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Characteristics and health risk assessments of heavy metals in $PM_{2.5}$ in Taiyuan and Yuci college town, China

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Abstract

To clarify the pollution sources of heavy metals in $PM_{2.5}$ and the health risks posed by them in heating and non-heating seasons, 42 samples were collected in 2017 and 2018 in Taiyuan and Yuci college town, China. Elemental analysis of the $PM_{2.5}$ samples through acid-dissolved plasma mass spectrometry was performed to determine the concentrations of 10 elements (As, Cd, Co, Cr, Cu, Mn, Ni, Pb, V, and Zn). We determined the types of pollution sources by enrichment factor (EF) and principal component analysis (PCA). We performed a health risk assessment based on the US Environmental Protection Agency (EPA) guidelines and the database of the International Agency for Research on Cancer (IARC) to assess both carcinogenic and non-carcinogenic risks of the heavy metals to adults and children. The results indicate that the EF values of all 10 elements were greater than 1, suggesting anthropogenic sources in both heating and non-heating seasons. PCA revealed that the three main components were soot dust, metal smelting emission, and industrial dust. Regarding the health risks caused by the heavy metals, children were more susceptible to non-carcinogenic risks than adults, and people faced higher non-carcinogenic risks during the heating season. For carcinogenic risk, Cr has the highest risk coefficient (1.68×10^{-4}), higher than the US EPA's threshold (1.00×10^{-6}). People were exposed to carcinogenic risk. The study explored specific pollution sources and explained their effect on health to assist with the development of prevention and control measures.

Keywords Heavy metal · Enrichment factor · Principal component analysis · $PM_{2.5}$ · Risk assessment · Taiyuan

Introduction

Ambient air quality is closely related to public health (Anderson et al. 2012), and groups such as newborns, pregnant women, and other adults are affected differently (Künzli 2000; Brunekreef and Holgate 2002). Air pollution can also increase the risk of disease and increase morbidity and mortality (Stafoggia et al. 2009; Matthew 2010). Atmospheric particulate matter such as PM_{10} (aerodynamic diameter ≤ 10 μm), $PM_{10\text{-}2.5}$ (2.5 μm ≤ aerodynamic diameter ≤ 10 μm), and $PM_{2.5}$ (aerodynamic diameter ≤ 2.5 μm) are key components of primary pollutants that can cause cardiovascular and respiratory diseases (Lu et al. 2015). However, due to the small particle size and mass of $PM_{2.5}$, residence time in the atmosphere is longer, and the surface area of $PM_{2.5}$ is relatively larger, which is more conducive to the adsorption of pollutants, thus causing greater harm to people and the environment (Johansson et al. 2007; Wu et al. 2014; Lu et al. 2015; Croitoru and Sarraf 2017).

The chemical components in $PM_{2.5}$ mainly include water-soluble inorganic ions, element carbon, organic carbon (Liu et al. 2019b), and elements (Nan et al. 2017). Heavy metals endanger human health and can accumulate in the human body through ingestion, environmental exposure, and inhalation (Zhang et al. 2015). Accumulation of a certain concentration can cause heart, lung, and respiratory diseases (Apte et al. 2015; Du et al. 2019).

Trace metals such as chromium (Cr), cadmium (Cd), and nickel (Ni) are associated with the formation of lung cancer (IARC 2019). Therefore, research on the emission characteristics of heavy metal elements in $PM_{2.5}$ from various industries has been widely carried out (Zhao et al. 2019a; Zhao et al. 2019c). Copper (Cu), zinc (Zn), arsenic (As), lead (Pb), and chromium (Cr) are mainly concentrated in inlet fly ash compared with coke during coking processes (Mu et al. 2012). In

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the iron and steel industry, iron (Fe), Zn, Pb, Cr, and manganese (Mn) are regarded as the marker elements of iron and steel production emission (Dai 2015). The metal concentrations in $PM_{2.5}$ in an informal electronic waste recycling site were higher than other Asian cities (V 2016). Most inorganic elements on fly ash in coal-fired power plants are more enriched in $PM_{2.5}$ than in PM_{10} (Li et al. 2017). Furthermore, the pollution level and hazard assessment of heavy metals in $PM_{2.5}$ in various countries and cities around the world have also been studied, such as in India (Satsangi et al. 2014); Wuhan, central China (Zhang et al. 2015); central Taiwan (Hsu et al. 2016); European cities (Chalvatzaki et al. 2019); and Dhaka, Bangladesh (Rahman et al. 2019). Heavy metal pollution can endanger public health. Wang et al. (2005) determined that vegetables and fish rich in heavy metals are the main sources of exposure among the Tianjin population. Yan et al. (2020) analyzed the characteristics of heavy metal pollution in a typical copper mining area, and the results indicated that both the hazard index and risk of carcinogenesis were higher than acceptable.

Taiyuan is the capital of Shanxi Province, China. It is a prominent, coal-heavy industrial city with high levels of particulate matter pollution (Meng et al. 2007). Its air quality reaches the standard 176 days per year, and the average annual concentration of fine particles ($PM_{2.5}$) is 65 $\mu g\ m^{-3}$ (Zhang et al. 2018). Researchers have determined that urban $PM_{2.5}$ concentrations of heavy metal elements are higher than in suburbs (Nan et al. 2017; Zhao et al. 2019b). Currently, research on heavy metal elements in $PM_{2.5}$ is based mainly on source analysis and potential risk assessment of elements in water and soil; source analyses and health risk assessments of heavy metal elements are more limited. Our study addresses this gap by analyzing the source of heavy metals in $PM_{2.5}$ in Taiyuan and conducting a health risk assessment.

In this study, the $PM_{2.5}$ in Taiyuan and Yuci college town during heating and non-heating seasons were the research object. The concentration levels and distribution characteristics of 26 elements—lithium (Li), beryllium (Be), natrium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), potassium (K), calcium (Ca), strontium (Sc), vanadium (V), Cr, manganese (Mn), Fe, cobalt (Co), Ni, Cu, Zn, As, strontium (Sr), Cd, stannum (Sn), antimony (Sb), barium (Ba), thallium (Tl), and Pb—were analyzed by inductively coupled plasma mass spectrometry, with 10 elements (As, Cd, Co, Cr, Cu, Mn, Ni, Pb, V, and Zn) analyzed in detail. Principal component analysis and factor analysis were used to investigate the causes of pollution in the region to trace the pollution source, thereby reducing the potential risk of disease. A health risk assessment was used to determine heavy metal pollution and health risks in the region.

Experiments and methods

Sample collection

The sampling sites were Yingxi Campus and Mingxiang Campus, Taiyuan University of Technology. Yingxi Campus is located in Taiyuan and Mingxiang Campus is located in Yuci, Shanxi Province. Yuci is in Jinzhong, near Taiyuan. The study was conducted in November 2017 (heating season), December 2017 (heating season), and September 2018 (non-heating season). Taiyuan is located in central Shanxi Province, at the northern end of the Taiyuan Basin and in the middle of the Yellow River in North China. The outline of the area is bat-shaped, with an east–west distance of approximately 144 km and a north–south distance of approximately 107 km. The west, north, and east of Taiyuan are mountainous, and the center and south are river valley plains. The terrain is high in the north and low in the south. The highest point is 2670 m, the lowest point is 760 m, and the average elevation is approximately 800 m. Taiyuan has a northern temperate continental climate, with an average annual temperature of 9.5 °C and an average annual precipitation of 456 mm. Taiyuan University of Technology Yingxi Campus is located on the west bank of the Weihe River. The geographical coordinates are 112°31', 37°52' (Fig. 1). The geographical coordinates of Mingxiang Campus in Yuci are 112°43', 37°45' (Fig. 1), approximately 25 km from the center of Taiyuan and 35 km from Yingxi Campus. The Yingxi and Mingxiang sampling points were 15 m and 10 m above ground, respectively. The locations of the sampling sites are presented in Fig. 1.

Chemical analysis

After the sample was digested, an analysis was mainly carried out through acid-dissolved plasma mass spectrometry (ICP-MS).

Instructions for experiment are as follows: Cut the filter sample into small pieces in Teflon with ceramic scissors; add 5 mL of rare water and 1 drop of HF; cover the lid; heat on a constant temperature electric plate at 120 °C for 2 h, and then raise the temperature to 130 °C. Open the lid and steam until no solution remains. Accurately add 10 mL of 2% hydrochloric acid; cover the lid; reflux on the hot plate for 20 min; remove; and pour directly into a plastic colorimetric tube, without constant volume, together with the standard solution.

The selected instrument was tested for optimal working conditions. A double blank test was conducted during the entire sample analysis process. Two to four samples of fly ash or the primary standard soil material were selected, and the quality control samples were weighed to 0.01 g and analyzed simultaneously with the sample.

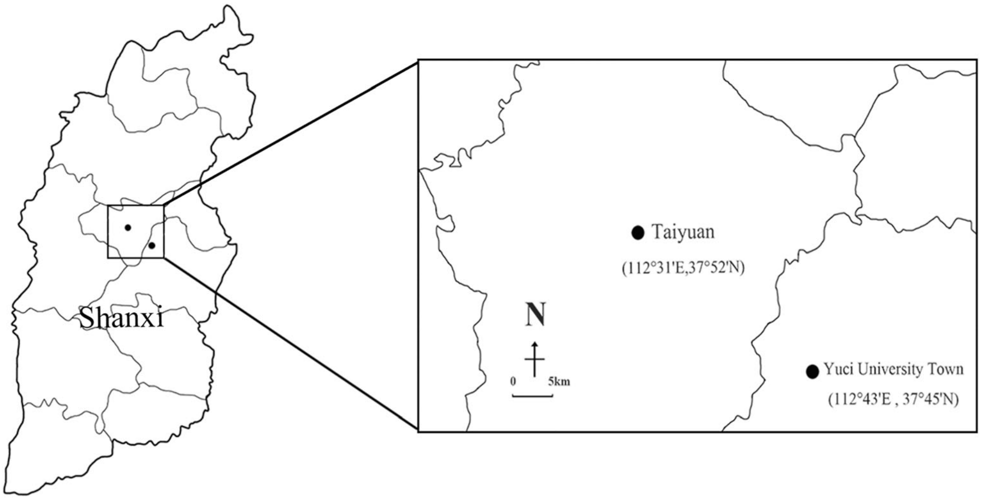


Fig. 1 The location of sampling sites in Taiyuan and Yuci

On-site sampling withdrew 10% of the sample for parallel sampling with 15% repeated determination during sample determination. The quantitative calibration method adopted was an internal standard calibration method. [ρ(103Rh) = 25 ng mL^{-1}] was selected as the internal standard element for the measurement.

The internal standard element solution was pumped into a three-way pipe valve by a peristaltic pump tube dedicated to the internal standard solution, and the internal standard element and the sample solution were combined and mixed and then pumped into the atomization system to enter the plasma flame.

Source identification methods

Enrichment factor

The enrichment factor (EF) is an indicator for evaluating the degree of enrichment of elements in ambient air, from which it can be ascertained whether the element is derived from an anthropogenic source or a natural source (Chen et al. 2008). The EF calculation is expressed as Formula (1):

$$EF = \frac{\left(C_i/C_{ref}\right)_{sample}}{\left(C'_i/C'_{ref}\right)_{background}} \tag{1}$$

where $(C_i/C_{\mathrm{ref}})_{\mathrm{sample}}$ is the concentration ratio of the $\mathrm{i_{th}}$ metal and the reference metal in the sample and $(C'_i/C'_{\mathrm{ref}})_{\mathrm{background}}$ is the concentration ratio of the $\mathrm{i_{th}}$ metal and the reference metal in the background.

In this paper, Al is used as the reference element, and we selected the values from the published Chinese values of background soil elements (CNEMC 1990). If the EF value is less than 1, the element is considered to have a natural source, mainly derived from soil particles. If the EF value is greater than 10, the element is considered to have an anthropogenic source, mainly derived from human activities (Khodeir et al. 2012).

Principal component analysis

Element concentration data were analyzed by principal component analysis (PCA) using SPSS version 13 for Windows (SPSS Inc., Chicago, IL, USA). PCA can achieve better dimensionality by linearly transforming and discarding some information to achieve better dimensionality and objectively determine the weight of each indicator (Feng 2003). PCA is now widely used for environmental air source analysis (Hu et al. 2012; Chen et al. 2015).

In this study, the data of the elements in the $\mathrm{PM}_{2.5}$ samples from November and December 2017 and September 2018 were used to represent the data of heating and non-heating seasons. The source analysis of the elemental components in the $\mathrm{PM}_{2.5}$ was performed by PCA. The maximum variance rotation factor analysis of each heavy metal element signifies that the larger the value of the interpretation variance, the stronger the ability to interpret the variables. The larger the value of the cumulative variance, the more representative the extracted factors were for the original variable.

Health risk assessment

A health risk assessment includes non-carcinogenic and carcinogenic risk assessments. Non-carcinogenic risk is evaluated by the exposure risk value, and carcinogenic risk is evaluated by the lifetime carcinogenic risk caused by human exposure to carcinogenic risk substances. We combined the health risk assessment model published by the US Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC) data reference values to investigate the risks to human health caused by elements carried in $\mathrm{PM}_{2.5}$ in ambient air for Taiyuan residents. Respiration, food intake, and skin contact are the main means by which people are exposed to the environment. However, because breathing is the main source of exposure risk, this study is mainly devoted to the elemental components carried by $PM_{2.5}$ in the atmospheric environment risk assessment. Because only the carcinogenic slope factor value from respiratory inhalation is now available, only the carcinogenic risk caused by respiratory inhalation was considered. The formulas for calculating non-carcinogenic risk—hazard index (HI), hazard quotient, and carcinogenic risk (R)—caused by the respiratory pathway are as in Formulas (2), (3), (4), and (5). The parameters for the formulas are provided in Table 1.

$$ADD = \frac{C \times lnhR \times EF \times ED}{BW \times AT} \tag{2}$$

$$LADD = \frac{C \times EF}{AT} \times \left[\frac{lnhR_c \times ED_c}{BW_c} + \frac{lnhR_a \times ED_a}{BW_a}\right] \tag{3}$$

$$Risk = LADD \times SF \tag{4}$$

$$HI = \sum HQ = \sum ADD/RfD \tag{5}$$

In our study, the data obtained from the test was processed in mathematical statistics. The EF method was used to determine whether the heavy metals in $PM_{2.5}$ came from anthropogenic or natural sources. Second, the main component analysis method was used to analyze the source, and the two were combined to obtain the specific source of pollution. Finally, a health risk assessment model was used to assess the risk to residents caused by heavy metals in $PM_{2.5}$.

Results and discussion

Element concentration levels during heating and non-heating seasons

In this study, a total of 26 elements (Li, Be, Na, Mg, Al, Si, P, K, Ca, Sc, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Sr, Cd, Sn, Sb, Ba, Tl, and Pb) were collected on filter membranes by inductively coupled plasma mass spectrometry. Ten elements (As, Cd, Co, Cr, Cu, Mn, Ni, Pb, V, and Zn) were investigated. The quantities of the other elements were either too low in ambient air (Li, Be, Sc, Sr, Sn, Sb, Ba, and Tl) or were not harmful to the human body (Na, Mg, Al, Si, P, K, Ca, and Fe), so they were not within the scope of the study.

Table 2 presents the element concentration levels in Taiyuan in $PM_{2.5}$. In heating and non-heating seasons, the levels of Mn, Pb, and Zn were 114.27 ± 78.36 ng m^{-3}, 73.41 ± 57.58 ng m^{-3}, and 195.54 ± 128.98 ng m^{-3}, respectively. These were the elements with the highest concentration in Taiyuan. Liu and Ren (2019) also studied heavy metal elements in $PM_{2.5}$ in the suburbs of Taiyuan in 2016. According to their findings, Zn (406.85 ng m^{-3}), Mn (360.54 ng m^{-3}), and Pb (164.32 ng m^{-3}) were also the three most highly concentrated elements, with respective concentrations 2.08, 3.16, and 2.24 times those of our study. In the present study, these three elements accounted for 79.90% in the heating season and 85.45% in the non-heating season of the total concentration of the ten elements, respectively. The concentrations of Cr, Cu, and V were similar and were lower than that of Pb. As, Cd, and Co exhibited the lowest concentration, together accounting for less than 5% of the total

Table 1 Health risk assessment indicators meaning and values

Parameters	Meaning	Values and references	
		Children	Adults
ADD [mg (kg d)$^{-1}$]	Average daily dose	-	-
C (mg m^{-3})	Metal concentration	-	-
lnhR (m^3 d^{-1})	Inhalation value	7.5 (Hu et al. 2012)	16 (Hu et al. 2012)
EF (d a^{-1})	Exposure frequency	365 (Hu et al. 2012)	365 (Hu et al. 2012)
ED (a)	Exposure duration	6 (Hu et al. 2012)	24 (Hu et al. 2012)
BW (kg)	Body weight	15 (Hu et al. 2012)	60 (Hu et al. 2012)
AT (d)	Average exposure time	365 × ED (non-carcinogenic) (Hu et al. 2012) 365 × 70 (carcinogenic) (Hu et al. 2012)	365 × ED (non-carcinogenic) (Hu et al. 2012) 365 × 70 (carcinogenic) (Hu et al. 2012)
LADD [mg (kg d)$^{-1}$]	Lifetime average daily dose	-	-
SF [mg (kg d)$^{-1}$]$^{-1}$	Carcinogenic slope factor	IARC (2019)	IARC (2019)
RfD (kg d)	Reference dose	IARC (2019)	IARC (2019)

Dash represents the results calculated using the parameters in the table and the formula in Section 2 (Experiments and methods)

Table 2 Element concentration levels in $PM_{2.5}$ during sampling in Taiyuan and Yuci

Elements	Mean ± SD (ng m^{-3})		Heating season		Non-heating season	
	TY	YC	TY	YC	TY	YC
As	6.84 ± 2.74	7.63 ± 4.89	8.15	9.45	3.57	3.06
Cd	0.87 ± 0.63	0.90 ± 0.67	1.07	1.12	0.37	0.35
Co	1.44 ± 1.97	0.73 ± 0.20	1.20	0.70	2.04	0.81
Cr	24.31 ± 15.61	10.07 ± 4.86	29.89	11.74	10.35	5.90
Cu	24.07 ± 16.18	12.07 ± 6.48	29.56	14.66	10.35	5.61
Mn	114.27 ± 78.36	56.57 ± 32.95	145.07	70.57	37.27	21.57
Ni	14.17 ± 11.39	6.21 ± 6.60	12.69	3.56	17.87	12.85
Pb	73.41 ± 57.58	70.02 ± 56.66	94.36	91.29	21.06	16.83
V	26.10 ± 18.20	22.73 ± 18.02	35.75	31.19	1.98	1.60
Zn	195.54 ± 128.98	201.23 ± 164.71	230.57	263.26	107.95	46.15

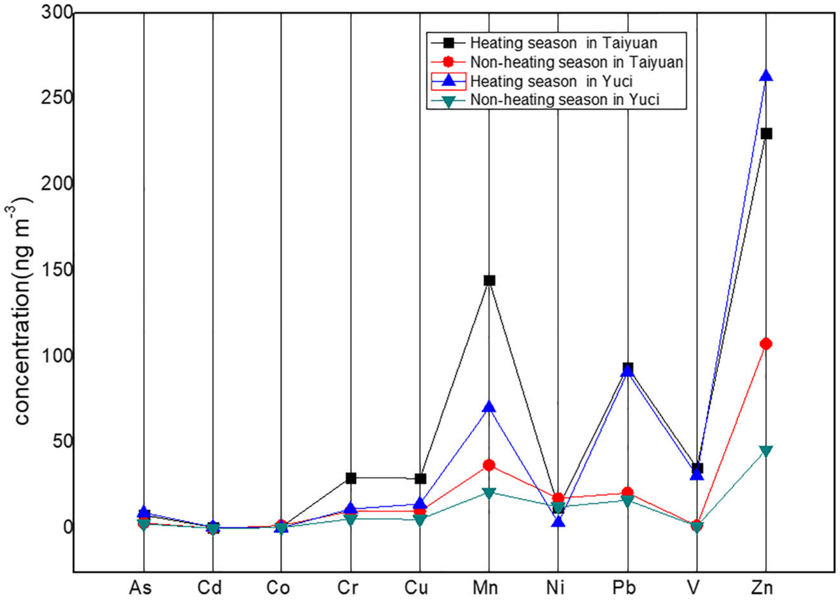
Values represent average ± standard deviation

concentration. Notably, the concentration of Ni in the non-heating season was relatively high—lower than only Mn, Pb, and Zn—which may be related to metal smelting and electroplating in the region.

Figure 2 presents the element concentration levels in $PM_{2.5}$ during sampling in Yuci college town. In heating and non-heating seasons, Mn, Pb, and Zn had the highest concentrations, together accounting for 78.14% and 73.70% of the total concentration of the 10 elements, respectively. The concentrations of Cr, Cu, and V were similar and lower than that of Pb. As, Cd, and Co had the lowest concentrations; in combination, they represented less than 4% of the total element concentration. Correspondingly, Ni also exhibited a relatively high concentration (only Zn and Mn levels were higher) in the non-heating season in Yuci college town. In the non-heating season, the concentration of these 10 elements in Taiyuan was higher than that in Yuci college town, which may be due to differing levels of economic development. In the heating season, the pollution levels of Taiyuan and Yuci were similar, and concentrations of As, Cd, V, and Zn were lower in Yuci.

The concentrations of elements in the non-heating season were significantly lower than those in the heating season, and as the heating continued, the concentrations of each element rose. In December, the concentration of each element was significantly higher than in November. Because Yuci is in Jinzhong, a suburb of Taiyuan, concentrations of all elements in both seasons were lower than in Taiyuan. Taiyuan is densely populated and has many types of pollution sources. Furthermore, air diffusion conditions are poor and not conducive to the migration of pollutants. This leads to higher concentrations of elements in Taiyuan. The research of Liu et al. (2019a) on $PM_{2.5}$ in ambient air in

Fig. 2 The concentration levels of heavy metals in heating and non-heating seasons in Taiyuan and Yuci



Xi'an determined that Zn, Ti, and As were the most abundant heavy metals, accounting for 72.1% of the total concentration. The average concentration of Zn from December 2015 through November 2016 in Xi'an was 200 ± 61.2 ng m^{-3}, comparable with that in our study (195.54 ± 128.98 ng m^{-3}). The three most abundant metals in Taiyuan were Zn, Pb, and Mn. In the winter, the concentrations of heavy metals such as Pb, Co, Cu, and Zn increase due to coal combustion. Wu et al. (2019b) conducted research on nine heavy metals—As, Cd, Cr, Mn, Ni, Pb, Sb, Se, and Tl—in the $PM_{2.5}$ of ambient air in Ningbo. The elements common to this study were As, Cr, Cd, Mn, Pb, and Ni. The concentration of Cd in Ningbo was higher than that in Taiyuan, and the concentrations of the other five metals were lower than those in Taiyuan. Therefore, regarding heavy metal pollution in ambient air $PM_{2.5}$, Taiyuan's ambient air quality was worse than Ningbo's.

We compared the heavy metal components in the dust of China and other countries in Table 3 and understand the approximate distribution of heavy metal in dust. At the same time, we also compared the concentration of heavy metals in $PM_{2.5}$ between our study and other countries. It can be seen from Table 3 that the level of heavy metals in $PM_{2.5}$ in Taiyuan had a greater increase than those in 2013. Except for Zn, all other elements were lower than the results of our study. Compared with other regions, the concentrations of Zn and Pb in $PM_{2.5}$ in Taiyuan were lower than those in Shanghai, Nanjing, and Agra. The heavy metal elements in $PM_{2.5}$ in Taiyuan are still at a relatively high level in the world and are worthy of further research.

Source and correlation analysis

EF analysis

EF analysis was used to ascertain whether the source of the ambient air emissions was anthropogenic or crust. Table 4 presents the element EFs in heating and non-heating seasons in Taiyuan and Yuci.

Table 4 showed the enrichment factor in heating season (only December) and non-heating season in Taiyuan and Yuci. In the heating season (Taiyuan and Yuci), the EF of Fe was less than 1, indicating that Fe was mainly derived from crust source interfered less by anthropogenic sources. In the non-heating season, the EFs of Ba and Fe were lower than 1, representing that they were mainly derived from crust sources. The EF values of other metals were greater than 1. The EFs of Ba, Be, Co, K, Li, Mg, Mn, Na, Sc, and Sr were between 10 and 100 (closer to 10), signifying that these elements were influenced by both anthropogenic and crust sources but the main factor was crust. The EFs of As, Ca, Cr, Cu, Ni, Sn, Tl, V, and Zn were between 10 and 100 (closer to 100), representing that these elements were influenced by both anthropogenic and crust sources but the main influencing factor was anthropogenic sources. The EFs of Cd, Pb, and Sb were higher than 100, representing that these elements mainly were anthropogenic sources. The EF values of Ba were greater than 1 during the heating season and lower than 1 during the non-heating season, suggesting the anthropogenic activity that enriches Ba may be heating.

Table 3 Comparison results with other studies

Location	Country	Methodology	Fraction (μm)	As	Mn	Zn	Pb	Cu	Cd	References
Taiyuan	China	ICP-MS	≤ 2.5	8.15	145.07	230.57	94.36	29.56	1.07	Current study
Yuci	China	ICP-MS	≤ 2.5	9.45	70.57	263.26	91.29	14.66	1.12	Current study
Taiyuan	China	ICP-9000 (N + M)	≤ 2.5	1.90	62.20	335.79	27.15	53.30	0.49	Li et al. (2014)
Beijing	China	ICP-MS	≤ 150	-	-	703.3	143.6	242.7	2.8	Xiong et al. (2018)
Shanghai	China	ICP-OES	≤ 2.5	-	-	359	137	45.7	-	Li et al. (2017)
Nanjing	China	ICP-OES	≤ 2.5	-	-	349	149	36.8	-	Li et al. (2017)
Xi'an	China	WDXRF	≤ 75	-	510.5	268.6	124.5	54.7	-	Pan et al. (2017)
Jeddah	KSA	AAS	≤ 50		267.9	291.2	45.2	51.3	0.5	Kadi (2009)
Al-Qunfudah	KSA	AAS	≤ 450	-	175	47	26	40	-	Harb et al. (2015)
Isfahan	Iran	ICP-MS	≤ 2.5	38.54	43.72	-	62.36	166.82	11.55	Soleimani et al. (2018)
Karachi	Pakistan	AAS	≤ 1.6	-	-	-	187.9	-	-	Ali et al. (2020)
Agra	India	ICP-AES	≤ 2.5	-	146.7	646.3	139.5	215.3	54.4	Sah et al. (2019)
Ottawa	Canada	ICP-MS	100 ≤ F ≤ 250	-	431.5	112.5	39.05	65.84	-	Rasmussen et al. (2001)
Massachusetts	American	EDXRF	≤ 2000	-	456	240	73	105	-	Apeagyei et al. (2011)

In the table, the Beijing, Ottawa, Massachusetts, and Saudi studies collected dust fall samples, while research on Iran, Pakistan, India, etc. studies collected particulate samples. All dustfall samples in ppm unit and all particulate samples in ng·m^{-3} unit

Table 4 Element enrichment factors in heating season (only December) and non-heating seasons in Taiyuan and Yuci

Elements	Heating season in Taiyuan		Non-heating season in Taiyuan		Heating season in Yuci		Non-heating season in Yuci	
	Mean ± SD (ng m^{-3})	EF	Mean ± SD (ng m^{-3})	EF	Mean ± SD (ng m^{-3})	EF	Mean ± SD (ng m^{-3})	EF
As	8.88 ± 1.61	20.97	3.57 ± 2.02	16.78	12.03 ± 5.05	31.54	3.06 ± 1.19	14.95
Cd	1.37 ± 0.60	394.70	0.37 ± 0.33	213.33	1.50 ± 0.61	476.71	0.35 ± 0.19	205.45
Co	1.22 ± 0.41	2.39	2.03 ± 3.78	7.93	0.75 ± 0.15	1.63	0.81 ± 0.30	3.27
Cr	35.92 ± 14.82	14.22	10.35 ± 5.27	8.15	14.40 ± 4.68	6.32	5.90 ± 2.69	4.83
Cu	37.35 ± 15.43	40.93	10.35 ± 6.60	22.58	17.09 ± 6.55	20.78	5.61 ± 1.35	12.72
Mn	164.50 ± 73.62	6.91	37.27 ± 19.16	3.12	84.46 ± 26.17	3.94	21.57 ± 10.82	1.88
Ni	14.97 ± 6.93	11.10	17.88 ± 18.92	26.39	4.05 ± 0.87	3.33	12.85 ± 9.88	19.72
Pb	121.30 ± 56.08	117.07	21.06 ± 12.10	40.49	116.29 ± 45.61	124.52	16.83 ± 10.92	33.63
V	36.37 ± 10.63	10.74	1.98 ± 0.46	1.17	38.35 ± 15.23	12.56	1.60 ± 0.57	0.98
Zn	276.58 ± 124.20	92.25	107.95 ± 108.78	71.73	349.13 ± 147.33	129.19	46.15 ± 21.29	31.86

PCA analysis

SPSS was used to analyze the maximum variance rotation factor of the 10 elements in the heating and non-heating seasons in Taiyuan. Figure 3 displays the factor load matrix after orthogonal rotation.

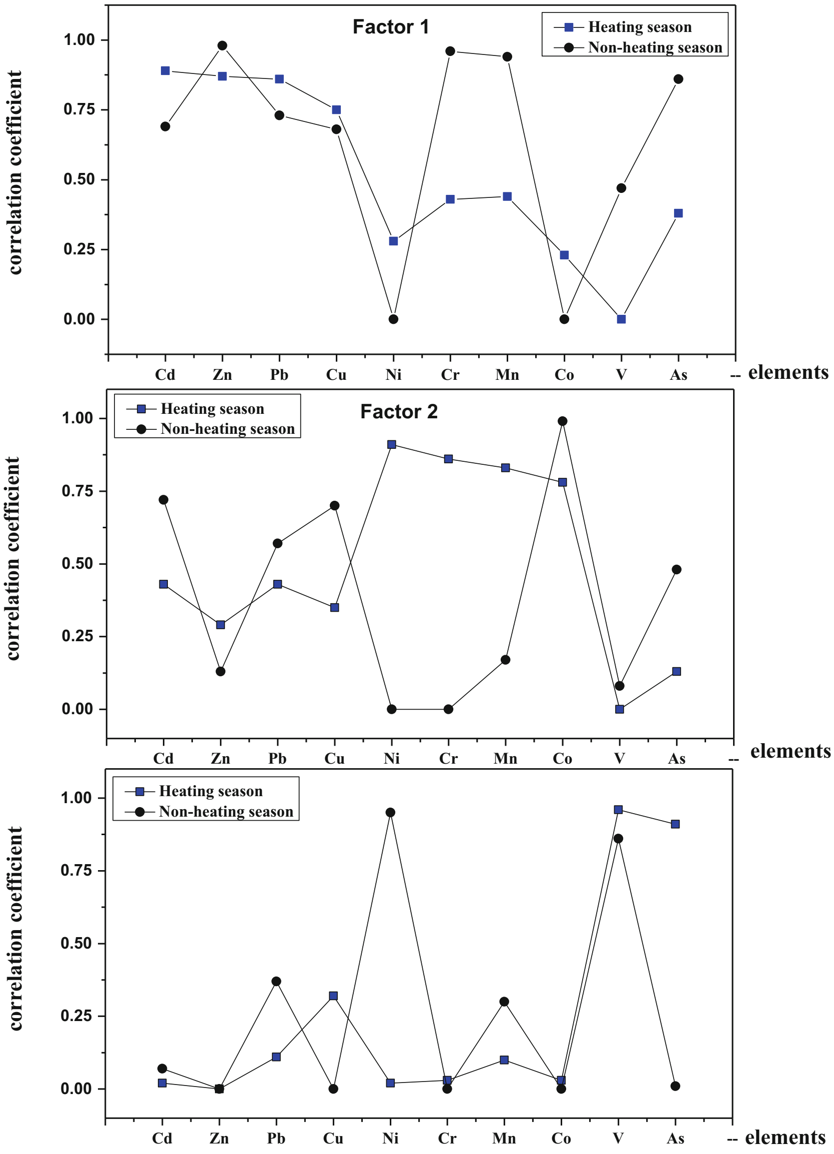
Taiyuan is a base for stainless steel production, new equipment manufacture, and magnesium–aluminum alloy processing and manufacture. Winter heating is mainly solved by burning coal. The Taiyuan sampling point was located in the urban area. Through analysis of the element data of the Taiyuan heating season, three main components were obtained, and the cumulative variance contribution rate reached 89.14%. The interpretation variance of Factor 1 was 35.41%. The elements with a higher Factor 1 load value were Cd, Zn, and Pb. The Cu, Zn, and Pb in ambient air mainly came from coal burning, which is consistent with the results of Duan and Tan (2013). Factor 1 can therefore be considered soot dust. The interpretation variance of Factor 2 was 34.77%. The elements with a higher Factor 2 load value were Ni, Cr, Mn, and Co. These four elements are easily concentrated on particles during the smelting process of steel and alloy. Therefore, Factor 2 can be considered metal smelting emissions. The interpretation variance of Factor 3 was 18.97%, and the elements with a higher Factor 3 load value were V and As. As is mainly derived from the smelting of non-ferrous metals and belongs to industrial emissions. Therefore, Factor 3 can be considered industrial dust.

Through analysis of the element data of the Taiyuan the non-heating season in Taiyuan, three main components were obtained, and the cumulative variance contribution rate reached 97.20%. The interpretation variance of Factor 1 was 52.24%, and the elements with a higher Factor 1 load value were As, Cr, and Zn. Iron and steel smelting processes are known to produce elements such as Fe, Mn, Cr, Zn, and As. Thus, Factor 1 can be considered metal smelting emissions. The interpretation variance of Factor 2 was 26.18%. The element with a higher Factor 2 load value was Co. Coal burning can produce smoke containing Co; therefore, Factor 2 can be considered soot dust. The interpretation variance of Factor 3 was 18.79%, and the elements with a higher Factor 3 load value were Ni and V. Because Ni and V are usually derived from power plant fuel and industrial fuel burning, Factor 3 can be considered industrial dust.

Figure 4 displays the results of the maximum rotational variance factor analysis of elements in Yuci $PM_{2.5}$. For the non-heating season data of Yuci university town, three main components were obtained, with a cumulative variance of up to 93.35%. The explanatory variance of Factor 1 was 52.26%, and the elements of its load value were As, Cr, Cu, Mn, Pb, V, and Zn. Iron and steel smelting produce elements such as Fe, Mn, Cr, Zn, and As, so Factor 1 can be regarded as smelting emissions of non-ferrous metals. The explanatory variance of Factor 2 was 21.22%, and the element with a higher load value was As, which is usually from the combustion of power plant fuel and industrial fuel. Therefore, Factor 2 can be regarded as soot. The explanatory variance of Factor 3 was 19.87%, and the elements with higher load values were Co and Ni. Coal burning produces fumes containing Co, so Factor 3 can be considered industrial dust.

In this study, the three factors extracted from the Taiyuan and Yuci in heating season and the non-heating season through PCA represent soot dust, industrial dust, and steel smelting emission. Li et al. (2014) also extracted three factors using PCA in Taiyuan—soot dust, industrial dust, and steel smelting emissions. This may be related to Taiyuan being one of China's energy and heavy industry bases, with the world's largest production capacity of stainless steel.

Fig. 3 Maximum rotational variance factor analysis of elements in $PM_{2.5}$ of Taiyuan



Health risk of heavy metals

The As, Cd, Co, Cr, Cu, Mn, Ni, Pb, V, and Zn identified in this study have chronic non-carcinogenic risks. Using Formulas (2) and (5) and Table 1, the non-carcinogenic risk values of heavy metal elements in heating and non-heating seasons in Taiyuan were calculated and are provided in Table 5. In the heating season, child and adult HI values were 5.84 and 3.11, which were significantly higher than the non-heating season HI values of 1.70 and 0.91. An HI value greater than 1 for non-carcinogenic risk merits attention. Both children and adults had non-carcinogenic risk during the heating season, and children also had non-carcinogenic risk during the non-heating season. Among the 10 elements, Mn was the largest contributor to non-carcinogenic risk in the heating and non-heating. The non-carcinogenic strength order of heavy metals in the heating season was Mn > Cr > Co > Pb > As > V > Cd > Zn > Cu > Ni. The non-carcinogenic strength order in the non-heating season was Mn > Cr > Co > As > Pb > Ni > Cd > Zn > Cu > V. People were more likely to have non-carcinogenic risks in the heating season than in the non-heating season, and children were at higher non-carcinogenic risk than adults, which is consistent with previous studies (Chen et al. 2019; Wu et al. 2019a; Zhang et al. 2019). For non-carcinogenic risks in this study ([non-heating] adults 0.91, children 1.70), both were lower than in 2012 (adults 2.11, children 2.94) and 2016 (adults 4.00, children 10.00) in Taiyuan (Li et al. 2014; Liu and Ren 2019). This suggests that air quality in Taiyuan has markedly improved in recent years.

As, Cd, Co, Cr, and Ni increase cancer risk. According to Formulas (3) and (4), the cancer risk of heavy metal elements in heating and non-heating seasons in Taiyuan is calculated (Table 6). Cr represented the largest carcinogenic risk factor in

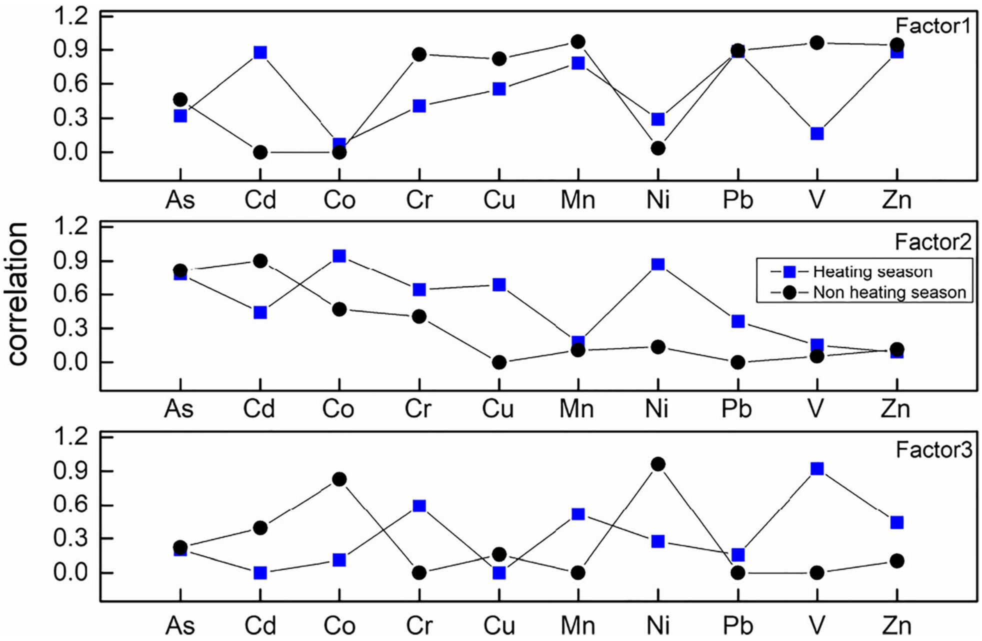


Fig. 4 Maximum rotational variance factor analysis of elements in $PM_{2.5}$ of Yuci

the heating season and non-heating season. The carcinogenic risk was as high as 1.68×10^{-4} and 5.82×10^{-5}, respectively, considerably exceeding the acceptable threshold identified by the EPA (10^{-6}). It therefore had an obvious carcinogenic effect. In the heating season, the risk of carcinogenicity of the five elements was higher than 1×10^{-6}, and the carcinogenic risks of the elements in the non-heating season, except Ni, were all lower than in the heating season. In the non-heating season, the cancer risk of Cd and Co was lower than 1×10^{-6}, meaning that Cd and Co did not confer a carcinogenic risk. As, Cr, and Ni were at an acceptable level (1×10^{-4}). The carcinogenic risk levels of the five elements in the heating and non-heating season were Cr > As > Cd > Co > Ni and Cr > As > Ni > Cd > Co, respectively. Therefore, the beginning of the heating season significantly increases both cancer and non-carcinogenic risk. During the heating season, controlling Mn can reduce non-carcinogenic risk, and controlling Cr can effectively reduce cancer risk.

Table 5 Non-carcinogenic risk of heavy metals in heating and non-heating seasons in Taiyuan

Elements	HQ (heating season)		HQ (non-heating season)	
	Children	Adults	Children	Adults
As	1.02×10^{-2}	5.43×10^{-3}	4.46×10^{-3}	2.38×10^{-3}
Cd	5.37×10^{-4}	2.87×10^{-4}	1.87×10^{-4}	9.95×10^{-5}
Co	1.05×10^{-1}	5.60×10^{-2}	1.78×10^{-1}	9.50×10^{-2}
Cr	5.23×10^{-1}	2.79×10^{-1}	1.81×10^{-1}	9.65×10^{-2}
Cu	3.68×10^{-4}	1.96×10^{-4}	1.29×10^{-4}	6.86×10^{-5}
Mn	5.18	2.76	1.33	7.10×10^{-1}
Ni	3.08×10^{-4}	1.64×10^{-4}	4.34×10^{-4}	2.31×10^{-4}
Pb	1.34×10^{-2}	7.32×10^{-3}	2.99×10^{-3}	1.60×10^{-3}
V	1.99×10^{-3}	1.06×10^{-3}	1.10×10^{-4}	5.87×10^{-5}
Zn	3.83×10^{-4}	2.04×10^{-4}	1.79×10^{-4}	9.56×10^{-5}
HI	5.84	3.11	1.70	0.91

Conclusion

In this study, the $PM_{2.5}$ of Taiyuan and Yuci during heating and non-heating seasons were investigated. The heavy metal element with the highest concentration in the heating and non-heating seasons in Taiyuan and Yuci was Zn, with concentration levels of 230.57 ng m^{-3} and 263.26 ng m^{-3} (heating season) and 107.95 ng m^{-3} and 46.15 ng m^{-3} (non-heating season), respectively. In the non-heating season, the concentrations of 10 elements (As, Cd, Co, Cr, Cu, Mn, Ni, Pb, V, and Zn) were higher in the Taiyuan area than in Yuci. However, the concentrations of five elements (As, Cd, Pb,

Table 6 Carcinogenic risk of heavy metals in heating and non-heating seasons in Taiyuan

Elements	SF (mg (kg d)$^{-1}$)	*R* (carcinogenic risk)	
		Heating season	Non-heating season
As	15.1	1.65×10^{-5}	7.22×10^{-6}
Cd	14.7	2.12×10^{-6}	7.35×10^{-7}
Co	9.8	1.58×10^{-6}	6.53×10^{-7}
Cr	42	1.68×10^{-4}	5.82×10^{-5}
Ni	0.91	1.55×10^{-6}	2.18×10^{-6}

V, and Zn) in the Taiyuan during the heating season were lower than in Yuci. According to EF analysis, Cd, Pb, and Sb were emitted by anthropogenic sources. As, Ca, Cr, Cu, Ni, Sn, Tl, V, and Zn EFs were between 10 and 100, indicating that anthropogenic and crust sources were combined, whereas Fe was obviously emitted from crust. In the factor analysis of the heating season in Taiyuan, three principal components were extracted, the contributions of which were 35.41%, 34.77%, and 18.97%. Factor 1 can be regarded as soot dust; Factor 2 is metal smelting emissions; and Factor 3 is industrial dust. For the non-heating season in Taiyuan, three principal components were also extracted. The interpretation variances for Factors 1, 2, and 3 were 52.24%, 26.18%, and 18.79%, respectively. Factor 1 represents metal smelting emissions, Factor 2 represents soot dust, and Factor 3 represents industrial dust. This study also investigated carcinogenic and non-carcinogenic risks in heating and non-heating seasons in Taiyuan. The HI values for children and adults in the heating season were 5.84 and 3.11, respectively, significantly higher than in the non-heating season (1.70 and 0.91). Regarding carcinogenic risk, the degree of exposure to Cr was worthy of attention. The results indicate that Cr had the highest contribution factor for carcinogenic risk in both heating and non-heating seasons in Taiyuan and Yuci. The risk coefficients of Cr were 1.68×10^{-4} (heating) and 5.82×10^{-5} (non-heating). The risk factors in the heating season of the other four elements were higher than 1×10^{-6} but were at an acceptable level. In the non-heating season, the risk factors for carcinogenicity of the elements (except Ni) were significantly reduced, with levels approximate to the EPA's threshold (1×10^{-6}). Sufficient attention must be paid to heavy metals in $PM_{2.5}$. However, China does not have a sound evaluation system for health risk assessment, and additional research is required to provide valuable references.

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