

Original Research

Annual Characteristics, Source Analysis, and Health Risk Assessment of Heavy Metals in PM₁ from a Low-Latitude, High-Altitude City: A Case Study of Kunming City

Jinjin Wang^{1,2°}, Pengfei Che², Yuhong Ran², Xiuxiang Meng³, Chenxin Liang², Jian Luo², Shucheng Tan^{1*}

¹School of Earth Sciences, Yunnan University, Kunming, 650500, China

²Xichang University, Xichang 615013, China

³School of Ecology and Environment, Renmin University of China, Beijing 100872, China

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Abstract

PM₁ samples were collected in Kunming City over a period of one year. The concentrations of HMs were analyzed using ICP-MS. EF, PCA, and health risk models were employed to evaluate the pollution level, sources, and carcinogenic risks. The results showed distinct seasonal variations in PM₁ mass concentration, with the highest level in winter ($40.35 \pm 9.16 \mu\text{g}\cdot\text{m}^{-3}$), the lowest in summer ($20.10 \pm 4.55 \mu\text{g}\cdot\text{m}^{-3}$), and the annual mean was $30.44 \pm 10.33 \mu\text{g}\cdot\text{m}^{-3}$. Among the seven HMs analyzed, Ti, Zn, Pb, and Ni exhibited relatively higher concentrations. The EF values were ranked as Cd (182.28) > Pb (39.62) > Ni (30.29) > Zn (18.56) > Cr (10.21), indicating that these metals are significantly influenced by anthropogenic activities. PCA further identified three major sources of PM₁: industrial and traffic mixed sources, manufacturing emissions, and natural sources. Health risk assessment results indicated that the carcinogenic risk values of Cr(VI) for adults and children were 1.19×10^{-4} and 2.38×10^{-5} , respectively. They surpassed the acceptable safety threshold (1×10^{-6}) and require continuous monitoring. Meanwhile, the risk value for adult exposure to Ni is 4.13×10^{-6} , which also requires consideration.

Keywords: heavy metal, pollution, sources, health risk, PM₁

Introduction

Particulate matter (PM) can serve as a transport medium for heavy metals (HMs) and other pollutants,

which may lead to widespread regional environmental contamination [1-5]. It is worth noting that PM₁ has drawn increasing attention due to its stronger penetration and toxicity, which can cause both acute and chronic health impacts on the human body [6, 7]. Many studies have confirmed that PM₁ is a key factor causing severe air pollution [8, 9]. Furthermore, exposure to PM₁ is correlated with an elevated risk of diverse diseases.

*e-mail: shchtan@ynu.edu.cn

Tel.: +86 13888422330

°ORCID iD: 0000-0002-5360-0785

These encompass respiratory diseases, cardiovascular and cerebrovascular diseases (e.g., stroke), thyroid diseases, and chronic kidney disease [10-13].

HM pollution refers to environmental contamination caused by metals or their compounds with a density greater than 4.5 g/cm^3 (e.g., Hg, Cd, Pb, Cr, Ni, Tl, etc.) [14, 15]. This type of pollution is primarily attributed to the persistence, bioaccumulative properties, and toxic effects of harmful elements in the environment, which pose significant risks to both ecological systems and human health [16-19]. HMs are crucial chemical components of PM_{10} , which contributes to its mass concentration and serves as a significant “fingerprint” for pollution source tracing [20]. However, the air quality regulatory frameworks in most countries currently lack specific standards for PM_{10} , and its emission control has not yet attracted widespread attention. Therefore, conducting a systematic investigation into the mass concentration, HM pollution characteristics, sources, and health risks of PM_{10} is of great significance for scientifically evaluating its environmental impact and formulating effective control strategies.

Kunming is renowned as the “City of Spring”, primarily attributed to its minimal seasonal temperature variations and a pleasant, temperate climate. Situated between $24^{\circ}23' \text{ N}$ and $26^{\circ}22' \text{ N}$ latitude, with an elevation ranging from approximately 1.5 to 1.8 km above sea level, it serves as a prime example of a low-latitude, high-altitude plateau city [21, 22]. During recent years, the process of urbanization has continued to progress [23], leading to increasingly

noticeable impacts of human activities on air quality and the living environment in Kunming. However, the pollution patterns, sources, and associated health risks of HMs in PM_{10} from this region remain insufficiently studied. Therefore, this study conducts a systematic analysis of the HM pollution levels in PM_{10} using samples collected over one year. Using the PCA model combined with HMs’ concentration characteristics, the sources were apportioned, and their contributions were quantified. Subsequently, a health risk assessment was conducted. The findings can provide a scientific basis for formulating targeted pollution control strategies and improving regional air quality in low-latitude and high-altitude cities.

Materials and Methods

Study Area and Sampling Site

Kunming, the capital city of Yunnan Province, experiences relatively mild annual temperature variations. The average temperatures across seasons are as follows: summer ($21.7 \pm 1.31^{\circ}\text{C}$) > spring ($19.1 \pm 2.25^{\circ}\text{C}$) > autumn ($17.2 \pm 3.21^{\circ}\text{C}$) > winter ($11.6 \pm 2.74^{\circ}\text{C}$). For this study, a PM_{10} sampling site was established at Kunming University of Science and Technology (KUST, Fig. 1), located in the northwest of Kunming. This site is situated in a composite functional area integrating residential activities, transportation, and commercial functions [21].

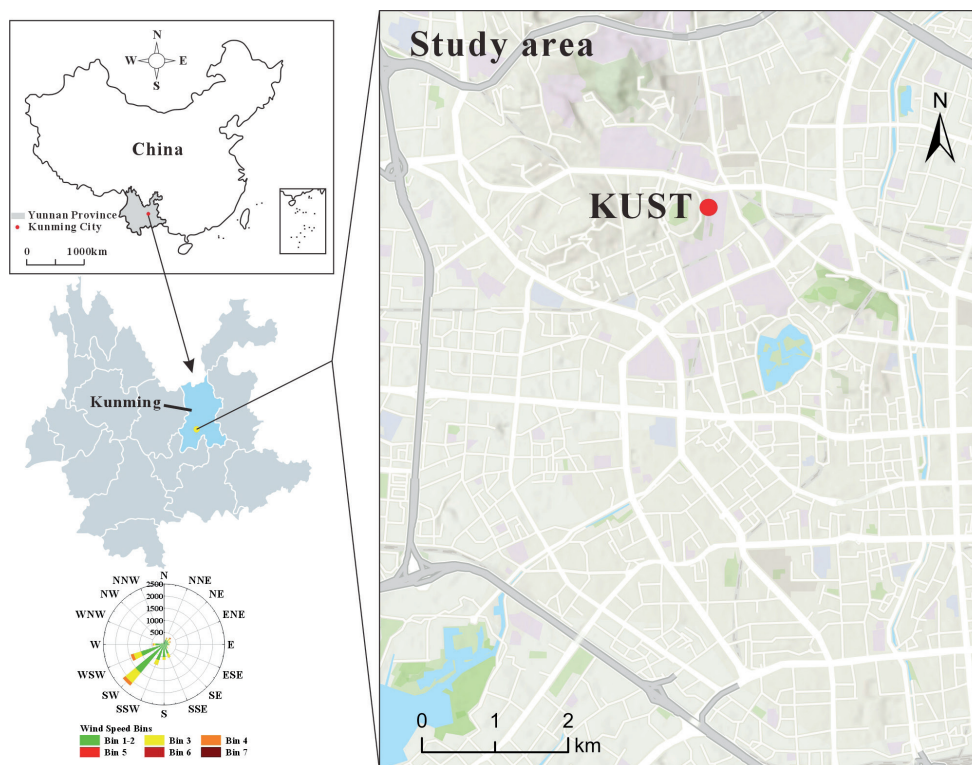


Fig. 1. Map of PM_{10} sampling sites in Kunming, China.

Sample Collection and Hms Analysis

PM₁ samples were collected on quartz fiber filters (size: 90 mm, QMA, Whatman, China) using a medium-flow sampler (TH-150C, Wuhan Tianhong Instrument Co., Ltd., China) operated at a constant flow rate of 100 L·min⁻¹. Prior to sampling, all filters were individually wrapped in aluminum foil and pre-baked at 450°C for 5 hours to remove organic contaminants that may have been introduced during transportation and storage. PM₁ samples were collected daily from November 1, 2023, to October 30, 2024, with each sample covering a 24-hour sampling cycle from 8:00 a.m. to 8:00 a.m. the following day. Upon completion of sampling, the filters were carefully transferred into sample cassettes following standard protocols and stored at -20°C until subsequent laboratory analysis.

Before and after sampling, all filter samples were conditioned in the same constant temperature and humidity chamber (25±1°C, 50±5% relative humidity) for 24 hours. Then, they were weighed using an analytical balance with 0.00001 mg precision (Sartorius CPA225D, Germany) to determine accurate sample mass. Prior to chemical analysis, a quarter of each filter was cut using ceramic scissors cleaned with absolute ethanol and placed into an acid-cleaned polytetrafluoroethylene (PTFE) digestion vessel. Nitric acid and hydrofluoric acid were added sequentially, and high-temperature and high-pressure digestion was carried out using a temperature-controlled oven and hot plate according to the procedure described in Wang et al. [24]. The concentrations of HMs were determined using inductively coupled plasma mass spectrometry (ICP-MS, PerkinElmer Corp., NexION 2000, USA). A calibration curve was established with standard solutions before analysis, and the national standard reference material GSS-4a was used for quality control and accuracy verification. Reagent blanks were included in each batch, and 10% of the samples were randomly selected for duplicate analysis to monitor procedural contamination and ensure reproducibility.

Meteorological and Air Quality Data Collection

Meteorological parameters, including temperature (T), wind speed (WS), relative humidity (RH), and wind direction (WD), were collected from the Huiju Atmosphere Environmental Data Platform (<http://www.hjhj-e.com/>).

Data Analysis

Enrichment Factor (EF)

The enrichment factor (EF) is an important indicator for assessing the enrichment degree of elements in PM_{10/2.5} and can effectively distinguish the sources of elements. This method has been widely applied in the source apportionment studies of fine particulate matter

in recent years. Its basic principle is to compare the relative ratios of the target element and the reference element in the particulate matter sample and the crustal (or soil) reference to identify whether there is an enrichment phenomenon caused by anthropogenic sources for the element. The calculation formula is as follows:

$$EF = \frac{\left(\frac{C_{\alpha}}{C_{\beta}}\right)_{sample}}{\left(\frac{B_{\alpha}}{B_{\beta}}\right)_{background}} \quad (1)$$

where, C_{α} is the measured value of HMs in PM₁, C_{β} is the measured value of Mn in PM₁ [24], B_{α} is the background value of HMs in the soil of Kunming, B_{β} is the background value of Mn in the soil of Kunming City. The specific classification of EF can be found in Supplementary Table S1.

Human Health Risk Assessment Approach

This study adopted the health risk assessment framework of the United States Environmental Protection Agency (EPA) to systematically assess the HQ and Risk_{cancer} of HMs in PM₁. In this work, inhalation was the only exposure route considered. Additionally, due to the toxicity of chromium, Cr(VI) was used to assess its risk in the calculation. The calculation formula is as follows:

$$EC = (C_{PM_1} \times EF \times ED \times ET) / AT \quad (2)$$

$$HQ = EC / RfC \quad (3)$$

$$Risk_{cancer} = EC_{cancer} \times IUR \quad (4)$$

where, EC is the exposure concentration, C_{PM_1} is the concentration in PM₁, EF is the exposure frequency, ET is the exposure time, ED is the exposure duration, AT is the averaging time, RfC is the reference concentration, IUR is the inhalation unit risk. The parameters and units used for calculating human exposure and health risks are presented in Table S2.

Statistical Treatment

To identify the pollution sources of heavy metals in PM₁, this study employed a combination of Principal Component Analysis (PCA) and correlation analysis. Prior to these analyses, the suitability of the data for factor analysis was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. The results showed a KMO value of 0.636, which exceeds the acceptable threshold of 0.5, and Bartlett's test yielded a significant result ($p < 0.05$), collectively justifying the application of PCA [25]. All data analyses

in this study were conducted using Origin Pro 2022, Minitab 22, and SPSS 26.

Results and Discussion

Mass Concentration of PM₁

During the study period, the average mass concentration of PM₁ from Kunming City was $30.44 \pm 10.33 \mu\text{g m}^{-3}$, ranging from 16.54 to $53.34 \mu\text{g m}^{-3}$. Given the absence of an annual average concentration limit standard for PM₁ in China, this study refers to the background concentration level of PM₁ ($11.9 \mu\text{g m}^{-3}$) reported by China's atmospheric background monitoring stations as the pollution assessment criterion [26]. In terms of seasonal variations, the average PM₁ concentrations were $26.00 \pm 5.76 \mu\text{g m}^{-3}$ in spring, $20.10 \pm 4.55 \mu\text{g m}^{-3}$ in summer, $35.31 \pm 7.42 \mu\text{g m}^{-3}$ in autumn, and $40.35 \pm 9.16 \mu\text{g m}^{-3}$ in winter, which were 2.2, 1.7, 3.0, and 3.4 times the background value, respectively (Fig. 2). The results indicate that PM₁ pollution from Kunming City was markedly elevated compared to the background levels across all seasons, with a particularly pronounced increase observed during autumn and winter. This trend highlights the importance of PM₁ as a crucial component of atmospheric fine particulate matter and emphasizes the need for heightened attention to the pollution challenges associated with it.

During the sampling period, we conducted synchronous monitoring and statistical analysis of meteorological parameters such as temperature, humidity, and wind speed. The results showed that the temperature ranked in the following order: summer (22.0°C) > spring (20.4°C) > autumn (12.5°C) > winter (10.3°C), which is opposite to the mass concentration. Specifically, the average temperature in winter was relatively low ($10.3 \pm 3.3^\circ\text{C}$) (Fig. 3). The lower temperature usually accompanied a more stable atmospheric stratification and weaker thermal

convection movement [27], which inhibited the vertical diffusion of pollutants and favored the accumulation of fine particulate matter near the ground, leading to an increase in PM₁ mass concentration. In contrast, the variation range of average relative humidity ($71.9 \pm 8.0\%$) and average wind speed ($2.0 \pm 0.5 \text{ m s}^{-1}$) during the observation period was relatively small (Fig. 3), suggesting that their contributions to the changes in PM₁ mass concentration were limited.

To assess the PM₁ pollution level in this study area, we compared the obtained annual average mass concentration value ($30.44 \pm 10.33 \mu\text{g m}^{-3}$) with the research data from other cities (Fig. 4). The results showed that the PM₁ pollution level in Kunming City presents obvious regional differences. Compared to major cities in developed countries, Kunming exhibits significantly higher PM₁ pollution levels. This disparity can be primarily attributed to differences in energy structures [8, 28]. However, within China, the PM₁ mass concentration in Kunming is markedly lower than that of major economic and industrial centers such as Beijing, Nanjing, Wuhan, and Xi'an. Kunming is located on the Yunnan-Guizhou Plateau [29], at a relatively high altitude, which is conducive to the dispersion of pollutants. Meanwhile, its industries are mainly low-pollution sectors such as tourism, biomedicine, and health, with a small scale of heavy industry and relatively limited primary pollutant emissions [30].

Characteristics of HMs in PM₁

The annual mean concentrations of seven HMs in PM₁ from Kunming exhibit significant differences (Fig. 5), with the concentration levels in the following descending order: Ti ($129.69 \pm 55.83 \text{ ng m}^{-3}$) > Zn ($42.04 \pm 35.58 \text{ ng m}^{-3}$) > Pb ($42.00 \pm 37.04 \text{ ng m}^{-3}$) > Ni ($32.98 \pm 13.42 \text{ ng m}^{-3}$) > Cr ($15.73 \pm 11.63 \text{ ng m}^{-3}$) > Cd ($1.03 \pm 0.37 \text{ ng m}^{-3}$) > Tl ($0.14 \pm 0.10 \text{ ng m}^{-3}$). In PM₁, the mean concentration of Ni was measured at 32.98 ng m^{-3} , which exceeds the guideline limit set by the World

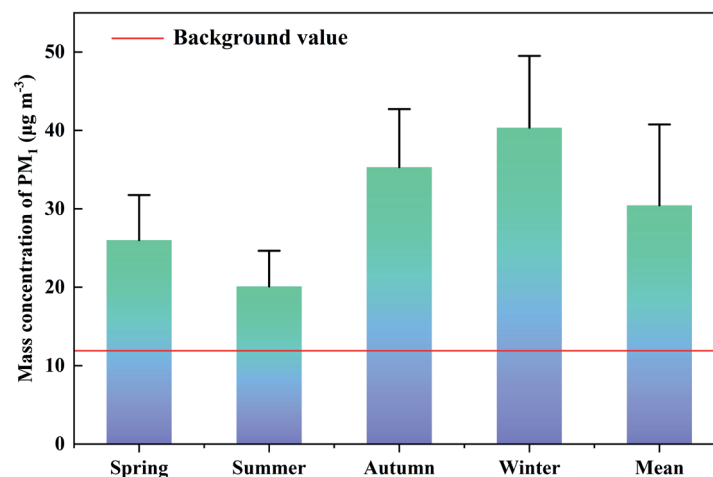


Fig. 2. Seasonal distribution characteristics of PM₁ mass concentration from Kunming City.

Health Organization (WHO) of 25 ng m^{-3} . In contrast, the concentrations of Pb and Cd were both below their respective WHO standards of 500 ng m^{-3} and 5 ng m^{-3} .

The concentrations of major HMs (such as Pb, Cd, Zn), except for Cr and Ti, were found to be significantly higher in autumn and winter than in spring and summer (Fig. 5). This distribution is mainly due to more stable meteorological conditions during the cooler seasons, which featured a lower average temperature (11.4°C) and wind speed (1.9 m s^{-1}) compared to the warmer seasons (21.2°C and 2.2 m s^{-1}) (Fig. 3), thereby weakening atmospheric dispersion and promoting pollutant

accumulation. These findings provide mechanistic evidence for the decisive influence of meteorological diffusion conditions and offer a direct scientific basis for prioritizing oversight in autumn and winter and for establishing differentiated seasonal prevention and control strategies.

The enrichment factor (EF) analysis of HMs in PM_{10} (Fig. 6) revealed significant differences in the degree of anthropogenic pollution [46]. The annual mean EF values followed a descending order: Cd (182.28) > Pb (39.62) > Ni (30.29) > Zn (18.56) > Cr (10.21) > Tl (6.59) > Ti (0.72). According to the EF classification criteria

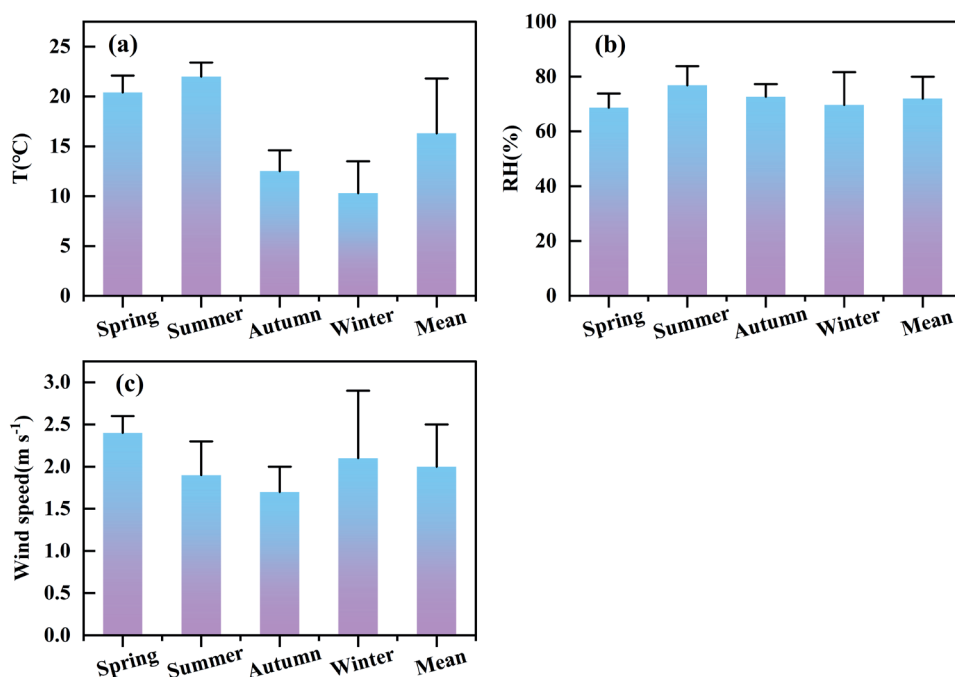


Fig. 3. Meteorological information of different seasons in Kunming City.

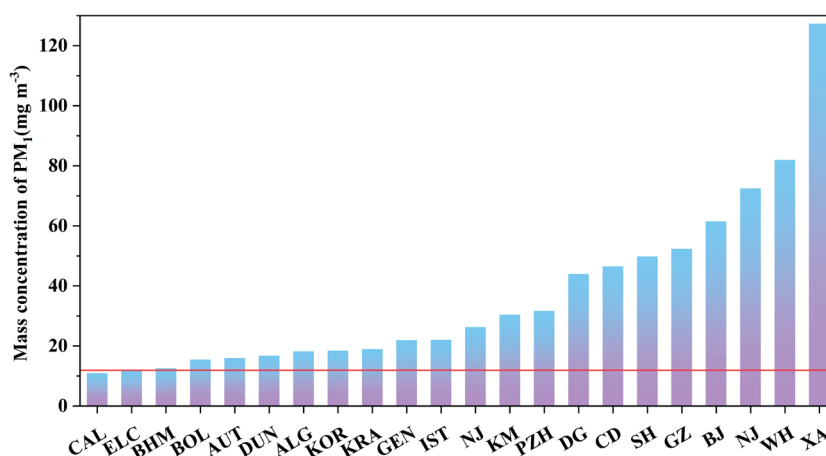


Fig. 4. A statistical comparison chart of PM_{10} mass concentration from Kunming City and other cities. CAL: California, USA [31]; ELC: Elche, Spain [32]; BHM: Birmingham, UK [33]; BOL: Bologna, Italy [34]; AUT: Austria [35]; DUN: Dunkirk, France [36]; ALG: Algiers, Algeria [27]; KOR: Korea [37]; KRA: Krakow, Poland [38]; GEN: Genoa, Italy [39]; IST: Istanbul, Turkey [40]; NJ: Nanjing, China [41]; KM: This study; PZH: Panzhihua, China [42]; DG: Dongguan, China [42]; CD: Chengdu, China [42]; SH: Shanghai, China [43]; GZ: Guangzhou, China [44]; BJ: Beijing, China [42]; WH: Wuhan, China [42]; XA: Xi'an, China [45].

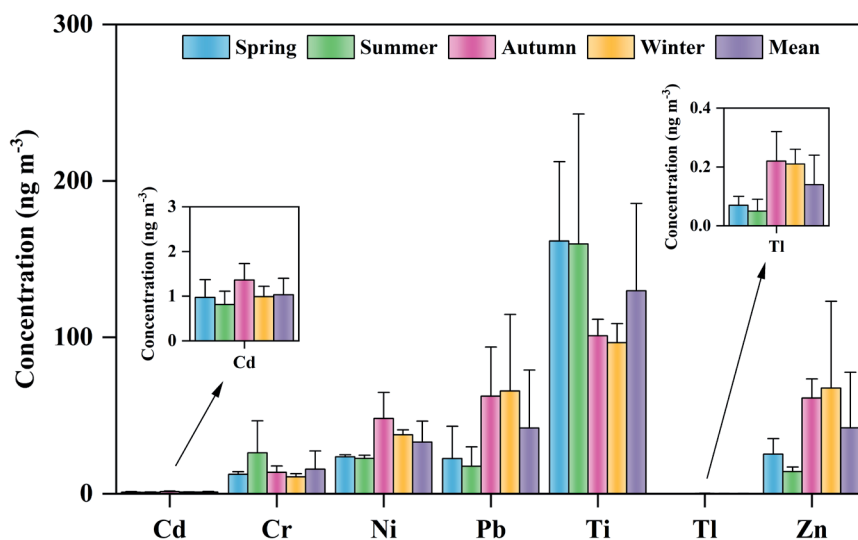


Fig. 5. Seasonal and annual average distribution of HMs in PM_{10} from Kunming City.

(Table S1), Cd, Cr, Ni, Pb, Tl, and Zn were influenced to varying extents by anthropogenic activities. Notably, the EF value of Cd far exceeded 100, indicating an intense anthropogenic pollution characteristic that is likely derived from industrial emissions and vehicle emissions [25]. In contrast, the EF value of Ti was less than 1, which clearly indicates that its primary source is natural processes such as crustal dust [20]. It is also noteworthy that the significantly elevated EF values of Pb and Ni likewise suggest substantial contributions from anthropogenic sources. Fig. S1 shows the seasonal variation trends of different HMs. Overall, Cd, Pb, Ni, Tl, and Zn showed higher enrichment levels during autumn and winter. Among them, Cd was particularly prominent, as its EF values consistently exceeded 100 across all seasons, revealing a persistent and high-intensity anthropogenic emission source largely unaffected by seasonal changes. In contrast, HMs such as Pb, Zn, and Tl demonstrated more pronounced enrichment specifically in winter, all reaching moderate

enrichment levels. This pattern underscores the significant influence of pollution conditions unique to the colder seasons.

Source Apportionment

Correlation analysis of HMs in PM_{10} from Kunming City revealed significant inter-element relationships (Fig. 7). The results indicated a strong correlation among Pb, Zn, and Tl, forming a unique combination of elements, with the Pb-Zn correlation coefficient reaching as high as 0.884. Simultaneously, Ni and Cd also showed significant correlations with elements in this group, particularly with Tl and Pb (0.724). These close associations collectively suggest that they likely share a similar mixture of pollution sources [47, 48]. To identify and analyze the main sources of HMs in PM_{10} in Kunming City, this study employed Principal Component Analysis (PCA). Three principal components were extracted, together accounting for 80.74% of the total variance (Table S3). PC1, attributable to industrial/traffic emissions, explained 48.52% of the variance and exhibited high loadings for Pb (0.904), Zn (0.866), Tl (0.856), Ni (0.734), and Cd (0.609) (Fig. 8; Table S3). These elements collectively indicate a mixed industrial and traffic source. Specifically, Pb, Zn, and Cd are commonly considered tracers of vehicle emissions, whereas Ni and Tl are primarily associated with metallurgical industrial activities [17, 49]. The results of the EF analysis indicate a predominant anthropogenic origin for Cd, Pb, Zn, and Ni. In particular, Zn and Pb are associated with traffic sources (e.g., exhaust emissions, brake wear, and tire wear), whereas Cd is predominantly linked to non-ferrous metal smelting activities [50, 51]. PC2, accounting for 17.55% of the variance and loading strongly on Ti (0.885), was identified as a natural-source factor. This interpretation is supported by the very low EF (<1) of Ti, which indicates a minimal anthropogenic

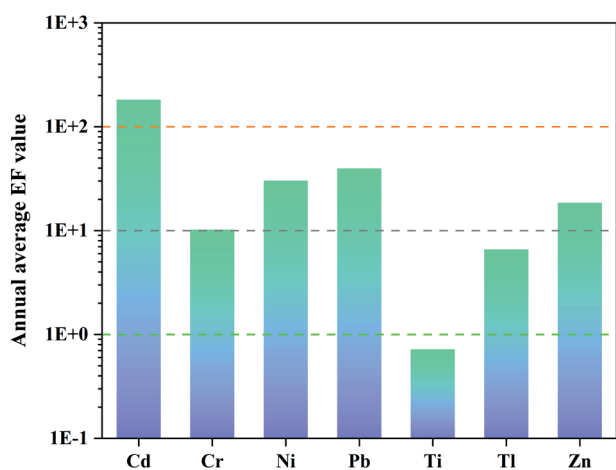


Fig. 6. Enrichment factors (EFs) of HMs in PM_{10} .

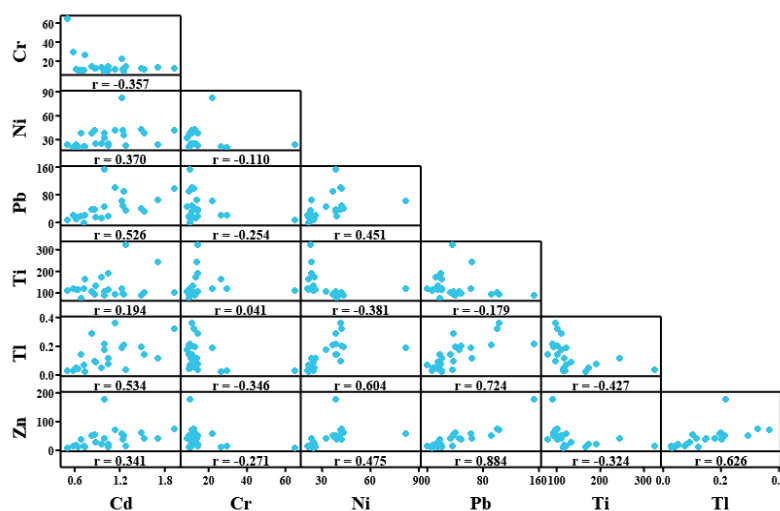


Fig. 7. Correlation matrix of HMs in PM_{10} from Kunming City. Here, r represents the linear correlation coefficient.

influence. PC3 explained 14.67% of the variance, with Cr showing a high loading of 0.956. Given that Cr is a typical tracer for the tannery and dyeing industries, PC3 can be attributed to manufacturing sources [52, 53].

Health Risk Assessment

Fig. 9 shows two types of risks that metals pose to human health: non-carcinogenic risks and carcinogenic risks. The assessment of HMs in PM_{10} in Kunming indicates that the non-carcinogenic risks of Ni, Cd, and Cr(VI) are all within the safe range ($HQ < 1$) [32], with risk values of 0.412, 0.057, and 0.033, respectively (Fig. 9a). The carcinogenic risk assessment results (Fig. 9b) show that the carcinogenic risk level of Cr(VI) has surpassed the acceptable threshold (1×10^{-6}), indicating a potential significant long-term health threat to local residents. Meanwhile, Ni also exhibits certain

carcinogenic risks for adult populations, warranting continuous attention. For typical high-altitude cities like Kunming, HMs are prone to accumulation and transformation due to specific meteorological conditions, such as a lower atmospheric boundary layer and stronger ultraviolet radiation [29], as well as limited diffusion capacity. Therefore, it is necessary to systematically strengthen the control of Cr(VI) and Ni emissions from

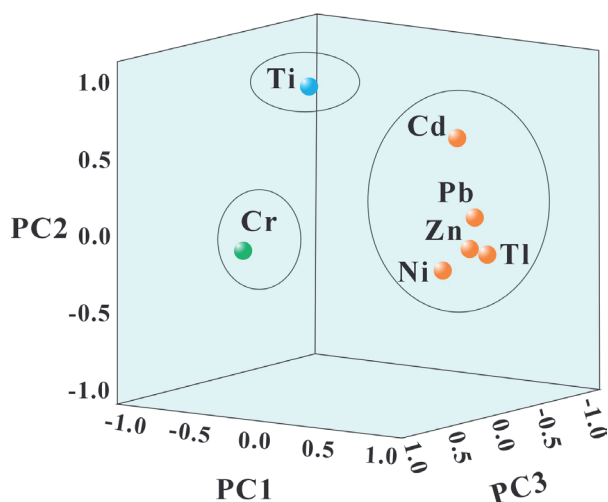


Fig. 8. Source analysis of seven HMs in PM_{10} from Kunming City.

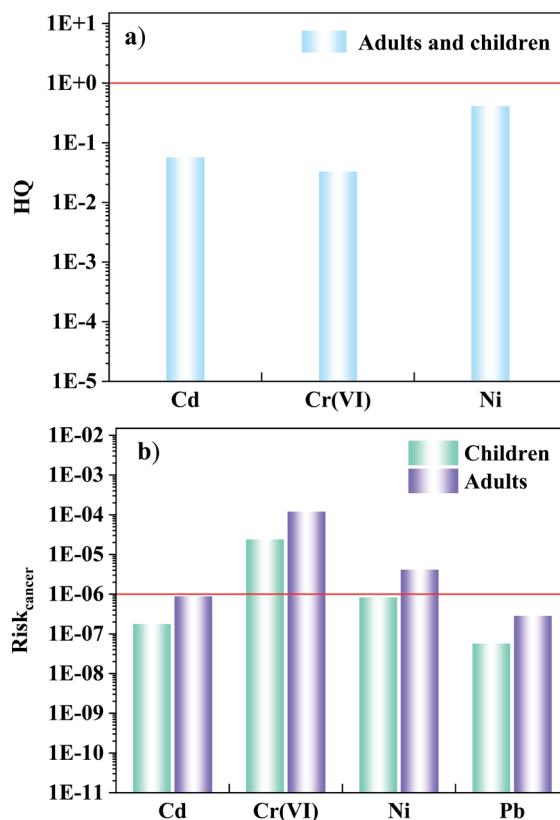


Fig. 9. The non-carcinogenic HQ and $Risk_{cancer}$ of HMs in PM_{10} from Kunming City.

industrial discharges, transportation sources, and energy structures, in order to reduce population exposure risks and safeguard public health.

Conclusions

This study takes Kunming City as an example to systematically explore the mass concentration of atmospheric PM₁, the characteristics of HM pollution, source apportionment, and health risks in low-latitude and high-altitude cities. The results showed that the average mass concentration of PM₁ was 30.44 µg·m⁻³. The assessment of HM pollution shows that the EF of Cd exceeds 100, and the pollution degree is the highest, followed by Pb, Ni, and Zn, reflecting the significant influence of human activities. PCA further confirmed that the mixed source of industry and traffic is the principal source of HMs in PM₁. For all HMs analyzed in PM₁, the calculated HQ values were below the threshold of 1, indicating acceptable non-carcinogenic risks. However, in terms of carcinogenic risk, the authorities should pay attention to Cr(VI) and Ni.

This study provides essential baseline data and a case reference for research on atmospheric ultrafine particulate matter in low-latitude, high-altitude cities. It also establishes an important foundation for a deeper understanding of the pollution characteristics, major sources, and population exposure risks of ultrafine particles under such unique geographical and climatic conditions. The findings can not only support the development of refined air pollution control and public health strategies but also offer a scientific basis and reference framework for environmental management and health risk assessment in cities of a similar type.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

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Supplementary Materials

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