionment is important for better understanding the sources of pollutants. Source apportionment of $PM_{2.5}$ measured at three sites located in inner urban districts of Hanoi was performed using two receptor models, UNMIX and principal component analysis with absolute principle component score (PCA/APCS). A total of 78 daily samples were collected consecutively during the dry and wet seasons in 2019 and 2020. The average $PM_{2.5}$ concentration (66.26 μg/m^3 ± 29.70 μg/m^3 with a range from 23.57 to 169.04 μg/m^3) observed in Hanoi metropolitan exceeded the National Ambient Air Quality standard QCVN 05:2013/BTNMT (50 μg/m^3). Both UNMIX and PCA/APCS expressed comparable ability to reproduce measured $PM_{2.5}$ concentrations. Additionally, both models identified similar potential sources of $PM_{2.5}$ including traffic-related emissions, scrap metal recycling villages, crustal mixed with construction sources, coal combustion mixed with industry, and biomass burning. Both UNMIX and PCA/APCS confirmed that traffic-related emission was the most influential $PM_{2.5}$ with a high percentage contribution of 59% and 55.97%, respectively. All the HQ and Cr values for both children and adults of toxic elements apportioned by both UNMIX and PCA/APCS in every source were within the acceptable range.

Keywords $PM_{2.5}$ · Trace metals · Source apportionment · UNMIX · PCA/APCS · Health risk assessments

Introduction

Over the past 30 years, many researchers have pointed out the association between airborne particulate matter and adverse health effects. This is especially true for fine particles (dynamic diameter < 2.5 μm) due to their high number concentration and deep penetration to the human respiratory system with high deposition efficiencies (Kim et al. 2004). $PM_{2.5}$ concentration in Hanoi exceeded the annual Ambient Air National Standard, ranging from 28.15 to 39.4 in 2019 (Nhung et al. 2022). Incidentally, the urban districts of Hanoi experienced the highest pollution levels due to high population density, large number of traffic fleets, and many socioeconomic activities. The number of premature deaths due to $PM_{2.5}$ exposure in Hanoi in 2019 was 2855 deaths, accounting for 12% of the total deaths in Hanoi residents aged 25 and above (Nhung et al. 2022). In addition, the $PM_{2.5}$ concentration in Hanoi is significantly higher than that of other developed countries worldwide (Nguyen et al. 2022; Bui et al. 2023). Thus, it is important to investigate the potential sources, and their contribution to the ambient concentration of $PM_{2.5}$ to inform an effective air pollution control strategy in Hanoi.

Different models use the chemical composition of airborne particles to determine the potential sources and their contributions to ambient particulate matter including chemical mass balance (CMB), principal component analysis (PCA), positive matrix factorization (PMF), and UNMIX. Each receptor model shows its advantages and disadvantages (Watson et al. 2008). For example, the weakness of the CMB model is the requirements of source profile result,

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✉ Thi Hieu Bui
Hieubt@huce.edu.vn; Buihieudhxd@gmail.com

Thi Phuong Mai Nguyen
maintp@hus.edu.vn; npmai82@gmail.com

[1] Faculty of Environmental Engineering, Hanoi University of Civil Engineering, 55 Giai Phong Road, Hai Ba Trung, Hanoi, Vietnam

[2] Faculty of Environmental Sciences, University of Science, Vietnam National University, Hanoi, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

which is not commonly available (Watson et al. 2008; Pant and Harrison 2012). Applying the PMF model for source apportionment is complicated and time-consuming (Song et al. 2006). On the other hand, principal component analysis/absolute principal component scores (PCA/APCS) and UNMIX are effective, relatively simple, and easy-to-perform source apportionment tools (Song et al. 2006). These two models do not require prior knowledge of emission sources and their composition (Pant and Harrison 2012). PCA/APCS determined factors using eigenvector decomposition of a matrix of pairwise correlation among concentrations of species (Thurston and Spengler 1985). UNMIX utilized the singular value decomposition method to derive meaningful factors (Lewis et al. 2003). The two models have been successfully used to identify the potential sources of particulate matter (Maykut et al. 2003; Almeida et al. 2005; Gupta et al. 2012; Adeyeye et al. 2016; Ghosh et al. 2018).

There have been many studies worldwide applying the receptors models to determine the emission source and their percentage contributions to particulate (Cohen et al. 2010; Duan et al. 2012; Wu et al. 2019; Kim et al. 2019; Rai et al. 2020; Jain et al. 2020; Bui and Nguyen 2022; Rabha et al. 2022; Barrera et al. 2023; Sharma and Mandal 2023; Zhang et al. 2023a; Bui et al. 2023; Doumbia et al. 2023). As shown in Table S1, the widely diverse conclusions in source identification within the same place could be attributed to different sampling locations, sampling times, and different source apportionment techniques (Pant and Harrison 2012). Furthermore, a massive overlap of markers for different emission sources has caused great challenges in apportioning the source with a high degree of confidence (Pant and Harrison 2012). Therefore, it is important to analyze results obtained from different receptor models to interpret the emission sources to improve the robustness of the results (Viana et al. 2008; Callén et al. 2009; Pant and Harrison 2012).

Potential sources of $PM_{2.5}$ in Hanoi have been determined recently using chemical speciation data. Automobiles and transport, crustal dust, smoke from biomass burning, industry sources, coal combustion, secondary sulfates, and construction activities have been identified as potential sources of $PM_{2.5}$ emission in Hanoi (Gatari et al. 2006; Cohen et al. 2010; Nguyen et al. 2021, 2022; Bui et al. 2023). Cohen et al. (2010) applied the PMF model to determine elemental source emission and their contributions to $PM_{2.5}$ mass from 2001 to 2008, which was out of date. This study reported the potential emission sources of $PM_{2.5}$ in Hanoi were automobiles and transport $(40 \pm 10)\%$, windblown soil $(3.4 \pm 2)\%$, secondary sulfates $(7.8 \pm 10)\%$, smoke from biomass burning $(13 \pm 6)\%$, ferrous and cement industries $(19 \pm 8)\%$, and coal combustion $(17 \pm 7)\%$. Gatari et al. (2006) collected $PM_{2.5}$ samples in the northeast rural area of Hanoi to investigate the emission sources. This study reported coal, heavy fuel oil combustion, biomass burning, road transport, and river transport as major sources of $PM_{2.5}$ in rural areas of Hanoi. Nguyen et al. (2021) performed PCA using a smaller number of samples (29 samples) collected before and during the COVID partial lockdown period in 2020 to characterize the impact of partial lockdown on the emission source of elements in $PM_{2.5}$ in Hanoi. Nguyen et al. (2022) performed source apportionment of $PM_{2.5}$ in a suburban area of Hanoi using principal component analysis with multiple linear regression (PCA/MLR). The obtained results indicated that crustal dust, pesticide, and industrial emissions contributed to 73.6% of the total contribution sources, while vehicle exhaust mixed with coal combustion accounted for 64.1% of the total contribution sources. Bui et al. (2023) only qualitatively analyzed the source apportionment of $PM_{2.5}$ in urban areas in Hanoi using PCA without determination of the source contributions. Shaping the air quality management policy needs quantitative results from the receptors models. All of the source apportionment studies in Hanoi so far utilized only one receptor model. However, the results obtained from different receptor models may be diverse due to the limitations of input data (Pekney et al. 2006). Therefore, this paper aims to apply UNMIX and PCA/APCS to estimate possible $PM_{2.5}$ emission sources using a large data set sampled at 3 sites located in inner urban areas of Hanoi. In addition, we also investigate the health risk assessments imposed by trace elements inherent in $PM_{2.5}$ in urban areas of Hanoi. We performed the detailed health risk assessment posed by individual toxic elements characteristics of sources apportioned from UNMIX and PCA/APCS for a better understanding of the influence of emission sources on human health. This is the first study that inter-compares the results of source apportionment obtained from UNMIX and PCA/APCS to improve the understanding of the sources of the pollutants.

Materials and methods

Study area

Hanoi is one of the biggest cities in Vietnam with an area of approximately 3359 km^2 and a large population of about 8.33 million people (General Statistic Office of Vietnam 2021). The rapid urbanization speed with heavy traffic has led to elevated air pollution problems in Hanoi (Nghiem et al. 2020; Nguyen et al. 2021, 2022). The climate of Hanoi is generally tropical and humid with the influence of two monsoon seasons: the northeast monsoon and the southeast monsoon (Hien et al. 2011). The north and northeast air masses carry dry and cold air from October to December. From January to March/April, the northeasterly airflow traveled over the Pacific Ocean with high humidity resulting in smog and drizzle. From May to September, Hanoi is

featured with hot and humid weather and plentiful precipitation (VARCC 2009). The average annual rainfall in Hanoi is about 1800 mm with heavy rainfall occurring in July and August (Hien et al. 2011). This study sampled $PM_{2.5}$ at three sites, namely, S1, S2, and S3 (Fig. 1) in inner urban Hanoi city during the dry season (October, November, February, March, and April) and wet season (July, August, and September) in 2019 and 2020. The high-volume air sampler was located on the rooftop of houses during the sampling period with the height above the ground ranging from 16 to 20 m. As described in our previous study (Nguyen et al. 2021), these sites were affected by different pollution sources including traffic, construction, industry, and coal combustion for domestic cooking. Thus, they can be considered as mixed sites, which are preferred for investigating the source apportionment with a reflection of the overall pollution picture in inner urban Hanoi (Oanh and Co 2009; Nghiem et al. 2020).

Sample collection and chemical analysis

A total of 78 daily samples were collected consecutively at three inner urban sites using quartz filters (Advance, QR-100, size 110 mm, Japan) by a high-volume air sampler (Shibata HV 500R, Japan) at an average flow rate of 15 m^3/h. The quartz filters were baked at 550 °C for 6 h before sampling. The total collected samples were 14 at S1, 29 at S2, and 35 at S3. The collected $PM_{2.5}$ samples were wrapped in aluminum foil, transported to the laboratory, and stored in a desiccator with silica gel particles until analysis. After being preconditioned before and after sampling (48 h in desiccators with a temperature of 25 ± 2 °C and relative humidity of 50 ± 5%), the filters were weighed using an electronic microbalance (Adam AEA-160DG, sensitivity ± 0.01 mg) to determine the mass of the $PM_{2.5}$. After gravimeter analysis, the filter samples were stored under refrigeration at – 30 °C until chemical analysis.

A quarter filter of the sample filter was treated for analysis of heavy metals by the digestion method according to EPA method IO-3.1 (US EPA 1999). The sample filter was first cut into pieces, then digested in 10 mL of mixed acid solution (HNO_3: HCl in a ratio of 1:3), and kept on a hot plate at a high temperature until the transparent solution was boiled. After complete digestion, the digested sample was heated at a low temperature until nearly dry to remove excess acid. Then, the solution was redissolved by 25 mL of HNO_3 1% solution containing internal standard (0.1 ppm of each element: Li, In, Sc, Ge, and Th) (Perkin Elmer, USA) in a calibrated flask. The concentration of Cd, As, Cr, Ca, Mn, Al, Fe, Mg, Ba, Co, Cu, Se, Pb, Ti, V, Zn, Ni, Sr, K, Na, Mo, Si, and Sn in $PM_{2.5}$ samples were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS, ELAN 9000, Perkin Elmer) with ELAN software. The regression coefficients (R^2) of the calibration curves for all elements were greater than 0.995. In addition, a standard reference material (National Metrology Institute of Japan (NMIJ) CRM 7302-a, Japan) was used to ensure the accuracy and reliability of the analysis. The mean recovery of the standard reference material ranged from 82 to 95%. In the analysis, a blank sample, a duplicated sample, and a spiked sample were measured for quality control. The relative standard deviation of each element is within 10%, and the analytical errors were < 10%. The detection limit of all the trace elements was 0.01 ng/m^3 except for Cd (0.002 ng/m^3). All reagents and element standard solutions were purchased from Sigma–Aldrich.

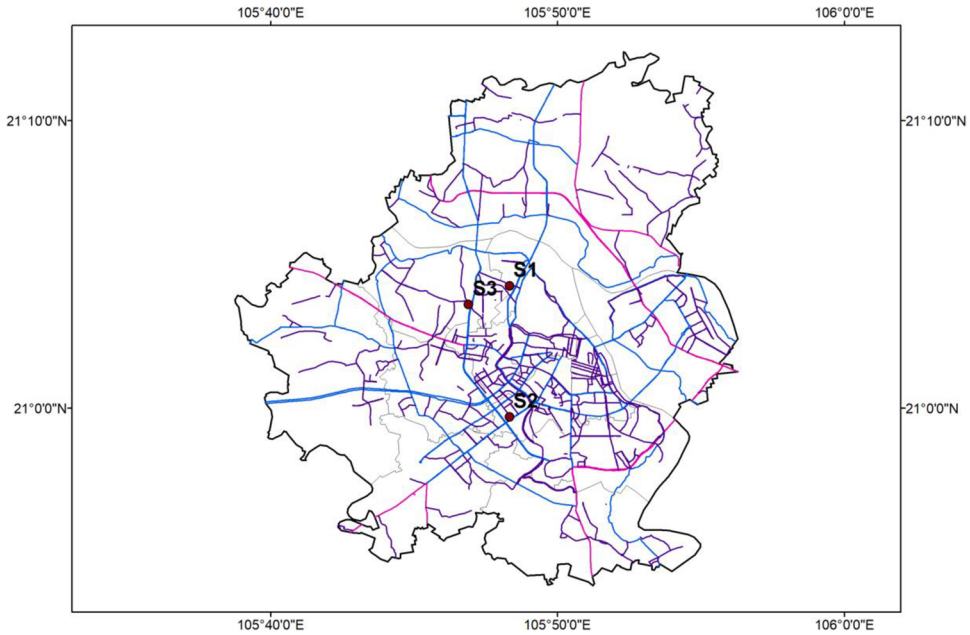

Fig. 1 Location of different sampling sites in inner urban areas of Hanoi, Vietnam

According to Pfeiffer (2005), the total $PM_{2.5}$ concentration was calculated using the following equation:

$$PM_{2.5} = \frac{(W_f - W_i)x10^{-6}}{Q_a xt}\left(\mu g/m^3\right)$$

where W_f was the final weight of the exposed filter (g), W_i was the initial weight of the unexposed filter (g), Q_a was the average sampler flow rate across the sampling time (L/min), and t was the total elapsed sampling time in minutes.

Meteorological data

This study used the fifth-generation global hourly climate reanalysis data (ERA5 data) of the European Center for Medium-Range Weather Forecasts (ECMWF), which was downloaded from the climate data store (https://cds.climate.copernicus.eu). The hourly meteorological reanalysis data during the sampling periods, including ambient air temperature (Temp.) and boundary layer height (BLH), were extracted for the study area and used to investigate the impacts of meteorological factors on the seasonal variation of $PM_{2.5}$ and chemicals bound in $PM_{2.5}$.

UNMIX and PCA/APCS

UNMIX is a multivariate receptor model developed by the United States Environmental Protection Agency (USEPA). Many studies worldwide applied UNMIX to determine possible sources of particulate matter-bound trace elements (Larsen and Baker 2003; Adeyeye et al. 2016; Doumbia et al. 2023). UNMIX estimates the number of sources k by minimizing the dimension of the ambient air data set with the matrix operation of singular value decomposition (SVD) (Lewis et al. 2003). An edge in a dimensional space was detected by a geometrically driven approach (Watson et al. 2008) to determine the source contributions and compositions of the k source. A full description of the UNMIX model with details on the algorithms and mathematical equation is available in (Jain et al. 2017). We employed a standalone US EPA UNMIX 6.0 version for source apportionment of $PM_{2.5}$ in this study.

PCA/APCS is a simple and exploratory statical analytical tool to investigate the pollution sources by minimizing the dimension of the original variables, investigating the connection between samples and observed variables by reducing the principal components, and quantifying the sources' contributions by combining factor analysis with multi-linear regression (Viana et al. 2008; Jain et al. 2018). Our study applied varimax rotation, which is widely used for atmospheric analysis to the matrix of loads to relate the individual variables with different components. All components with eigenvalues less than 1 (before rotation) were removed in the successive analysis. PCA/APCS was performed to identify the possible sources of $PM_{2.5}$ with the assumption of a linear relationship between the $PM_{2.5}$ mass concentration and the absolute principal component scores (APCS). The method to estimate APCS was represented in detail by (Thurston and Spengler 1985). The source contributions of the total $PM_{2.5}$ mass can be obtained using the following regressions:

$$M_i = a_0 + \sum_{k=1}^{p} a_k APCS_{ki}$$

where M_i is the total mass of $PM_{2.5}$ measured using gravimetric filter weighing. $APCS_{ki}{}^{*}a_k$ is the mass contribution in sample i made by source k.

The source contribution to the j^{th} species of the source k can be derived from the multiple linear regression (Shi et al. 2011):

$$C_i = \left(b_0\right)_i + \sum_{k=1}^{p} APCS_p b_{pi}$$

where $\left(b_0\right)_i$ is the intercept of the multiple linear regression (MLR) for i^{th} element and b_{pi} is the coefficient of the MLR for factor p^{th} and species i^{th}.

The percentage source contribution (k) was estimated based on the ratio of the regression coefficient for the factor, a_k, to the sum of the entire regression coefficient $\sum a_k$ as shown in the equation below (Larsen and Baker 2003). We used the SPSS software package (version 22.0) and employed an orthogonal transformation method using varimax rotation to perform PCA/APCS. Only chemical variables with factor loadings > 0.5 were used for source apportionment (Kothai et al. 2008).

Health risk assessment

Risk assessment regarding exposure to elements in $PM_{2.5}$ was performed to identify cancer or non-cancer risk according to US EPA (US EPA 2009). Based on the classification group orders defined by the International Agency for Research on Cancer (IARC) (IARC 2018), Mn, Zn, V, and Cu were determined as non-carcinogenic elements, and As, Cr, Ni, Cd, Co, and Pb were identified as both non-carcinogenic and carcinogenic elements (Zhang et al. 2018a). Because human exposure to the toxic elements in atmospheric particulate matter is mainly through the inhalation pathway (Zhang et al. 2018a), this study assessed the health risk due to heavy metals in $PM_{2.5}$ exposures via inhalation pathway for both children and adults using the following equation:

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

where C is the concentration of harmful elements (μg/m^3), EF is the exposure frequency (365 days/year), ED is

the exposure duration (6 years for children and 24 years for adults) (US EPA 2001), ET is the exposure time (24 h/day), and AT_n is the average time (for non-carcinogens, $AT_n = ED \times 365$ days $\times 24$ h/day; for carcinogens, $AT_n = 70$ years $\times 365$ days/year $\times 24$ h. The hazard quotient (HQ) is used to evaluate the non-carcinogenic risk and the carcinogenic risk (CR) impact of individual elements in $PM_{2.5}$, which were calculated as follows:

$$HQ_{inh} = \frac{EC_{inh}}{RfC_i \times 1000\mu g\ mg^{-1}}$$

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

where RfC_i is inhalation reference concentrations (mg/m^3) and IUR is inhalation unit risk ($(\mu g/m^3)^{-1}$). The RfC_i and IUR for harmful elements (Table S2) were downloaded from regional screening levels (US EPA 2012) (available at http://www.epa.gov/region9/superfund/prg/). The cumulative CR was calculated as the sum of CRs of individual carcinogenic elements. When CR is $> 10^{-4}$, the potential risk of cancer is high. If CR is between 10^{-6} and 10^{-4}, the risk can be defined as acceptable or tolerable, and CR $< 10^{-6}$ indicates that the risk is negligible. HQ < 1 indicates that adverse health effects could be ignored, and HQ > 1 suggests that the risk of cancer has possibly occurred.

Results and discussions

$PM_{2.5}$ mass concentration

The average $PM_{2.5}$ concentration (66.26 μg/m^3 ± 29.70 μg/m^3 with a range from 23.57 to 169.04 μg/m^3) observed in Hanoi metropolis was about 1.33 times higher than the daily average concentration of $PM_{2.5}$ prescribed in the National Ambient Air Quality standard QCVN 05:2013/BTNMT (50 μg/m^3). The average $PM_{2.5}$ concentration was lower than that recorded in Delhi, India (131 μg/m^3) (Jain et al. 2020) and (122 μg/m^3) (Sharma and Mandal 2023), Darkar, Senegal (138.2 μg/m^3), Bamako, Mali (276.8 μg/m^3) (Doumbia et al. 2023), Kolkata, India (313 μg/m^3) (Das et al. 2015), in Zhengzhou, China (146 μg/m^3) (Jiang et al. 2017). The average $PM_{2.5}$ concentration was comparable to the values found in Northern Zhejiang, China (63 μg/m^3), and in Ningbo, China (62.7 μg/m^3) (Wu et al. 2019). The obtained average $PM_{2.5}$ concentration was higher than that reported in Windsor, Canada (9.1 μg/m^3) (Zhang et al. 2023b), in Singapore, Singapore (28.88 μg/m^3) (Zhang et al. 2017), in Bien Hoa, Vietnam (63 μg/m^3) (24.1 μg/m^3) (Linh et al. 2023), in San Luis Potosi, Mexico (30.7 μg/m^3) (Barrera et al. 2023), and in Gwangju, Korea (35.34 μg/m^3) (Kim et al. 2019). The average $PM_{2.5}$ concentration found in this study was slightly higher than the average $PM_{2.5}$ concentration observed in Hanoi from 2001 to 2008 (54 μg/m^3) (Cohen et al. 2010), and from February 2021 to March 2021 (41.03 μg/m^3) (Bui et al. 2023).

As shown in Table 1, the variation of average seasonal concentration decreased in the order of dry season (82.95 ± 33.47 μg/m^3) > transition season (58.95 ± 20.19 μg/m^3) > wet season (45.23 ± 15.86 μg/m^3). The higher $PM_{2.5}$ concentration in the dry season than in the wet season was also reported in a previous study (Linh et al. 2023). This seasonal variation trend could be attributed to the scavenging effects of strong precipitation during the wet season (Wang et al. 2018; Nguyen et al. 2022). The collision and coalescence between $PM_{2.5}$ and raindrops would lead to a significant decrease in $PM_{2.5}$ concentration (Li et al. 2016; Wang et al. 2018).

Table 1 The average concentration of $PM_{2.5}$ and elements in inner urban areas of Hanoi (unit: ng/m^3, except for the units of $PM_{2.5}$ with *μg/m^3)

Country	Hanoi, Vietnam	Hanoi, Vietnam	Hanoi, Vietnam
Season	Dry	Wet	All sampling period
$PM_{2.5}$	71.34 ± 30.16	45.23 ± 15.86	66.26 ± 29.70
Cd	1.13 ± 0.78	1.07 ± 0.91	1.11 ± 0.8
As	2.87 ± 1.87	2.29 ± 2.05	2.74 ± 1.91
Cr	6.43 ± 6.42	6.77 ± 2.26	6.55 ± 5.76
Ca	1683.72 ± 908.27	1232.17 ± 754.7	1617,28 ± 892,4
Mn	33.24 ± 32.01	17.15 ± 10.45	29.71 ± 29.43
Al	193.57 ± 141.13	148.19 ± 97.34	186.67 ± 133.58
Fe	715.82 ± 736.97	435.54 ± 273.73	656.03 ± 672.57
Mg	321.51 ± 549.32	217.83 ± 153.09	301.36 ± 491.79
Ba	7.12 ± 3.91	4.63 ± 2.89	6.7 ± 3.83
Co	0.28 ± 0.25	0.14 ± 0.11	4.3 ± 18.28
Cu	7.41 ± 6.15	9.1 ± 5.51	7.78 ± 6.02
Se	1.77 ± 1.47	1.57 ± 2.15	1.71 ± 1.63
Pb	34.31 ± 24.78	31.55 ± 27.4	33.62 ± 25.22
Ti	10.38 ± 7.64	5.96 ± 3.76	9.49 ± 7.19
V	2.93 ± 4.41	8.78 ± 4.94	4.3 ± 5.17
Zn	38.87 ± 385.89	254.88 ± 193.97	351.73 ± 355.86
Ni	1.53 ± 1	1.06 ± 1	2.19 ± 4.74
Sr	5.4 ± 3.18	4.47 ± 2.66	5.31 ± 3.08
K	376.4 ± 296.45	310.05 ± 189.67	363.08 ± 276.98
Na	111.07 ± 107.93	42.46 ± 31.53	101.21 ± 100.48
Mo	0.67 ± 0.65	1.51 ± 0.87	0.85 ± 0.78
Si	96.96 ± 115.83	167.74 ± 174.86	112.27 ± 132.74
Sn	2.06 ± 1.57	2.33 ± 2.29	2.09 ± 1.67

Characteristics and influence of meteorological conditions on trace metals in $PM_{2.5}$

This study analyzed 23 elements (Cd, As, Cr, Ca, Mn, Al, Fe, Mg, Ba, Co, Cu, Se, Pb, Ti, V, Zn, Ni, Sr, K, Na, Mo, Si, and Sn) in the atmosphere of the Hanoi metropolitan area in $PM_{2.5}$ fractions. Table 1 expresses the average concentrations of the trace metals bound to $PM_{2.5}$. Ca, Fe, K, Zn, and Mg were the most abundant elements in $PM_{2.5}$ fractions. The high concentration of Ca, Fe, and Mg could be associated with crustal dust (Geiger et al. 2010; Kim et al. 2019). Besides, Ca, Mg, and Fe could come from vehicular emissions, construction activities, and industrial emissions (Cadle et al. 1997; Harrison et al. 2003; Cohen et al. 2010; Das et al. 2015; Police et al. 2016). Additionally, K could be released from biomass-burning sources (Police et al. 2016). The remaining metals were classified into two groups: 1) Group 1 contained Al, K, and Si and 2) Group 2 contained other persisting heavy constituents (Cd, As, Cr, Mn, Ba, Co, Cu, Se, Pb, Ti, V, Ni, Sr, Sn, and Mo). Al, K, and Si with concentrations were 186.67 ng/m^3, 101.21 ng/m^3, and 105.58 ng/m^3, respectively. The heavy metal constituents of group 2 were exhibited in trace quantities (less than 50 ng/m^3). The concentrations of these heavy metals ranged from 0.85 to 33.62 ng/m^3. The average concentration of $PM_{2.5}$ bound Pb, Ni, Cd, V, Cr, and As satisfied the established guideline values of the EU and WHO.

A comparison of trace metal concentrations in the Hanoi urban area obtained in this study and a previous study from 2001 to 2008 showed significantly increasing levels of Ca and Fe, dramatically decreasing levels of Pb, Si, K, Ti, and Mn, moderate reduction of Al, Cu, Zn, and Ni. Ca and Fe are tracers for construction activities (Das et al. 2015). Therefore, a significant increase of Ca (3.52 times) and Fe (1.66 times) could be attributed to rapid urban development with high demand for new construction projects including building and infrastructure. Si is one of the most abundant elements in crustal soil (Geiger et al. 2010). Thus, a plunge of Si (about 9.62 times) could also be the result of fast urbanization in Hanoi during recent decades leading to the shrinkage of vacant urban land. A dive of Pb (approximately 7.02 times) could be associated with government policy about controlling the lead content in gasoline. In addition, the Vietnam government has imposed a policy (Directive 15/CT-UBND issued in October 2019) on replacing and eliminating the use of coal as fuel in daily life, business, and services to minimize negative impacts on the environment in Hanoi. This also contributed to the reduction of Pb because Pb is known as a coal combustion marker (Cohen et al. 2010). The concentration of Fe obtained in our study was comparable with the value reported in recent research (629 ng/m^3) conducted in an urban area of Hanoi from February 2021 to March 2021 (Bui et al. 2023). However, the level of Cd, Cr, Al, Ba, Cu, Pb, and Ti in our study was moderately lower than in the previous research (Bui et al. 2023). This discrepancy could be probably due to the impacts of local sources at different sampling locations and the influence of meteorological conditions during different sampling periods. While the concentrations of Cr, Ca, Al, Cu, K, Ni, and Na observed in Bien Hoa city (Linh et al. 2023) were dramatically higher than the values we obtained, most of the remaining elements displayed the same order of magnitude. In general, a comparison with the concentrations of heavy metals measured in other urban areas worldwide (Table 2) indicated higher pollution levels in Kolkata, India (Das et al. 2015), in Northern Zhejiang, China (Xu et al. 2021), in San Luis Potosi, Mexico (Wu et al. 2019) in Darkar, Senegal, and in Bamako, Mali (Doumbia et al. 2023), in Delhi, India (Jain et al. 2020; Sharma and Mandal 2023). However, the concentration of trace constituents obtained in our study was higher than those in Singapore, Nicosia, Cyprus, Gwangju, Korea, and Windsor, Canada (Zhang et al. 2023b).

Generally, most trace metals bound to $PM_{2.5}$ exhibited higher levels in the dry season than in the wet season. This seasonal variation trend would be attributed to the meteorological conditions and the long-range transport pollution sources. The dry season in Hanoi features with relatively lower temperature, lower precipitation rate, and lower boundary layer height (BLH). As shown in Table S3, the average temperature, precipitation, and BLH in Hanoi during sampling time in the dry season were lower than those values recorded in the wet season. Low temperature and low BLH reduced atmospheric turbulence (Yang et al. 2016). The stable meteorological condition during dry months reduces the dispersion of particulate matter in the atmosphere (Jiang et al. 2017), consequently increasing the level of $PM_{2.5}$ and elements bound in $PM_{2.5}$. The negative correlation between precipitation rate and particulate matter pollutants was emphasized in previous atmosphere studies (Li et al. 2016; Nguyen et al. 2022). Thus, higher precipitation rates during wet and transition months would also be attributed to the lower concentration of elements in $PM_{2.5}$. Furthermore, the long-range transport of air mass from Southeast Asia and air mass from the north and northeast, passing through China territory would exaggerate the air pollution in Hanoi during winter (including dry months) (Gatari et al. 2006; Hien et al. 2011; Nguyen et al. 2022). In addition, the average concentration of K and Zn (tracers for biomass burning (Cohen et al. 2010; Jain et al. 2020; Luo et al. 2023) in dry months were higher than in wet months could be attributed to open rice straw burning after harvesting of the farmers in October in Hanoi (Lasko et al. 2018; Bui et al. 2021; Pham et al. 2021).

As shown in Fig. 2, the average concentration of Cd, As, Cr, Se, Pb, and Sn displayed a small seasonal discrepancy. However, Si, Cu, V, and Mo expressed higher concentrations in the

Table 2 The average concentration of $PM_{2.5}$ and elements in urban areas of different places of the world. (unit: ng/m^3; except for the units of $PM_{2.5}$ with *μg/m^3)

Country	Hanoi, Vietnam	Hanoi, Vietnam	Bien Hoa, Vietnam	Ningbo, China	San Luis Potosi, Mexico	Nicosia,Cypru	Singapore, Singapore	Gwangju, Korea	Windsor, Canada	Northern Zhejiang, China	Kolkata, India	Delhi, India	Darkar, Senegal	Banako, Mali	Delhi, India
$PM_{2.5}$	41.03	54 ± 33	24.1	62.7	30.7		28.88 ± 5.92	35.34 ± 18.99	9.1	63 ± 18.0	313	131 ± 79	138.2	276.8	122
Cd	3.79		0.9	1.5		0.12 ± 0.08	0.15 ± 0.07	1.03 ± 0.64	4.4	1.8 ± 0.4	8.6		0.4	0.8	
As	1.66		1	4.7		0.5 ± 0.3	3.50 ± 0.73	3.35 ± 2.09	0.2	122.6 ± 19.3		90 ± 140	1.4	3	260 ± 130
Cr	43.48	5	60	3.4	390	3.3 ± 1.6	7.29 ± 3.10	5.47 ± 1.17	0.3	88.1 ± 40.5	101	180 ± 130	20	90	240 ± 140
Ca		459	5250		603				89						960 ± 1170
Mn	25.24	61	30	35.6	550	8.6 ± 5.7	24.24 ± 11.03	16.16 ± 6.86	4.6	38.8 ± 19.0	249	10 ± 10	60	220	120 ± 120
Al	634.60	224	460		76.9	226.3 ± 353.5	286.66 ± 83.63	307.41 ± 111.32		502.4 ± 143.7		1870 ± 1150	14,280	17,980	510 ± 570
Fe	629	394	370		1020	352.1 ± 211.4	257.32 ± 75.04	430.23 ± 141.25	120	434.3 ± 94.2	11,242	4110 ± 560	3490	14,280	930 ± 570
Mg			380			199.2 ± 139.3		124.14 ± 56.20		263.4 ± 62.5					140 ± 210
Ba	30.52						18.63 ± 5.95	12.72 ± 5.58	2.9	63.0 ± 29.4					
Co	0.4	2	0.3			0.33 ± 0.25	0.14 ± 0.07	0.18 ± 0.06	0.03	1.1 ± 0.1			1.6	5	
Cu	109.78	10	110		242	11.4 ± 4.2	16.46 ± 4.98	9.67 ± 6.46	4.8	19.1 ± 6.7	107	100 ± 150	130	40	290 ± 240
Se	2.42								0.7						
Pb	184.14	236	40	4.0	2350	16.3 ± 23.5	29.67 ± 6.92	28.88 ± 16.07	3.9	43.7 ± 6.1	394	300 ± 290	20	40	570 ± 500
Ti	15.96	31		57.2	114	19 ± 15.8	0.03 ± 0.02	21.46 ± 7.98	4.1			90 ± 360	340	1470	270 ± 230
V	12.43	3			149	5 ± 3.5		4.59 ± 1.81	0.5	172.8 ± 59.0			50	50	
Zn	161.88	487	450	4.2	378	17.6 ± 8.7	119.25 ± 30.22	98.28 ± 50.39	26	248.1 ± 48.1	761	380 ± 330	110	120	620 ± 430
Ni	4.75	4	7		569	1.9 ± 1.2	8.08 ± 3.26		0.5	15.6 ± 8.9	48		30	30	140 ± 40
Sr	7.79								1.6						
K		974	3500		388	182.9 ± 183	660.21 ± 195.80	241.71 ± 79.34	120	759.1 ± 102.0					2050 ± 1830
Na		123	2730		283	320.8 ± 203.6		238.66 ± 49.96							
Mo	24.69					0.6 ± 0.3		0.65 ± 0.28		38.5 ± 13.1					190 ± 110
Si		1080			305				410						
Sn									0.2						
Sampling time	Feb–Mar, 2021	2001–2008	Oct 2021, and Mar 2022	2017–2018	May, 2017–July, 2018, 2018	Nov 2015–Feb, 2016	Oct, 2016–Apr, 2017	April, 2021–Oct, 2021	Dec, 2014–Dec, 2015	2017–2018	2013–2014	Jan 2013–Dec 2016	Jan–Feb, 2009	Jan–Feb, 2009	Jan, 2017–Dec, 2021
Reference	(Bui et al. 2023)	(Cohen et al. 2010)	(Linh et al. 2023)	(Wu et al. 2019)	(Barrera et al. 2023)	(Iakovides et al. 2021)	(Zhang et al. 2017)	(Kim et al. 2019)	(Zhang et al. 2023b)	(Xu et al. 2021)	(Das et al. 2015)	(Jain et al. 2020)	(Doumbia et al. 2023)	(Doumbia et al. 2023)	(Sharma and Mandal 2023)

wet season. Si is one of the most abundant species in the crustal soil (Taylor 1964; Geiger et al. 2010). In addition, high ambient air temperature heats the soil, resulting in loose soil particles rising from the ground surface (Tesfaye et al. 2011; Kumar et al. 2012; Bui et al. 2021). In addition, the temperature during the wet season was higher than in the dry season in Hanoi. As a consequence, this would contribute to larger Si content in $PM_{2.5}$ in wet months. The higher concentration of Cu, V, and Mo indicated that the sources of these elements would be attributed to local sources such as heavy oil combustion, industry sources, and traffic-related emissions. The detailed results and discussion of $PM_{2.5}$ emission sources in the urban area of Hanoi are presented in "Source identification by UNMIX and PCA/APCs."

Source identification by UNMIX and PCA/APCs

In this study, we applied the principal component analysis (PCA/APCS) and UNMIX for all $PM_{2.5}$ samples to identify the potential main sources influencing the aerosol composition in Hanoi. Major constituents (Si, Sn, Cd, Cr, Ca, Mn, Fe, Mg, Pb, V, Zn, Sr, Na, K, and Mo) were selected as input data. These species were chosen based on the result of the influential point algorithm. They had high edge resolution with a 90th percentile greater than 0.80, except for K. K was selected because it is a key tracer for biomass burning which was reported as one of the air pollution sources in Hanoi (Pham et al. 2021). Both UNMIX and PCA/APCS created four source factors with the source compositions as shown in Table 3. UNMIX suggests some criteria to determine the factors including the variance of species explained by the factor and the minimum signal-to-noise ratio. The numerical values for the solution's diagnostic indicators of UNMIX ($R^2 = 0.78$ and S/N ratio = 2.16) were consistent with the recommendation (Jain et al. 2018). PCA/APCS also requires the smallest eigenvalue for factor extraction restricted to more than unity. In this study, PCA was applied with 8 samples (N) and 15 variables (p). The variable ratio (N/p) was 5.20, which is within the recommended values ranging from 3 to 20 (Mundfrom et al. 2005; Winter et al. 2009). Furthermore, the Kaiser–Meyer–Olkin (KMO) was 0.76 indicating all data were suitable for PCA/APCS analysis (Jain et al. 2018).

Source 1 was explained by traffic-related emissions with a high composition of Ca, Fe, and Mg. Pb, Na in UNMIX results and high factor loading of Si, Sn, Cd, Mn, Pb, Zn, and V. These elements have been typical tracers of vehicular emissions. Mg, Ca, Si, and V compounds were reported as the components of motor oil and engine additives (Cadle et al. 1997; Harrison et al. 2003; Cohen et al. 2010). The use of diesel additives that contain Fe compound would emit Fe into the ambient air environment (Ramadan et al. 2000; Maykut et al. 2003). In addition, Fe, Zn, Cd, and Mn would be released from wear of tires, brake pads, and other metal parts in vehicles (Garg et al. 2000; Pant and Harrison 2013; Pio et al. 2013; Banerjee et al. 2015). In addition, Pb and V appear to be associated with petrol/diesel combustion (Dai et al. 2015). Sn could be emitted into the atmosphere during the vehicle abrasion process because Sn exists in alloys of automobile parts prone to wear (Das et al. 2015). Although Si is reported as a crustal origin (Geiger et al. 2010), this metal is present in road dust and is being lifted into the atmosphere during the movement of the traffic fleet (Thorpe and Harrison 2008). The percentage contribution of Si to source 1 in UNMIX result was small (7%). However, the value obtained by PCA/APCS was much higher (79.33%). This discrepancy between the two models' results could be

Table 3 UNMIX mass fractions ($\times 10^{-2}$) and PCA factor loadings (present only values larger than 0.5) for $PM_{2.5}$

	UNMIX				PCA/APCS			
	S3	S2	S1	S4	F1	F2	F3	F4
Si	0.76	1.00	0.38	8.89	0.74			
Sn	0.13	−0.04	0.02	0.09	0.80			
Cd	0.05	−0.01	0.01	0.06	0.92			
Cr	0.02	0.29	0.14	0.08				0.77
Ca	129.00	−20.20	7.43	35.10	0.51			
Mn	−0.17	0.63	0.45	2.25	0.69			
Fe	2.45	66.20	−3.82	6.18		0.831		
Mg	6.19	−6.52	32.80	0.39				0.77
Pb	2.17	−0.25	0.03	1.05	0.68			
V	−0.07	0.01	0.10	0.29	0.68			
Zn	−1.34	6.74	1.00	30.60	0.80			
Sr	0.45	−0.06	0.01	0.09			0.83	
Na	15.60	−1.64	0.70	22.90			.695	
K	11.80	−2.31	−0.27	−1.53	0.85			
Mo	0.00	0.01	0.02	0.06	0.70			

attributed to the difficulty in separating vehicular emission from the resuspended road dust and crustal soil because the soil is contaminated by vehicles and the road dust contains crustal constituents (Pant et al. 2012). Therefore, it showed high factor loading in PCA/APCSs results along with other typical tracer elements of vehicular emissions. A large number of traffic vehicles transported in Hanoi was one of the major air pollution sources in Hanoi (Nghiem et al. 2020; Bui et al. 2023). As of 2019, the total number of means of transport in Hanoi is 6,649,596 including 739,731 cars, 5,761,436 motorbikes, and 148,429 electric motorbikes (Thai 2022).

Source 2 was interpreted as scrap metal recycling villages because Fe and Zn were enriched in UNMIX and PCA/APCS results. Fe and Zn were reported as tracers of the ion and steel melting process (Yatkin and Bayram 2008; Lestari and Mauliadi 2009; Tauler et al. 2009; Ogundele et al. 2016; Zhang et al. 2020). Both the two models showed high percentage contributions to source 2 (88% for UNMIX and 94.87% for PCA/APCS). The percentage contributions of Zn to source 2 were relatively lower (18% for UNMIX and 24.28% for PCA/APCS). High concentrations of these metals could be linked with the activities from the recycling process involves remelting the scraps in a furnace and reheating the formed steel bars in a furnace to produce various types of products including ion rods, rolled steel, wire steel, and housewares such as knives, scissors, needles, nails, and pickaxes. The scrap metal recycling villages producing ion and steel products located in Hanoi Da Sy or the provinces in the vicinity of Hanoi including Van Chang village, Xuan Tien village (Nam Dinh), Da Hoi village (Bac Ninh) utilize manual methods with outdated technology for metal recycling process. In addition, the air treatment systems were reported for ineffective performance or even not being installed in recycling villages in Vietnam, which contributed to higher levels of air pollution in recycling villages and surrounding areas.

Source 3 was characterized by a high composition of Ca and Mg in UNMIX results and high factor loadings for Ca, Sr, and Na in PCA/ and PCA/APCS results. Therefore, source 3 was interpreted as a crustal and construction source. Ca, Mg, Sr, and Na were known to be typical elements of crustal/geologic dust (Geiger et al. 2010; Zhang et al. 2018b; Kim et al. 2019; Lough et al. 2005; Jaeckels et al. 2007; Begum et al. 2011; Stone et al. 2010; Yin et al. 2010; Fujiwara et al. 2011; Gu et al. 2011). In addition, Ca and Mg could be released from construction dust (Zhang et al. 2020). The rate of urbanization has increased rapidly (about 67%), followed by a series of construction sites that have blossomed in Hanoi (Thai 2022). Construction activities of apartment buildings, bridges, and roads, building retrofit, transportation of construction materials, and waste resulted in air pollution problems. The percentage contributions of Ca to source 3 obtained from the two models were high (83% for UNMIX, and 57.22% for PCA/APCS).

Source 4 was interpreted as a mixture of coal combustion, industry, and biomass burning with a high composition of Si, Ca, Mn, Fe, Pb, K, and Zn in UNMIX results and high factor loadings of Fe, Cr, and Mg in PCA/APCSs results. The percentage contributions of Fe to source 4 of both models were less than 4%. Cr, Pb, and Zn can be emitted into the atmosphere from coal combustion (Lee et al. 1999; Callender and Rice 2000; Pacyna and Pacyna 2001; Das et al. 2015). Food stalls/restaurants, street food vendors, and households in Hanoi commonly use coal for cooking (Nguyen et al. 2022; Bui et al. 2023). It was also reported that the thermal power

Table 4 A comparison between measured and UNMIX modeled and PCA/APCS modeled chemical species $PM_{2.5}$

Species	UNMIX			PCA/APCS		
	r-Pearson	RMSE	R^2	*r*-Pearson	RMSE	R^2
PM	0.62	21.61	0.38	0.65	20.60	0.42
Si	0.78	0.07	0.61	0.76	0.07	0.57
Sn	0.78	0	0.61	0.87	0.00	0.76
Cd	0.92	0	0.85	0.95	0.00	0.90
Cr	0.72	0	0.52	0.86	0.00	0.74
Ca	0.82	0.44	0.67	0.96	0.22	0.91
Mn	0.82	0.02	0.68	0.85	0.02	0.72
Fe	0.9	0.33	0.81	0.84	0.41	0.70
Mg	0.98	0.12	0.96	0.80	0.34	0.80
Pb	0.71	0.01	0.5	0.73	0.01	0.74
V	0.83	0	0.69	0.88	0.00	0.88
Zn	0.85	0.21	0.72	0.86	0.20	0.86
Sr	0.76	0	0.58	0.91	0.00	0.92
K	0.89	0.14	0.8	0.90	0.13	0.90
Na	0.7	0.04	0.5	0.81	0.03	0.81
Mo	0.76	0	0.58	0.83	0.00	0.82

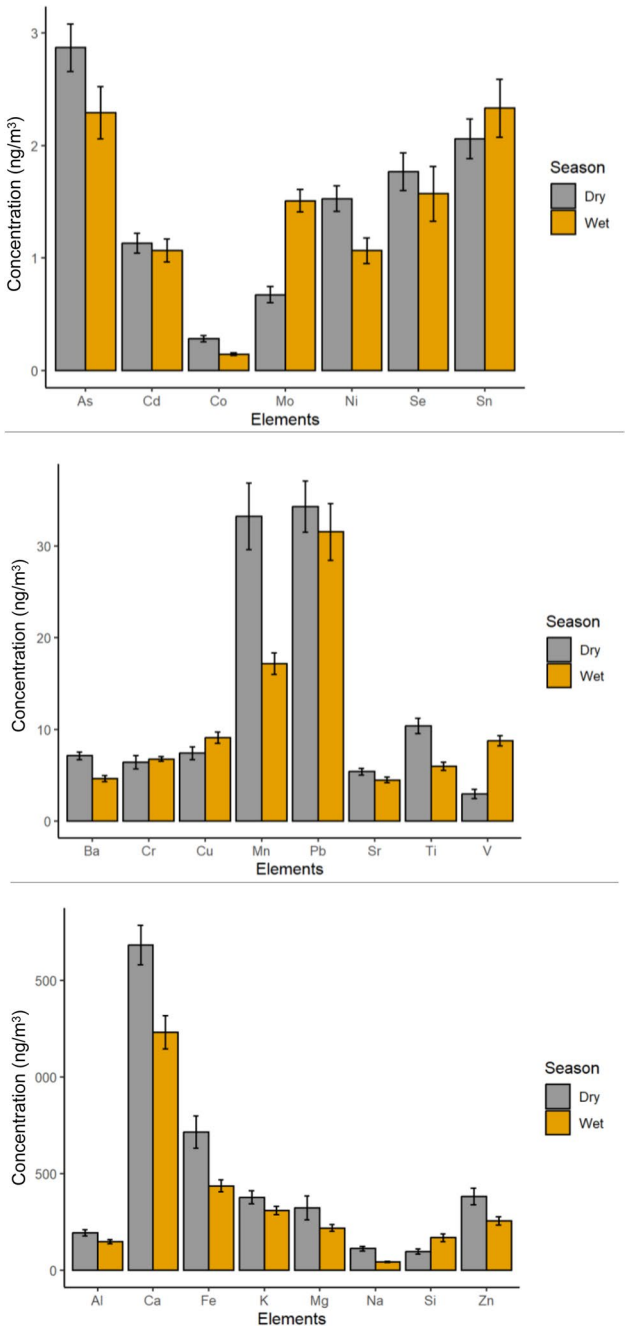

Fig. 2 Seasonal variation of trace elements bound in $PM_{2.5}$ in inner urban areas of Hanoi, Vietnam

plants were the major source of coal combustion emissions that imposed an impact on the air environment in Hanoi (Gatari et al. 2006; Jonhson et al. 2011). In addition, coal was widely used for producing bricks and pottery in suburban areas (Jonhson et al. 2011). Ca, Zn, and Fe are elements known to come from the cement production industry (Barrera et al. 2023). Mg, Fe, Mn, Zn, Pb, and Cr are marker elements related to the metallurgical production industry (Owoade et al. 2015). While Fe is a maker for the ferrous

Table 5 Non-carcinogenic risk (HQ) and carcinogenic risks (CRs) of harmful metals via inhalation exposure in inner urban areas of Hanoi

	HQ-values		CR-values	
	Children	Adults	Children	Adults
As (inorganic)	1.6E−03	1.9E−05		9.09571E−09
Cd (diet)	1.0E−03	1.1E−05		1.55106E−09
Cr(VI)[c]	5.9E−04	6.6E−06		6.01879E−08
Co	6.5E−03	7.4E−05		3.02115E−08
Mn (diet)	5.3E−03	6.1E−05		
Ni (refinery dust)	3.9E−04	4.4E−06		4.01169E−10
Pb[d]	8.6E−05	9.8E−07		3.11882E−10
V (compounds	3.9E−04	4.4E−06		
Zn (metallic)	1.1E−05	1.2E−07		

[b]According to User's guide and background technical document for US EPA region 9'S preliminary remediation goals (PRG) table (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/usersguide.htm)

[c]No RfD_o and GIABS for Pb. RfD_o was set according to Ostapczuk et al. (1987) and JECFA (1993) and 1 was set for GIABS in the present study

metals industry (Kar et al. 2010), Zn and Mn are markers for non-ferrous industry (Negi et al. 1967). Zn, Cr, and Pb were also found in industrial emission sources from various scale industries and industrial effluents (Jain et al. 2020). In addition, it was concluded that ceramic and brick manufacturing sources released Si, Ca, Fe, and Zn elements (Herrera Murillo et al. 2012). Furthermore, Pb, K, and Cr were known to be associated with biomass burning, especially crop straw burning (Jain et al. 2020; Luo et al. 2023). One of the considerable air pollution sources in Hanoi due to agricultural activities is rice straw open burning after harvest (Pham et al. 2021). Hanoi has large areas of rice cultivation occupying about 90% of the total agricultural land of Hanoi (General Statistic Office of Vietnam 2019).

Comparison of receptor models

Receptor models distinguished the source contributions of particulate matter based on their physical assumptions and constraints. Compared results obtained by different models provide a better understanding of source apportionment. The analysis by the two receptor models of the same $PM_{2.5}$ data was investigated by considering the number of resolved factors to identify sources, their contributions, and the extent of agreement between the measured and modeled concentrations of $PM_{2.5}$ and elemental species. Four potential sources of ambient $PM_{2.5}$ were produced by both the UNMIX and PCA/APCS models. Previous studies reported good agreement between different multivariate receptor models regarding source identification. However, the discrepancies in percentage contributions of different sources would be

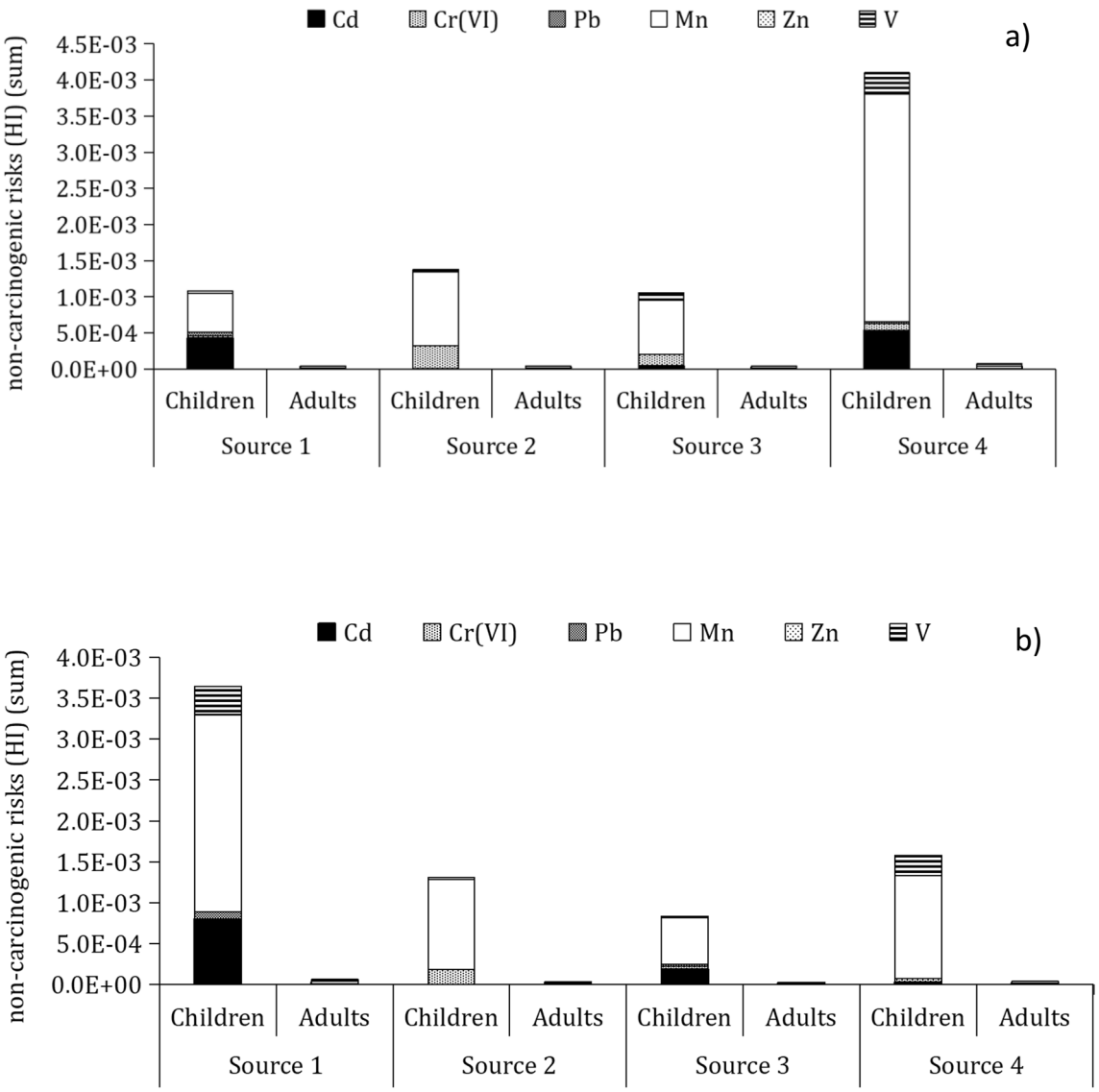

Fig. 3 Non-carcinogenic risks (sum HI) of elements in $PM_{2.5}$ samples apportioned by **a** UNMIX and **b** PCA/APCS in inner urban areas of Hanoi

large (Lee et al. 2008). According to UNMIX results, traffic-related emissions, scrap metal recycling villages, crustal mixed with construction sources, coal combustion mixed with industry, and biomass burning accounted for 59%, 7%, 4%, and 30% of total $PM_{2.5}$ mass concentration, respectively. PCA/APCS model reported traffic-related emissions (55.97%), scrap metal recycling villages (23.37%), crustal and construction sources (2.74%), coal combustion, industry, and biomass burning (17.91%). While source contributions of traffic-related emission (the most influential source) tracked well for the two models, the remaining source contribution magnitude for the remaining sources exhibited a discrepancy between UNMIX and PCA/APCS. The ability of UNMIX and PCA/APCSs to predict the major particulate matter sources was also reported in previous research (Callén et al. 2009; Ogundele et al. 2016). It was concluded that UNMIX distinguished preeminently the most dominant sources but exhibited difficulties in producing agreement between the expected and estimated contribution for weaker sources (Henry 2003; Jain et al. 2018). Callén et al (2009) also reported the weakness of UNMIX concerning identifying the sources that had a low contribution to the total mass. These sources could be associated with ubiquitous, infrequent, and relatively small sources. In addition, source 2 and source 4 were both characterized by a high mass fraction of Fe. This could be the possible reason that UNMIX apportioned a lower percentage contribution for scrap metal recycling villages and a higher percentage contribution for coal combustion, industry, and biomass burning than PCA/APCS.

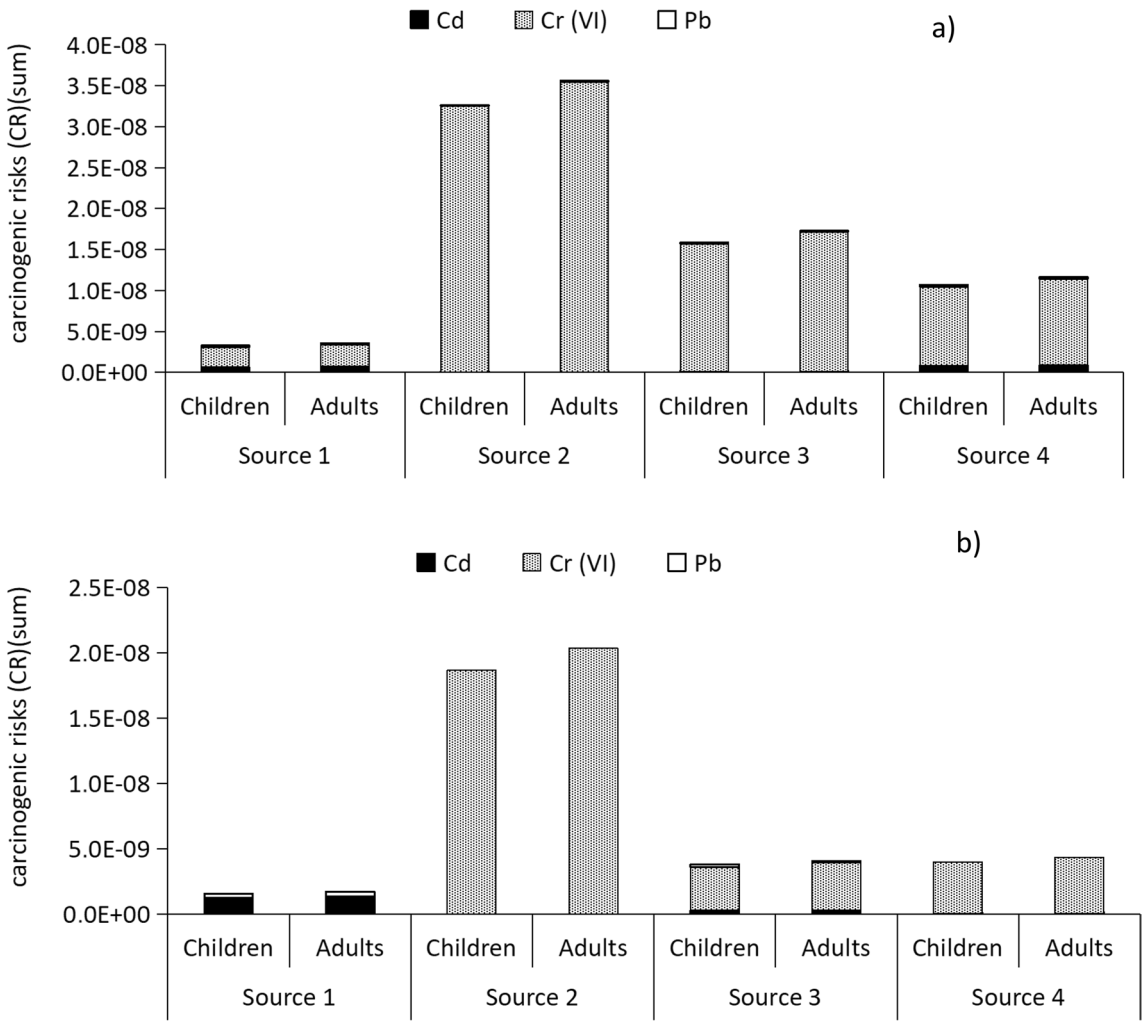

Fig. 4 Carcinogenic risks (sum CR) of elements in $PM_{2.5}$ samples apportioned by **a** UNMIX and **b** PCA/APCS in inner urban areas of Hanoi

As shown in Table 4, UNMIX and PCA/APCS exhibited comparable ability to reproduce measured $PM_{2.5}$ concentrations with small discrepancy values of *r*-Pearson, R^2, and RMSE. The two models showed moderate to good agreement between the measured and modeled $PM_{2.5}$ and chemical constituents. Values of *r*-Pearson, R^2, and RMSE of UNMIX (PCA/APCS) ranged from 0.62 to 0.98 (from 0.65 to 0.96), from 0 to 21.61 (from 0 to 20.60), and from 0.38 to 0.96 (from 0.42 to 0.92), respectively.

A comparison of previous research by (Cohen et al. 2010) suggested that the most prevailing source releasing $PM_{2.5}$ in Hanoi was from the traffic fleet accounting for $40 \pm 10\%$. On the other hand, the major $PM_{2.5}$ emission sources in suburban areas of Hanoi were crustal dust, pesticide, and industrial emissions accounting for 73.6% (Nguyen et al. 2022). Traffic-related emission was also reported as the dominant source of $PM_{2.5}$ in cities worldwide including Bamako (45%), Darka (49%) (Doumbia et al. 2023), Windsor, Canada (47%) (Zhang et al. 2023b), and Ningbo, China (46.3%) (Wu et al. 2019). In addition, Pant et al. (2012) performed a critical review of the receptor model for particulate matter and reported that vehicular pollution contributed to a large portion of $PM_{2.5}$ in Delhi, India.

Potential risk assessment for human health

Table 5 expressed the non-carcinogenic and carcinogenic risks owing to exposure to trace elements in $PM_{2.5}$ via inhalation exposure pathway in urban areas of Hanoi. The detailed health risk assessments accounting for the contribution of emission sources to the concentration of individual toxic elements can provide useful information about the impacts of the sources and support the policy decision-making processes. The source apportionment of seriously harmful elements Cd, Cr, Mn, Pb,

V, and Zn were investigated in detail by UNMIX and PCA/APCS models. Because PCA/APCS has the problem of generating negative contributions (Larsen and Baker 2003), we eliminated the negative contribution values in health risk assessment processes. As shown in Fig. 3, among the considered toxic elements, Mn apportioned by the two receptor models posed the highest non-carcinogenic risks for children in all sources. As regards non-carcinogenic risks, the HQ values of all considered toxic elements for both adults and children considering all sources and in each source were smaller than 1 indicating the non-carcinogenic risks could be minor. However, it can be seen from Table 5 and Fig. 3 that the cumulative risk for children was much higher than for adults, suggesting that children suffered more influence by non-carcinogenic risks. Generally, the accumulative non-carcinogenic risk of toxic elements apportioned by UNMIX and PCA/APCS exhibited the same order of magnitude. Both UNMIX and PCA/APCS had similar cumulative non-carcinogenic risks for source 2 and source 3. However, the source with the highest influence on the sum of non-carcinogenic risk was source 1 apportioned by PCA/APCS, and source 4 apportioned by UNMIX. This result can be attributed to the different magnitude of contribution by each source to the ambient concentration of individual elements (Pekney et al. 2006).

Concerning carcinogenic risk, six metals (As, Cd, Co, Cr, Ni, and Pb) via inhalation pathway experienced a CR less than acceptable value (10^{-4}) for both children and adults. Thus, the carcinogenic risk posed by those toxic elements could be negligible. Figure 4 shows the carcinogenic risks of each source for Cd, Cr, and Pb apportioned by both UNMIX and PCA/APCS. From Fig. 4, the sum CR values of the two elements apportioned by the two models exhibited the same order of magnitude in every single factor. All the CR values of all elements in every source of both UNMIX and PCA/APCS were considerably less than the safety level, suggesting negligible carcinogenic risk exposed to adults and children. Cr apportioned by both UNMIX and PCA/APCS in each source contributed the largest portion of carcinogenic risks, except for source 1 of PCA/APCS. This result can be explained that Cr was not used to estimate the health risk due to its negative contribution generated by PCA/APCS for source 1. The negative contribution was a known problem of PCA/APCS reported in a previous study (Larsen and Baker 2003). The health risk assessment results obtained from both UNMIX and PCA/APCS showed the highest influence of source 2 and the lowest influence of source 1 on carcinogenic risk.

Conclusions

Our study investigated seasonal variations of $PM_{2.5}$ and trace metals bound in $PM_{2.5}$ identified their potential emission sources using two receptor models (UNMIX and PCA/APCS) and performed the human health risk assessment owing to exposure to toxic elements bound in $PM_{2.5}$. Both models apportioned 4 potential source factors of $PM_{2.5}$ including traffic-related emission, scrap metal recycling villages, crustal mixed with construction sources, coal combustion mixed with industry, and biomass burning. UNMIX and PCA/APCS confirmed that traffic-related emissions dominated the mass of $PM_{2.5}$ in the inner urban of Hanoi. Although the two models showed good agreement in source determination, the source percentage contribution exhibited moderate discrepancy. The potential carcinogenic risk for both children and adults could be negligible. However, the accumulative non-carcinogenic risk for adults was far higher than the safe level, implying that the non-carcinogenic risk for adults should be paid special attention in Hanoi. In addition, generally, the two receptor models exhibited comparable results of health risk assessment for individual emission sources.

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Author contribution BTH designed the structure; wrote the manuscript; processed, analyzed, and interpreted data; prepared figures and the manuscript; evaluated the results; and discussed the results. NTPM contributed to the design of the structure, analyzed the samples, and evaluated the results. All authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval Not applicable.

Consent to participate All authors have consent to participate in this study.

Consent for publication The authors agree to public in the Environmental Science and Pollution Research.

Competing interests The authors declare no competing interests.

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