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Characterization of ^{210}Po activity and trace heavy metals in aerosols from traffic-dominated areas in urban, Hanoi, Vietnam: implications for air pollution sources and human health risks

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ABSTRACT

Air pollution has become a serious problem in densely populated urban areas in recent years. The ^{210}Po activity (a toxic radionuclide) and trace heavy element concentrations in 24 aerosol samples from Hanoi, Vietnam, were measured . ^{210}Po activity ranged from 92.2 to 3500 μBq.m^{-3}. Notably,^{210}Po activity in roadside samples was much higher compared to global reference values. Among the trace heavy metals analyzed, Co showed the lowest concentrations, while Al had the highest. Most metal levels in roadside areas were higher than those in residential areas. Enrichment factor analysis indicated that metals such as Li, Al, Ti, V, Mn, Fe, Co, and Ba mainly came from crustal sources. In contrast, Cr, Ni, Cu, Zn, Cd, Sb, and Pb were linked to vehicle emissions such as fossil fuel combustion. The relationship between ^{210}Po and these metals revealed factors affecting its presence in urban air. In residential areas,^{210}Po negatively correlated with Ni and positively with Al, indicating a crustal origin. By contrast, its strong positive correlation with Cr and Ni in roadside areas suggests fossil fuel combustion as main source. Despite the diverse ^{210}Po sources in Hanoi, the findings suggest that its presence in aerosols is largely determined by local characteristics and supply on-site.

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^{210}Po; aerosols; high ^{210}Po activity; radionuclide; trace heavy metal; Hanoi

1. Introduction

Air pollution is increasingly recognized as one of the most serious global challenges. A report by the World Health Organization states that most people are exposed to air with pollutant levels that exceed the limits recommended guidelines, especially in large urban areas (WHO 2021). Recent studies have found that urban air pollution is mainly caused by human activities (Wu et al. 2009; Boreddy et al. 2021). Concentrations of heavy metal elements in aerosols are significantly higher than natural background levels

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due to anthropogenic emissions such as vehicular emission (Hashimoto et al. 1994; Wu et al. 2009; Boreddy et al. 2021). Previous studies showed that combustion processes such as coal burning, fuel use, and non-ferrous metal production are major man-made sources of trace heavy metal elements in the atmosphere (Pacyna and Pacyna 2001; Wu et al. 2009). Vehicle emissions, mainly caused by incomplete fuel combustion, are a leading source of pollution in large urban air (Molina and Molina 2004; Lawrence et al. 2007; Chan and Yao 2008; Gurjar et al. 2008; Krzyzanowski et al. 2014). However, the level of air pollution varies across different urban areas, depending on factors such as the number of vehicles, technology, urban planning, culture, and economic activities (Phan et al. 2020).

The investigation and monitoring of air quality, especially the levels of trace heavy metals and natural radionuclides, are crucial to protecting public health in each country. Tracking these substances in aerosols helps understand their characteristics and potential health risks (Wu et al. 2009; Sorooshian et al. 2013; Kanakidou et al. 2018; Boreddy et al. 2021). The presence of radioisotopes in the atmosphere is of particular interest because of their toxicity and their role in studying atmospheric processes (Henricsson et al. 2011; Długosz-Lisiecka 2016; Persson 2016; Behbehani et al. 2020).

^{210}Po is a highly toxic isotope in the natural decay series of ^{238}U. ^{210}Po in the atmosphere originates from both natural sources, such as ^{222}Rn emission from soil, rocks, surrounding materials, oceans, volcanic activity, soil resuspension, bioaerosols, forest and savanna fires, and artificial sources including the combustion of fossil fuels, phosphate production, and metals processing (Schmidt and Hamel 2001; Długosz-Lisiecka 2016; Ouyang et al. 2018). As a particle-reactive radionuclide, ^{210}Po attaches to aerosol after being generated from the decay of its parent isotope (^{222}Rn-radon), and is transported through the air by weather and atmospheric conditions (McNeary and Baskaran 2007; Carvalho et al. 2017; Thakur and Ward 2020). Its distribution depends on factors like the parent isotope content, meteorological conditions, removal processes such as wet and dry deposition, and the enrichment of atmospheric dispersion influenced by human activities (Persson 2014; Długosz-Lisiecka 2016; Carvalho et al. 2017). Due to its relatively long half-life (138.4 days), the ^{210}Po plays a vital role in tracking environmental processes (Thakur and Ward 2020). It has been effectively used to identify air pollution sources and study atmospheric processes (Ouyang et al. 2018). For example, ^{210}Po is a valuable tool for tracking sources, determining removal rates, residence times, and the exchange of natural aerosols in the troposphere and stratosphere (Długosz-Lisiecka 2016; Persson 2016; Ouyang et al. 2018; Aba et al. 2020; Behbehani et al. 2020). The application of ^{210}Po in atmospheric processes studies has yielded positive results, making significant contributions to air quality monitoring and investigations. The ^{210}Po has been linked to traffic emissions, tobacco smoking, and diseases affecting the lungs and nervous systems (dos Santos et al. 2020). Long-term exposure to ^{210}Po, can pose significant carcinogenic risk (Behbehani et al. 2020). According to UNSCEAR, the radiation dose from inhaling radon daughters, including ^{210}Po can be relatively high, leading to adverse effects on public health (UNSCEAR 1993).

In recent years, air pollution in Vietnam has become extremely severe, especially in Hanoi, the capital city, where rapid industrialization and urbanization have taken place. Several studies have been conducted to evaluate pollution levels and air quality in this area. The results indicate that $PM_{2.5}$ concentrations can reach up to 150 μg/m^3 during the dry season (Ly et al. 2018). Notably, aerosol concentrations across various particle sizes have been reported to reach 143 μg/m^3 indoors and up to 205 μg/m^3 outdoors during the winter season (Le Ha et al. 2020). These values are significantly higher than the WHO-recommended limit of 25 μg/m^3. With a population of around ten million and heavy traffic, transportation is a major contributor to air pollution in Hanoi. According to Vietnam's Ministry of Transport, traffic accounts for 70% of the smog-causing air pollution in the city (https://mt.gov.vn/moitruong/Pages/ChiTietTin.aspx?groupID=1129&IDNews=52054). Although numerous studies have examined particulate matter (TSP) content and heavy metals in aerosols (Ly et al. 2018; Le Ha et al. 2020; Phan et al. 2020), research on natural radionuclides, particularly ^{210}Po, in the atmospheric aerosols in Vietnam remains limited. The WHO reported that over 60,000 deaths in Vietnam in 2016 were linked to air pollution (https://www.who.int/vietnam/news/detail/02-05-2018-more-than-60-000-ca-vong-in-viet-nam-each-year-Link-to-air-Pollution). Therefore, assessing the levels of ^{210}Po and metal pollution in urban aerosols is crucial for understanding potential health and environmental risks. This data provides a baseline for early detection of unusual radioactive pollution, allowing for timely responses to reduce harmful effects on humans and the environment. Identifying the sources of ^{210}Po emissions in aerosols can assist authorities in implementing more effective pollution control and mitigation strategies. Additionally, scientific data on ^{210}Po and metal concentrations can inform sustainable urban planning efforts, reducing future negative impacts on health and the environment. This highlights the urgent need for air quality management in Hanoi and throughout Vietnam. This paper aims to: (1) develop a database of ^{210}Po and selected trace heavy element, metal concentrations in aerosols from traffic-dominated roadside and residential areas in Hanoi, and (2) investigate the main sources of air pollution contributing to high ^{210}Po activity in aerosols in Hanoi, Vietnam.

2. Materials and methods

2.1. Study area and sampling

Hanoi, located in northern Vietnam, is the capital city with a population of about ten million people and an area of only around 3000 square kilometers. Environmental concerns, especially air quality, have become a pressing issue in recent years (Ly et al. 2018; Le Ha et al. 2020).

To study the database of ^{210}Po and selected trace heavy metal element concentrations in Hanoi's aerosols, a total of 24 aerosol samples were collected from two types of locations: roadside and residential areas. A summary of the sampling locations is presented in Table 1. Since air pollution is higher in winter, samples were collected during this season in 2019 (Oanh et al. 2006; Cohen et al. 2010; Hien et al. 2011). The sampling process was carried out simultaneously in both areas to ensure that the influence of weather conditions was minimized during the period from November 1st to December 3rd (dry season). Aerosol samples (total suspended particulate matter) were collected using a high-volume air-sampling model (DF-60810E), with the air passing through filters at a flow rate of 1.2 m^3/m. The total air volume and pumping time were recorded,

Table 1. ^{210}Po Activity in the aerosol of the studied samples.

Sample	Coordinates		Site	Concentration of ^{210}Po ($\mu Bq.m^{-3}$)
	Longitude	Latitude		
S1	21°03′47.8″N	105°49′44.1″E		1080 ± 54
S2	21°00′50.3″N	105°51′26.8″E		1550 ± 124
S3	21°01′32.8″N	105°50′47.5″E		1980 ± 176
S4	21°00′16.4″N	105°47′55.0″E		1780 ± 41
S5	21°00′47.7″N	105°51′07.3″E		2840 ± 108
S6	21°00′43.6″N	105°51′37.7″E		1880 ± 207
S7	21°00′58.5″N	105°51′22.2″E	Roadside area	2960 ± 95
S8	21°00′30.7″N	105°50′54.9″E		2350 ± 136
S9	21°01′39.6″N	105°51′29.1″E		1640 ± 98
S10	20°58′07.9″N	105°49′24.6″E		2540 ± 107
S11	21°01′35.8″N	105°49′23.0″E		2150 ± 185
S12	21°02′28.7″N	105°45′43.5″E		3500 ± 175
S13	20°59′42.5″N	105°51′20.8″E		2300 ± 44
S14	20°59′16.4″N	105°52′15.0″E		1400 ± 125
S15	20°59′23.9″N	105°50′33.4″E		496 ± 28
S16	21°01′20.5″N	105°49′09.7″E		202 ± 7.5
S17	21°01′32.3″N	105°47′58.9″E		106 ± 6.9
S18	21°00′52.4″N	105°51′03.8″E		987 ± 148
S19	21°00′39.1″N	105°46′59.7″E		285 ± 14
S20	20°58′23.4″N	105°50′43.2″E	Residential area	362 ± 20
S21	21°03′56.3″N	105°48′36.7″E		385 ± 23
S22	21°03′12.4″N	105°45′06.5″E		92 ± 7.7
S23	21°03′08.0″N	105°44′41.8″E		192 ± 16
S24	21°04′37.6″N	105°46′25.0″E		423 ± 27
Total			Average	1395 ± 129
			Min	92.2 ± 7.4
			Max	3500 ± 175

with each sample collected over approximately 72 h, corresponding to an average air intake of ∼ 5000 m^3. The samplers were installed at approximately 1.5 meters above ground level. ^{210}Po is known to attach to aerosol particles with a wide diameter ranging from 10^{-3} µm to 10^2 µm. Due to the increased specific surface area, ^{210}Po exhibits a preferential affinity for finer aerosol particles, with its concentration generally inversely proportional to particle diameter (Długosz-Lisiecka 2016). Accordingly, filters with an aerodynamic cutoff diameter of approximately 0.3 µm were employed to efficiently capture fine particulate-bound ^{210}Po. Sampling time was carefully documented to allow decay correction, given the relatively short half-life of ^{210}Po (138.4 days) (Figure 1).

2.2. Analysis methods

2.2.1. Analysis of ^{210}Po

After collecting, the samples were sealed and transported to the laboratory for analysis. The ^{210}Po activity in aerosols was determined by alpha spectroscopy, following established procedures (McNeary and Baskaran 2007; Behbehani et al. 2020). A ^{209}Po tracer with 50 mBq activity was added to the sample. Then, the sample was decomposed using a mixture of HCl and HNO_3 acids with a ratio of 3:1 and H_2O_2 was added. Polonium was co-precipitated with MnO_2 by a sufficient amount of $KMnO_4$ and $MnCl_2$ under conditions where the pH was greater than 9. The polonium was then separated using ion exchange chromatography and prepared for spontaneous deposition onto a silver disk (IAEA 2009; Dubey et al. 2015; Van Hao et al. 2022). Ascorbic acid was added

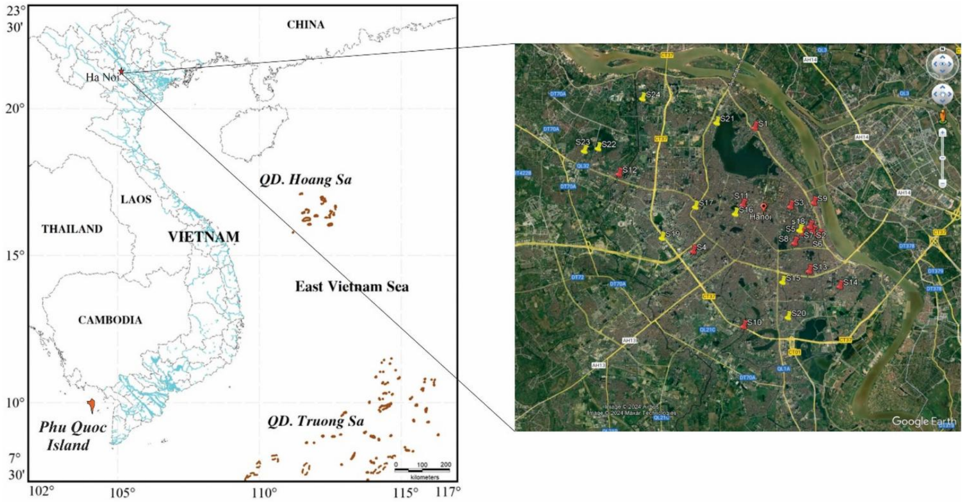

Figure 1. Study area and sampling points.

to reduce Fe^{3+} to Fe^{2+} (IAEA 2009). The ^{210}Po activity in the studied samples was determined using an ORTEC Alpha-Ensemble-4 alpha spectroscope (ALPHA-DUOM1 – 450 mm^2 area detector). The MDA of the detector was 0.5mBq. The method recovery rate and quality control were based on using a ^{209}Po tracer and the IAEA-384 (Fangatuafa sediment) standard reference material.

2.2.2. Trace elemental analysis

To analyze the trace heavy metal elements in the aerosols, inductively coupled plasma mass spectrometry (ICP-MS) was used, following the procedure described by Boreddy et al. (2021). Samples were digested using an appropriate amount of HNO_3 in a microwave-assisted digestion system. After digestion, the solutions were diluted with deionized water, filtered, and subsequently analyzed by ICP-MS. The calibration standards used in the analysis were ICP-Multi-element standards with the calculated limit of detection (LOD) at the ppb level. The limits of detection (LODs) for Li, Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Sb, Ba, and Pb were 0.04, 0.015, 0.019, 0.012, 0.001, 0.001, 0.012, 0.003, 0.008, 0.003, 0.038, 0.003, 0.007, 0.002, and 0.001 ppb, respectively. The recovery efficiency of the method was greater than 90% based on tests with the standard reference materials.

2.2.3. The enrichment factor

The enrichment factor (EF) is used to determine the influence of anthropogenic factors on the presence of elements in the atmosphere. Based on EF values, trace heavy elements are typically classified into three categories: $EF < 2$, indicating a crustal origin; $2 \leq EF \leq 10$, suggesting a mixed origin; and $EF > 10$, indicating a predominantly anthropogenic origin (Hsu et al. 2010; Cui et al. 2020). The Ef of elements can be calculated using the following equation (Hsu et al. 2010; Xu et al. 2022):

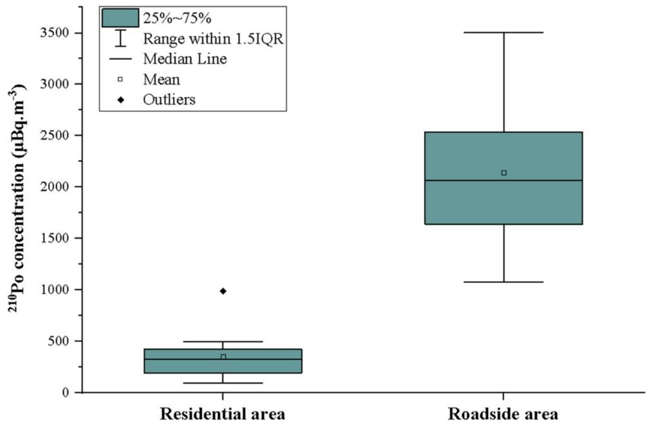

Figure 2. Average ^{210}Po activity between roadside and residential areas.

$$Ef = \frac{(C_X/C_{Al})_{aerosol}}{(C_X/C_{Al})_{crust}},$$

where C_X is the concentration of element X; C_{Al} is the concentration of Al because it is ubiquitous in the environment and has no significant anthropogenic origin (Cui et al. 2020). $(C_X/C_{Al})_{aerosol}$ and $(C_X/C_{Al})_{crust}$ refer to the ratio of element X and Al in aerosol and crustal samples, respectively. In this study, $(C_X/C_{Al})_{crust}$ is the ratio in crustal material obtained from Mason and Moore compilation for trace elements in crust earth (Mason and Moore 1982).

2.3. Statistical analysis

T-tests were performed to evaluate the differences between mean values. The Pearson correlation coefficient was used to describe the correlations between trace heavy metals and ^{210}Po. Statistical analyses were performed by IBM SPSS Statistics 20.

3. Results

3.1. The ^{210}Po activity in aerosol samples

The ^{210}Po activity in aerosol samples at two study sites (including both roadside and residential areas) range from 92 ± 7.7 μBq.m^{-3} to 3500 ± 175 μBq.m^{-3}, with an average value of 1395 ± 129 μBq.m^{-3} (Table 1). This value is far higher than the worldwide reference level of 50 µBq.m^{-3} recommended by UNSCEAR (2000). This large variation indicates the uneven distribution of ^{210}Po in the two selected study areas. The ^{210}Po concentration in the roadside area was far higher than that in the residential area (six times difference, T-test with p value < 0.05) with the mean values of 2140 ± 200 and 350 ± 30 μBq.m$^{-3,}$ and range from 1080 ± 54 to 3500 ± 175 μBq.m^{-3} and from 92 ± 7 to 987 ± 148 μBq.m^{-3}, respectively (Figure 2). The uneven distribution of ^{210}Po in the aerosols suggests that it is interesting to discuss air pollution sources and factors that influence this distribution. Tables 2 and 3 show the relationships between trace heavy

Table 2. Relationship between trace heavy metals.

	Li	Al	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Cd	Sb	Ba	Pb
Li	1.00														
Al	0.38	1.00													
Ti	0.05	0.49*	1.00												
V	−0.04	−0.22	0.02	1.00											
Cr	−0.02	0.37	0.41*	0.33	1.00										
Mn	0.16	0.58**	0.91**	0.13	0.63**	1.00									
Fe	0.02	0.56**	0.77**	−0.26	0.47*	0.83**	1.00								
Co	0.19	0.50*	0.56**	0.52*	0.78**	0.78**	0.43*	1.00							
Ni	−0.01	−0.31	−0.13	−0.37	−0.77**	−0.38	−0.21	−0.75**	1.00						
Cu	−0.59**	−0.40	−0.31	−0.22	−0.29	−0.53**	−0.22	−0.65**	0.27	1.00					
Zn	0.06	0.46*	0.89**	0.07	0.30	0.81**	0.70**	0.47*	−0.01	−0.29	1.00				
Cd	0.41*	0.39	0.42*	0.22	0.32	0.47*	0.11	0.49*	−0.21	−0.41	0.47*	1.00			
Sb	0.29	0.12	0.56**	0.44*	0.29	0.57**	0.16	0.56**	−0.11	−0.56**	0.64**	0.74**	1.00		
Ba	0.11	0.60**	0.75**	−0.30	0.54**	0.84**	0.94**	0.51**	−0.33	−0.34	0.61**	0.21	0.22	1.00	
Pb	0.23	0.18	0.54**	0.55**	0.31	0.56**	0.12	0.65**	−0.25	−0.49*	0.65**	0.69**	0.84**	0.15	1.00

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

Table 3. Relationship of ^{210}Po to trace heavy metal elements in aerosols.

	Pearson correlation with ^{210}Po concentration		
Trace metal	Roadside area	Residential area	Total
Li	0.16	0.12	0.03
Al	0.41	0.57**	0.17
Ti	0.31	−0.05	0.09
V	0.36	0.51*	0.13
Cr	0.55**	0.40	0.3
Mn	0.43	0.27	0.19
Fe	0.49	0.49	0.24
Co	0.43	0.51*	0.19
Ni	0.70**	−0.65**	−0.48*
Cu	0.43	−0.40	0.19
Zn	−0.20	−0.16	−0.04
Cd	−0.20	−0.11	−0.05
Sb	−0.45	−0.20	−0.21
Ba	0.47	0.32	0.22
Pb	−0.28	−0.14	−0.08

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

metals and the ^{210}Po concentration in aerosols. These relationships provide into their enrichment processes and potential sources.

3.2. The selected trace heavy metal contents and enrichment factor

Table 4 presents the concentrations of trace metals (Li, Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Sb, Ba, Pb) in the aerosol samples from both sites too. Al was recorded as the element with the highest concentration, whereas Co exhibited the lowest value. Al is recognized as the most abundant trace metal in the atmosphere, characterized by its stable concentrations (Majumdar et al. 2020; Boreddy et al. 2021). The average concentrations of Co, Cd, Li, Sb, V, Cu, Pb, Cr, Ba, Mn, Zn, Ti, Ni, Fe and Al are recorded with

Table 4. Trace heavy metal elements concentration and enrichment factor (EF) in the aerosol of the studied samples.

	Trace heavy metal concentration (ng.m-3)									EF		
	Roadside area			Residential area			Total					
Metals	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max
Li	6.68	1.21	9.31	6.25	3.70	7.64	6.50	1.21	9.31	4.34	1.16	7.84
Al	6458	4072	10431	6044	3308	9594	6285	3308	10431	1.00	1.00	1.00
Ti	1307	339	4286	889	340	1806	1133	339	4286	3.10	0.91	8.56
V	39.6	20.5	64.8	34.9	27.7	43.4	37.6	20.5	64.8	3.96	1.92	6.86
Cr	92.5	50.2	133	73.8	49.4	99.5	84.7	49.4	133	11.6	5.9	19.4
Mn	185	67.0	465	132	66.7	200	163	66.7	465	2.14	0.85	3.81
Fe	6745	2628	34843	4029	2574	6721	5614	2574	34843	1.36	0.62	5.43
Co	2.04	0.73	2.75	1.63	0.73	2.87	1.87	0.73	2.87	0.96	0.34	1.74
Ni	1501	1058	2288	1907	1083	2301	1670	1058	2301	328	122	747
Cu	70.6	44.0	164	68.4	48.7	91.4	69.7	44.0	164	19.8	7.35	57.2
Zn	797	9.72	2868	744	271	1463	775	9.72	2868	123	1.57	319
Cd	1.99	1.09	2.97	1.75	0.66	3.63	1.89	0.66	3.63	122	51.2	246
Sb	8.71	3.99	12.7	8.45	5.09	13.8	8.60	3.99	13.83	576	215	933
Ba	130	13	474	95	58	170	116	13	474	3.30	0.43	8.70
Pb	83	23	154	77	22	156	80	22	156	76.7	22.5	168
Ni/Pb	28.5	10.5	99.3	53.4	9.43	105	38.8	9.43	105			

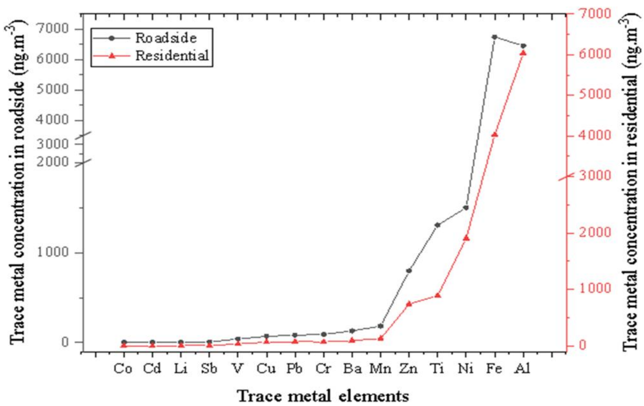

Figure 3. Distribution of trace heavy metal elements in roadside and residential areas.

values of 1.87, 1.89, 6.50, 8.60, 37.6, 70, 80, 84.7, 116, 163, 775, 1133, 1670, 5614 and 6285 $ng.m^{-3}$, respectively. The results show variations in metal concentrations between sites and between locations (roadside and residential areas). Most metal concentrations in the roadside area were higher than those in the residential area; an exception is Ni (Table 4). The distribution of trace heavy metal elements in roadside and residential areas are shown in Figure 3. Some metals, such as Cr, Ni, Cu, Zn, Cd, Sb, and Pb, have significantly higher concentrations than other metals. The data also includes the enrichment factor (EF) for each metal, which indicates the degree of enrichment of the metal in the aerosol samples relative to the earth's crust. The enrichment factor (EF) indicates that the concentration of these metals exceeds natural levels, especially Ni, Cd, Sb, and Pb. The Ni/Pb ratio in the study aerosols ranged from 9.43 to 105, with an average of 39. The Ni/Pb ratio can provide additional information about the source of contamination, and it will be discussed in the discussion section.

4. Discussions

4.1. Characteristics of the ^{210}Po activity and selected trace heavy metals in aerosol samples

The distribution of ^{210}Po concentrations appears to be uneven, with higher levels observed in roadside areas compared to residential areas. Sample sites S5, S7, S8, S10, S12, and S13 are recorded significantly higher ^{210}Po activities than the average value. The sample sites S7 and S12 (Roadside area) had the highest activity, suggesting the influence of traffic activities. The high ^{210}Po activity observed in the study aerosol samples from roadside areas could be related to the high air pollution and the high traffic density. This result partly comes from the relationship between aerosol concentrations with traffic activity reported in a previous study (Phan et al. 2020). The small-sized aerosol from industrial activities and combustion can reach higher polonium activity concentrations than would be generally expected (Behbehani et al. 2020). (Phan et al. 2020) also showed the correlation between aerosol concentration and the level of air pollution. While sample sites S15, S16, S17, S19, S20, S22, and S23 (Residential area) show significantly lower ^{210}Po activity than the average. This suggests that the Residential area may have factors that reduce the accumulation and enrichment of ^{210}Po in aerosol dust. In comparison with literature data on aerosol ^{210}Po concentrations in different regions of the world (Table 5), it is clear that the ^{210}Po activity in this study was higher than in most of those other areas (Radiation and Annex 2000; Baskaran and Shaw 2001; Dueñas et al. 2004; Daish et al. 2005; McNeary and Baskaran 2007; Silva 2007; Ram and Sarin 2012; Jia and Jia 2014; Długosz-Lisiecka 2016; Ouyang et al. 2018; Behbehani et al. 2020).

Similar to ^{210}Po, most trace heavy elements exhibited higher concentrations in roadside areas compared to residential areas. Some metals, such as Cr, Ni, Cu, Zn, Cd, Sb, and Pb, have significantly higher concentrations than other metals. This result may be attributed to the varying impact of human activities in different areas, with roadside locations experiencing heavy traffic and fossil fuel combustion, which can be contributors to the presence of heavy and trace metals in aerosols (Allen et al. 2001; Cui et al. 2020; Xu et al. 2022).

4.2. The primary sources of air pollutants and factors influencing ^{210}Po activity in aerosols

The enrichment factor (EF) was calculated to assess the anthropogenic contributions of metals to the atmosphere (Table 4). The origins of metals can be classified into three categories. First, metals associated with crustal sources, such as Al and Fe, exhibited enrichment factor (EF) values ranging from 1 to 2. The high concentrations of Fe and Al suggest the dominance of metals derived from the Earth's crust. This indicates that the primary aerosol sources in the study area may originate from surface soil (a local supply source). Next, metals with mixed origins - including Li, Ti, V, Mn, Fe, and Ba - showed EF values between 2 and 10. These metals are likely influenced by both natural crustal and anthropogenic sources. Finally, metals such as Cr, Ni, Cu, Zn, Cd, Sb, and Pb are identified as being of anthropogenic origin, with EF values $>$ 10. Relationships

Table 5. ^{210}Po activity in this study aerosols and from the cities worldwide.

Location	^{210}Po ($\mu Bq.m^{-3}$)	References
Alaska (USA Poker Flat)	100	(Baskaran and Shaw 2001)
Kuwait	34–4200	(Behbehani et al. 2020)
Germany	12–80	(Radiation and Annex 2000)
India (Kampur)	2–280	(Ram et al. 2012)
China (Beijing)	430	(Ouyang et al. 2018)
Italy (Taranto)	34.5–1100	(Jia and Jia 2014)
England (Chilton, Oxfordshire)	2–69	(Daish et al. 2005)
Poland (Lodz)	9.44–136.9	(Długosz-Lisiecka 2016)
US (Michigan)	72	(McNeary and Baskaran 2007)
USA	10–40	(Radiation and Annex 2000)
Brazil (São José dos Campos)	249 ± 209	(Silva 2007)
Spain (Malaga)	45–70	(Dueñas et al. 2004)
Hanoi, Vietnam	92.2–3500 (1395 ± 129)	This study

between metals like Cd-Zn, Cd-Sb, Cd-Pb, Zn-Sb, Zn-Pb, Cu-Sb, Cu-Pb, and Ni-Cr suggest they have a similar source (Table 2), primarily fossil fuel combustion (Allen et al. 2001; Cui et al. 2020; Majumdar et al. 2020). Additionally, Zn may be linked to industrial activities and tire rubber abrasion (Pacyna and Pacyna 2001; Majumdar et al. 2020), while Cd and Ni are associated with battery manufacturing and recycling (Teixeira et al. 2008). Metallurgical processes have also been reported to emit significant amounts of Cd, Cu, and Ni (Allen et al. 2001).

The Ni/Pb ratio is a useful indicator for assessing the relative contributions of mobile and point-source combustion aerosols (Boreddy et al. 2021). Ni primarily originates from oil-diesel combustion (Hao et al. 2018), while Pb is associated with solid waste burning and coal consumption (Liang et al. 2010; Emsley 2011; Zhao et al. 2017; Popoola et al. 2018; Sun et al. 2022). On this basis, the high Ni/Pb ratio may reflect the predominance of liquid fuel combustion (gasoline and diesel) related to traffic activities compared to other combustion sources, such as coal consumption from thermal power plants and metallurgy. Thus, trace heavy metals in Hanoi's aerosols are predominantly of local origin (local supply), derived from the Earth's crust and fossil fuel combustion. Traffic activities using liquid fuels are the primary contributors, with additional contributions from local industrial activities.

The relationship between ^{210}Po and metals is presented in Table 3. In the roadside area, ^{210}Po exhibited strong positive correlations with Cr (Rp=0.55) and Ni (Rp=0.70) (both significant at the 0.01 level), two metals associated with fossil fuel combustion. These findings suggest that one of the primary sources of aerosol ^{210}Po in this area is anthropogenic activity, particularly liquid fossil fuel combustion and high traffic density, which likely contribute to the observed elevated ^{210}Po levels. In the residential area, ^{210}Po showed a negative correlation with Ni ($Rp=-0.65$) and a positive correlation with Al (Rp=0.57) (both significant at the 0.01 level), indicating a crustal origin. ^{210}Po may originate from the decay of ^{222}Rn evaporated from the surface. This suggests that the sources of ^{210}Po differ between the two areas. Previous studies have identified anthropogenic sources of ^{210}Po in aerosols in major cities worldwide, particularly from combustion processes (e.g., coal combustion) and industrial activities (Długosz-Lisiecka 2016; Ouyang et al. 2018; Behbehani et al. 2020; dos Santos et al. 2020). Polluting activities facilitate the transport of ^{210}Po into urban areas. Based on the findings of this study, we suggest that aerosol ^{210}Po in the study area (Hanoi) is primarily influenced by local sources relating to liquid fossil fuel combustion, high traffic density and specific characteristics of the area.

Study on the ^{210}Po activities and selected trace metal concentrations in aerosols from traffic-dominated in urban areas, this study provides new insights into the behavior and origin of ^{210}Po in the urban atmosphere. One of the significant findings is the identification of distinct differences in ^{210}Po sources between different areas within the same urban environment. The combination of quantitative analysis and qualitative interpretation based on the socio-economic characteristics of the study areas provided a comprehensive understanding of air pollution sources in Hanoi. The study represents the first investigation to provide systematic data on the relationship between ^{210}Po and trace metals in urban aerosols in Vietnam. The findings support the potential of ^{210}Po as a sensitive tracer for particulate emissions, especially for applications in the study of atmospheric processes. The identification of specific sources of ^{210}Po and heavy metals provides a scientific basis for developing targeted pollution control policies, especially those related to traffic management, fuel standards, and urban planning. The ^{210}Po activity concentrations provide important baseline information for monitoring air pollution trends and assessing the effectiveness of future mitigation measures. This approach can also be applied to other cities with similar characteristics in Vietnam, where traffic density is high, and urbanization is rapid. However, some limitations remain in comprehensively assessing the behavior of ^{210}Po in the atmospheric environment. The temporal variation of ^{210}Po and the influence of meteorological factors on ^{210}Po concentrations in aerosols remain unclear. In addition, although the inhalation dose is generally considered negligible compared to the ingestion dose, quantitative assessment of exposure from inhalation of aerosols containing ^{210}Po remains necessary to contribute to an evaluation of health impacts. Future studies should include seasonal sampling to assess temporal variation and calculate the annual effective dose from inhalation of aerosols containing ^{210}Po to provide more accurate health risk assessments.

5. Conclusions

This study provides new insights into the distribution and sources of ^{210}Po and selected trace heavy metals in atmospheric aerosols collected from roadside and residential areas in Hanoi, Vietnam. The ^{210}Po activity in the aerosol samples showed a wide range and relatively high values compared to the worldwide reference level. The ^{210}Po activity in roadside areas was six times higher than in residential areas. This may be attributed to high levels of air pollution and traffic density. The metal concentrations were determined, with the lowest values found for Co and the highest for Al. Most metal concentrations in roadside areas were also higher than those in residential areas. The enrichment factors enabled the classification of metals into crustal (Al, Fe), mixed (Li, Ti, V, Mn, Fe, and Ba), and anthropogenic sources (Cr, Ni, Cu, Zn, Cd, Sb, and Pb), offering a clearer understanding of their atmospheric behavior and origins. The relationships among anthropogenic metals suggested common sources, primarily fossil fuel combustion. The high Ni/Pb ratio reflected the dominant contribution of liquid fuel combustion (e.g., gasoline and diesel) associated with transportation activities, rather than other sources such as coal burning from thermal power plants or metallurgical processes. Notably, correlation analysis between ^{210}Po and metals revealed distinct source characteristics: in roadside areas, ^{210}Po was strongly correlated with Ni and Cr, indicating a link to liquid fossil fuel combustion; in residential areas, its positive correlation with Al and negative correlation with Ni suggested a crustal origin and influence from natural radon decay. Overall, this research provided knowledge regarding the behavior of particle-reactive radionuclides like ^{210}Po in urban environments. It highlights the role of local anthropogenic sources, particularly high-density traffic, in shaping the atmospheric composition of both trace heavy metals and radionuclides. The findings are valuable for future air quality assessments and risk evaluations, particularly concerning radiological exposure from urban aerosols.

Author contributions

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All authors read and approved of the final manuscript.

Consent to participate

Informed consent to participate was obtained from all individuals included in the study.

Consent to publication

Consent to publish has been received from all participants of the study.

Disclosure statement

The authors declare that they have no conflict of interest.

Ethics statement

This article does not contain any studies with human participants or animals by any of the authors.

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Data availability statement

Data used in the present work is available on request.

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