



# Source profile and health risk assessment of PM<sub>2.5</sub> from coal-fired power plants in Fuxin, China

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## Abstract

In order to improve and establish the localized source profile of PM<sub>2.5</sub> in Fuxin, the ashes under dust catcher were collected from four typical coal-fired power plants in Fuxin and twenty-eight components were measured. The source profile of PM<sub>2.5</sub> in the soot of the four coal-fired power plants was established. SO<sub>4</sub><sup>2-</sup> was the most abundant component in the PM<sub>2.5</sub> of the soot of the four coal-fired power plants, followed by Ca<sup>2+</sup> and organic carbon (OC). The content of element components in PM<sub>2.5</sub> smoke ranges from 5.06 to 10.97%, the content of ionic components ranges from 36.53 to 48.59%, and the total carbon content ranges from 9.43 to 11.36%. The divergence coefficient of PM<sub>2.5</sub> source profile in Fuxin coal burning smoke is mostly similar to that of Fushun, whereas the divergence coefficient of Colorado reaches 0.65, indicating that Fuxin coal burning power plant smoke has no similarity to Colorado. The order of the geological accumulation index of Ni, Cu, V, Mn, and Cr was Cr (4.58) > Mn (4.42) > V (4.38) > Cu (4.09) > Ni (4.06), showing a heavy pollution level. The health risk assessment model recommended by the USEPA was used to assess the health risk of heavy metals in soot of coal-fired power plants, and the non-carcinogenic risk values of As for children and adults were 45.7 and 4.90, respectively. The carcinogenic risk values of Cr for adults and children were the highest, with values of  $3.66 \times 10^{-5}$  and  $2.06 \times 10^{-5}$ , respectively, followed by As.

**Keywords** Coal dust · PM<sub>2.5</sub> · Coefficient of divergence · Enrichment factors · Health risk assessment

## Introduction

PM<sub>2.5</sub> is one of the most serious pollutants, affecting urban air quality in China (Feng et al. 2018). According to the 2018 Bulletin on the State of the Ecological Environment in China, only 35.80% of the 338 prefecture-level cities meet the ambient air quality standards. At present, coal is the first fossil fuel in China's energy structure, and particulate matter emitted by coal-fired power plants has become an important source of atmospheric PM<sub>2.5</sub> in Chinese cities (Lu et al. 2011;

Qi et al. 2015; Wang et al. 2000). The PM<sub>2.5</sub> of soot from coal-fired power plants is mainly composed of heavy metal elements, water-soluble anions and cations, carbon-containing components, and other chemical components (Calvo et al. 2013). These elements and components are very harmful to the human neurocardiovascular system (Calderon-Garciduenas et al. 2011) and respiratory system (Browman et al. 2008), and they also affect the regional rainfall acidity (Wang et al. 2015; Yao et al. 2003). Jin (2007), Teng et al. (2015), and Wang (2016) analyzed the source profile of coal-fired soot in Fushun, Changzhou, and Yangquan cities, respectively, by analyzing the download ash components of dust collectors in coal-fired power plants. In another study, Lu et al. (2011) have reported the similarities and differences between the source profile of two kinds of particulate matter (PM<sub>10</sub> and TSP) in Zhengzhou coal-fired power plant boiler download ash. Recently, Ma et al. (2015) used a dilution sampler to study the source profile characteristics of more fine soot particles (PM<sub>2.5</sub>) from Beijing coal-fired power plants. Kang et al. (2018), Wang (2017), Du (2012), and Ji et al. (2018) evaluated the health risks caused by the heavy metals in the atmosphere of Harbin, Nanjing, Shenzhen, and Tianjin,

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respectively. In view of the influence of sampling methods and particle size, there are great differences in the composition spectra of coal-fired soot in different cities established by the different researchers. At present, there are few reports on the PM<sub>2.5</sub> composition characteristics and health risk assessment of soot from coal-fired power plants in ecologically fragile areas of northern China.

Fuxin City is located on the important atmospheric passage connecting the Horqin Sandy Land in the north and the Bohai Bay in the south to the east of the Hu Huanyong Line. As a typical coal resource-based city in the north, Fuxin City is located in the contiguous zone between the sandy land of Horqin left-wing Houqi Banner and Liaohe Plain in Inner Mongolia. It is a typical ecologically fragile area with extremely unstable meteorological conditions. The winter heating period in Fuxin City is from November 1 to March 30 of the next year. During the heating period, coal-fired soot combined with the northern Horqin wind and sand dust seriously affects the quality of the atmospheric environment. In this study, soot from four coal-fired power plants in Fuxin was collected according to this phenomenon (the location of the power plant is shown in Fig. 1). The contents of elements, ions, and carbon elements (EC, OC) in PM<sub>2.5</sub> were determined, and the health risks of 9 kinds of heavy metals to adults and children in Fuxin were evaluated. The purpose of this study is to provide scientific basis and reference for the study of PM<sub>2.5</sub> source profile and public health protection in Fuxin.

## Materials and methods

### Sample collection and pre-treatment

Dust samples of four main coal-fired power plants in Fuxin (Table 1) were collected using a sampler for about 1 kg and then transferred into sealed polyethylene bags for transport to the

laboratory. The sampling period was 1 year from June 2015 to June 2016 and a total of 48 samples were collected once a month. The collected samples were dried naturally, screened (150 mesh), and stored at low temperature (− 4 to 4 °C) in a dark place. The resuspension device 1108A-1 with medium flow gas velocity was used to collect PM<sub>2.5</sub>, which was developed by Nankai University (National Ministry of Environmental Protection 2013). Polypropylene (for elemental analysis) and quartz filters (for ions and carbon analysis) were used.

### Sample analysis

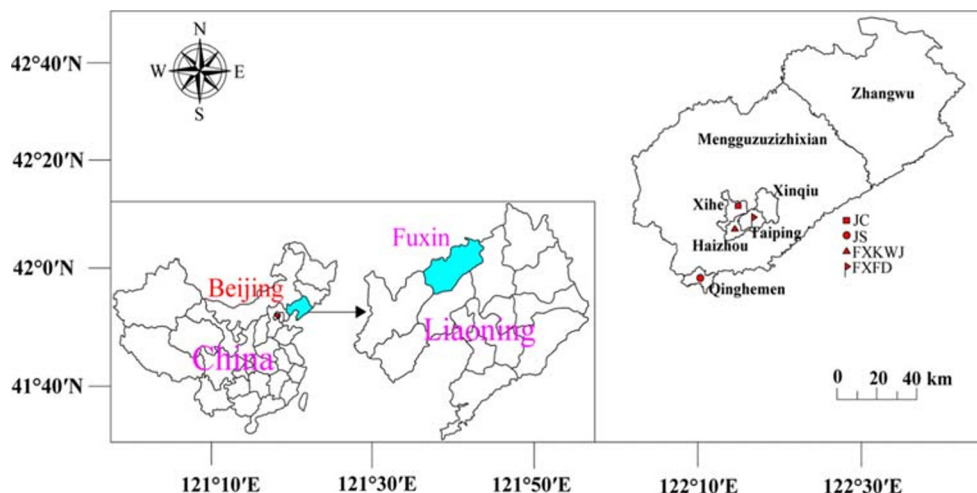
The sampled polypropylene filter film was cut into pieces and then placed in a conical flask. The filter film was immersed in a mixed solution (10 mL) of nitrate-hydrochloric acid. We covered the surface dish and heated for 2 h at 100 °C and then cooled the surface dish at room temperature. Then, we add about 10 mL of ultra-pure water to the conical flask, let it stand for half an hour, filter it, and set the volume to 50.00 mL. The eighteen elements of Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Pb, As, Cd, and Hg were analyzed with a NexION 350X inductively coupled plasma mass spectrometer (ICP-MS).

Next, a sample of 1/4 quartz film was soaked in 10 mL of deionized water and shaken well. For the extraction, the sample was placed in an ultrasonic bath for 10 min and then left to stand. The superfine liquid was taken for the ion chromatography analysis. The eight ions of Na<sup>+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, K<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>, and NO<sub>3</sub><sup>-</sup> were determined by ICS3000 ion chromatograph. The DRI MOD1aL 2001 Thermo-optic carbon analyzer developed by the American Desert Research Institute was used to analyze TC, OC, and EC.

### Quality assurance and quality control

Prior to sampling, polypropylene and quartz filters were calcined at 60 °C for 0.5 h and 800 °C for 2 h to remove any organic compounds that may be present on the filters,

**Fig. 1** Location of four coal-fired power plants in Fuxin



**Table 1** Sampling site information of four power plants in Fuxin

Sampling site	East longitude	North latitude	Removal way	Efficiency (%)	Traffic (m <sup>3</sup> h <sup>-1</sup> )	Coal
FXFD (4 <sup>#</sup> )	121° 40' 04.2"	42° 00' 16.5"	E、 B removal	99.5	1,834,588	Lignite 80% Bituminous coal 20%
JSDC (3 <sup>#</sup> )	121° 26' 15.8"	41° 47' 04.3"	Bag removal	99.85	1,300,000	Lignite 40% Coal gangue 60%
JCRD	121° 40' 52.5"	42° 01' 35.8"	E、 B removal	99.8	225,000	Lignite 50% Coal gangue 50%
FKRD	121° 38' 44.1"	42° 00' 47.4"	E dust removal	99.0	210,000	Coal gangue 100%

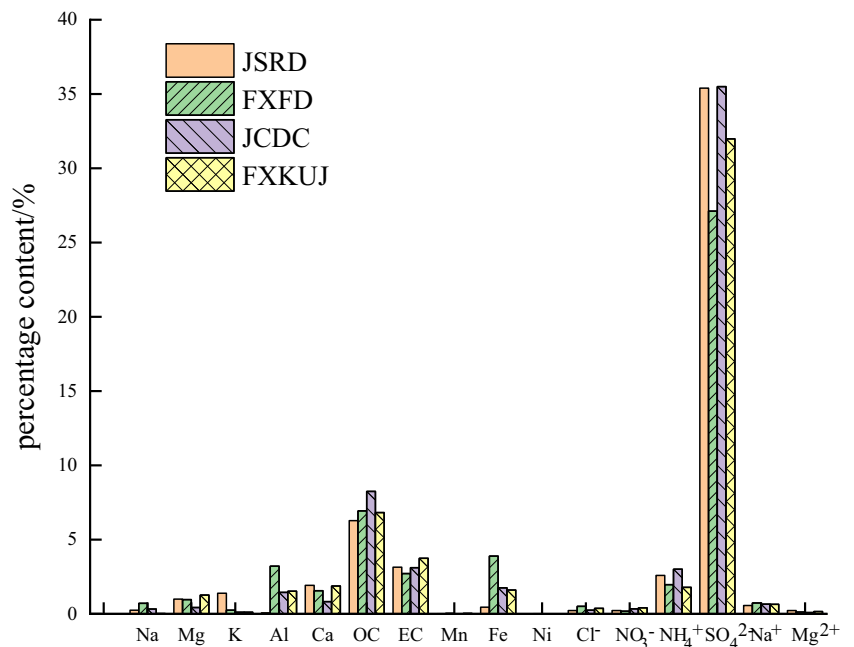
respectively. The filters were precisely weighted using an analytical balance. During the entire sampling period, the normal operation of devices should be ensured. After sampling, the quartz-fiber filters were weighted and stored at 4 °C with aluminum foil and polypropylene filters stored at 22 °C before further chemical analysis. To ensure the reliability of the method, a standard sample of GSD6 sediment was pre-treated and analyzed with the same procedure and the blank filter was simultaneously conducted for parallel analysis. The results showed that the target was greater than 85% and the recovery of parallel determination on the relative standard deviation (RSD) was less than 9%, and ensured the contents of elements and ions in the blank filter were lower than the detection limit, and there was no interference with the results.

## Results and discussion

### Analyzing test results

The ashes under dust catcher of 4 typical power plants in Fuxin were collected and tested. The results are shown in Fig. 2.

**Fig. 2** Percentage content of components of coal dust in Fuxin



It can be seen from Fig. 2 that the most abundant component of PM<sub>2.5</sub> in the dust of the four coal-fired power plants was SO<sub>4</sub><sup>2-</sup>, followed by Ca<sup>2+</sup> and OC. The content of SO<sub>4</sub><sup>2-</sup> in the dust of the two coal-fired power plants, Jinshan Thermal Power Plant and Jiechao Power Plant, was roughly the same, i.e., about 32.50 ± 8.13%. The total elements and ionic and carbon contents of PM<sub>2.5</sub> in power plants range from 5.06~10.97%, 36.53~48.59%, and 9.43~11.36%, respectively. The amount of PM<sub>2.5</sub> emission in this study was about 5.6 times as compared to that of the study reported by Ma et al. (2015) and also confirmed that OC was the highest, up to 5.86%, followed by Si and SO<sub>4</sub><sup>2-</sup>. Teng et al. (2015) pointed out that the content of Al was the most abundant component, and the content of OC and Ca was relatively high in the study of the characteristics of PM<sub>2.5</sub> source profile from coal-fired power plants. The results derived from this study show subtle similarity from those reported in the literature. OC was in the top three of element contents in each city.

The quality of burning coal, the amount of air supplied during combustion, and the temperature in the furnace of the combustion are the main factors that can affect the carbon content in the dust (Zhou et al. 2005). Wang (2016) concluded that the total content of metal elements was 39.72% as

established by the source profile of PM<sub>2.5</sub> in Shanxi, which was about 1.43 times of that in Fuxin, and the content of Ca was the highest, followed by Si. The study also established the source profile of PM<sub>10</sub> in coal dust and found that the content of OC and EC in PM<sub>2.5</sub> was higher than that of PM<sub>10</sub> (particulate matter with aerodynamic diameter less than 10 μm), indicating that OC and EC were more likely to be enriched in fine particulate matter.

### Determination of PM<sub>2.5</sub> source profile

Normalizing the results, the PM<sub>2.5</sub> source profile of dust collectors downloaded from four coal-fired power plants in Fuxin was obtained. The major contributors to PM<sub>2.5</sub> profiles of coal dust were Ca, Al, Fe, EC, OC, NH<sub>4</sub><sup>+</sup>, SO<sub>4</sub><sup>2-</sup>, and Ca<sup>2+</sup>, and the sum of them is 57.62% as shown in Table 2. The same study was done by Wang et al. (2016) who pointed out that Si, Al, Fe, Na, Mg, EC, OC, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Ca<sup>2+</sup>, and Cl<sup>-</sup> were the main components of PM<sub>2.5</sub> in the Yangquan coal-fired power plant. The results were different as compared to this study, but they were basically the same; the proportion of other trace elements was low. Wang et al. (2019) found that Fe had the highest average concentration of 602.83 ± 352.48 ng/m<sup>3</sup>, followed by Zn (79.92 ± 47.29 ng/m<sup>3</sup>), Pb (84.91 ± 75.44 ng/m<sup>3</sup>), and Cr (44.66 ± 47.79 ng/m<sup>3</sup>). Fe, Zn, Pb, and Cr emerged as the dominant contributors.

### Comparison of source profiles with other cities

The PM<sub>2.5</sub> source profile of coal-fired power plant dust in different regions was obtained by consulting the literature and collecting the relevant data, and compared them with the PM<sub>2.5</sub> source profile of Fuxin. There are large differences in the main chemical component in PM<sub>2.5</sub> source profile established by different researchers in different regions (Wang et al. 2016). Some researches pointed that different kinds of coal, different combustion conditions, different sampling methods, different pre-treatment methods of samples, etc. may cause the difference of components in the source profile. The same conclusion was drawn by Zhou et al. (2005), who pointed out that combustion mode, fuel properties, pulverized coal fineness, excessive air coefficient of the boiler load, air distribution mode, and aerodynamic field in the furnace would affect the emission characteristics of coal composition.

Table 3 lists the coal dust profiles of PM<sub>2.5</sub> in Fuxin and other cities. The content of SO<sub>4</sub><sup>2-</sup> in Fuxin was significantly higher than that in other cities except for Texas and Mexico. SO<sub>4</sub><sup>2-</sup> exhibited higher values in Beijing, but still far lower than that in Fuxin. Compared with other areas in China, the OC was only lower than that in Ningbo. These results may be caused by poor coal burning conditions and imperfect dust removal devices (Wang et al. 2016). Al exhibited lower values in Fuxin when compared with other cities except for Colorado. Ca<sup>2+</sup> exhibited similar values with other cities, except for far higher than Colorado and Fushun; its content was similar to other areas.

Similarities between the PM<sub>2.5</sub> profiles in this study and those of other cities can be identified by using coefficient of divergence (CD). The values are calculated in Table 4.

According to Table 4, the source profile of PM<sub>2.5</sub> established in this study shows significant differences from other regions except for Fushun. The CD value between Fuxin and Colorado is 0.65 which indicated that the PM<sub>2.5</sub> profiles in this study for coal dust were most dissimilar with Colorado, but it exhibited similarity with Beijing, Shanghai, Ningbo, Hangzhou, Nanjing, Texas, and Mexico with the CD values ranging from 0.22 to 0.41. More or less similar results were reported by Wang et al. (2016), who pointed out that the PM<sub>2.5</sub> profiles in Yangquan were dissimilar with those in Shijiazhuang and Colorado in the USA, and the CD value between Yangquan and Colorado was 0.59. These results illustrated the importance of establishing source profiles, specific to local emission sources to improve the accuracy and reliability of the results.

### Enrichment and pollution of heavy metals in PM<sub>2.5</sub> from coal dust

In this study, the potential pollution of the heavy metals in PM<sub>2.5</sub> from the Fuxin coal-fired power plant was analyzed using the enrichment factor (EF) and the geoaccumulation index (*I*<sub>geo</sub>).

*I*<sub>geo</sub>, commonly known as the Muller index, takes into account not only the influence of background values caused by natural geological processes but also the influence of human activities on heavy metal pollution. Therefore, this index not only reflects the natural variation characteristics of heavy metal distribution but also can distinguish the impact of human activities on the environment. It is an important parameter to distinguish the impact of human activities (Muller 1969;

**Table 2** Major component content in PM<sub>2.5</sub> source profiles of coal dust of power plants in Fuxin (%)

PM <sub>2.5</sub> source profile	SO <sub>4</sub> <sup>2-</sup>	Ca <sup>2+</sup>	OC	EC	NH <sub>4</sub> <sup>+</sup>	Fe	Al	Ca
Components (> 1)	32.50 ± 8.13	7.50 ± 1.88	7.07 ± 1.77	3.18 ± 0.80	2.34 ± 0.59	1.92 ± 0.48	1.56 ± 0.39	1.55 ± 0.39

**Table 3** Comparison of different chemical source profiles of PM<sub>2.5</sub> from coal dust (%)

City	Ca <sup>2+</sup>	Si	Al	Fe	Mg	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	EC	OC
Fuxin	7.50	0.6 × 10 <sup>-2</sup>	1.56	1.92	0.913	0.34	32.50	3.18	7.07
Beijing <sup>a</sup>	-	-	-	-	-	14.05	17.09	2.66	2.47
Shanghai <sup>b</sup>	8.01	-	7.84	3.21	1.22	0.69	6.12	0.34	1.05
Ningbo <sup>c</sup>	6.88	12.51	7.24	3.41	0.37	0.12	0.70	8.24	9.76
Hangzhou <sup>d</sup>	6.90	7.28	15.35	6.54	0.30	0.14	6.36	6.70	3.40
Nanjing <sup>e</sup>	7.70	-	11.01	5.76	2.66	0.07	0.27	10.56	3.37
Fushun <sup>f</sup>	1.05	-	9.57	6.79	0.47	-	-	13.13	1.30
Texas, Mexico <sup>g</sup>	16.55	-	5.30	3.61	0.84	0.89	28.74	1.38	27.18
Colorado <sup>h</sup>	0.21	-	0.06	0.07	0.04	0.04	3.32	26.08	69.49

<sup>a</sup> Song et al. (2007); <sup>b</sup> Zheng et al. (2013); <sup>c</sup> Xiao et al. (2012); <sup>d</sup> Zhao (2015); <sup>e</sup> Chen (2016); <sup>f</sup> Jin (2007); <sup>g</sup> Chow et al. (2004); <sup>h</sup> Watson et al. (2001)

Forstner and Muller 1981; Orstner et al. 1990; Zhang and Lu 2015).

According to Fig. 3, the EF values are close to 1, suggesting that all nine heavy metals have slight and insignificant contamination. The nine metal contents were in the following order: Ti < Mn < Cr < V < Cu < Ni < Pb < Zn < Cd, among them Cd was the largest, followed by Zn whereas Ti was the smallest. Different results were reported by Wang et al. (2016) and they concluded that Pb contributed a large fraction, followed by Ni, and the EF values were 15.91 and 6.48, respectively, while Zn and Zr were moderately enriched. The different coal quality, dust removal methods, and combustion methods will cause the different results between this study and the research reported by Wang et al. (2016). A similar issue was studied by Wang et al. (2016) in Shanxi coal-fired power plants, and in this fraction, the highest contribution was noted for Zn, followed by V. A relatively lower contribution was observed for Ti, Co, Mn, and Ni by the EF values. The EF values obtained by using different elements as reference elements would be different (Li et al. 2014), that is why the results reported by Wang (2016) are different from this study.

It can also be seen from Fig. 3 that in the PM<sub>2.5</sub> of the Fuxin coal-fired power plant, the most serious pollution is caused by Zn, followed by Cd, with *I*<sub>geo</sub> values of 6.38 and 6.02, respectively. Both of them reached pollution level 7, indicating extremely contaminated. The *I*<sub>geo</sub> values in coal dust decreased in the order of Cr (4.58) > Mn (4.42) > V (4.38) > Cu (4.09) > Ni (4.06), indicating high to low contamination. Ti and Pb were heavily contaminated and their corresponding *I*<sub>geo</sub> values were 3.02 and 3.59, respectively.

**Table 4** Coefficient of divergence of PM<sub>2.5</sub> source profiles between Fuxin and other cities

City	Beijing	Fushun	Shanghai	Ningbo	Hangzhou	Nanjing	Texas, Mexico	Colorado
CD	0.45	0.15	0.35	0.38	0.39	0.41	0.22	0.65

### Health risk assessment of heavy metals in PM<sub>2.5</sub> from the Fuxin coal-fired power plant

#### Health risk assessment model

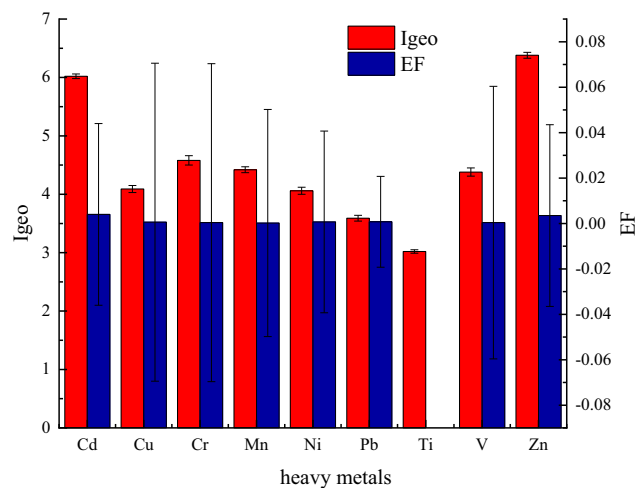
Air pollution describes the relationship between inhalation, ingestion, dermal contact, and the concentration of environmental pollutants (USEPA 1997) in terms of pollutant concentration, duration, frequency, or intensity. The health risk assessment of carcinogens and non-carcinogens should be based on the exposure calculation.

#### Non-carcinogenic risk assessment

The potential non-carcinogenic risk for an individual heavy metal was usually characterized by calculating the hazard quotient (HQ). The total non-carcinogenic risk of all heavy metals was estimated by the accumulation of single heavy metal HQ and the risk index HI. The estimated average non-carcinogenic health risk due to heavy metal exposure for children and adults in the study area through ingestion, inhalation, and dermal contact is given in Table 5.

It can be seen from Table 5 that the HQ<sub>ing</sub> values of As for children and adults were 45.70 and 4.90, respectively, at the highest non-carcinogenic intakes. The HQ<sub>inh</sub> values of Cd for children and adults were 1.11 × 10<sup>-5</sup> and 6.29 × 10<sup>-6</sup>, respectively, at the lowest non-carcinogenic intakes. The trends of HI for nine heavy metals for adults in the study were in the following sequence: As > Cr > V > Mn > Pb > Ni > Zn > Cd > Cu, and the trends of HI for nine heavy metals for children in the study were ranked as V > Pb > As > Mn > Ni > Cr > Zn > Cd > Cu. The HI values of the nine heavy metals for children





**Fig. 3** Geoaccumulation index and enrichment factor of heavy metals in PM<sub>2.5</sub> from coal dust

are relatively higher than those for adults, indicating that children will be influenced easily by heavy metals than adults.

For adults, the HQ<sub>ing</sub> values of all heavy metals except As and Cr were less than 1 and have a slight impact on the population. Furthermore, the HQ<sub>dermal</sub> value of As was also more than 1, which indicated that As contributed the most to the potential non-carcinogenic risks for human health. The impact of all heavy metals through inhalation can be ignored due to the fact that the total non-carcinogenic risk value was 0.26. The total non-carcinogenic values for adults through ingestion and dermal contact were 8.01 and 1.99, respectively. Therefore, it can be concluded that the heavy metals in coal dust of the study area had higher non-carcinogenic risks to human health.

For children, the HQ<sub>ing</sub> values of As, Cr, V, Pb, Mn, Ni, and Zn were more than 1 and the value of As was the largest, reaching 45.70, suggesting that children might experience greater health risks from As. While the HQ<sub>inh</sub> values of all heavy metals were less than 1 and the total non-carcinogenic

risk value was  $4.62 \times 10^{-1}$ , this indicates that children might experience minor health risks from heavy metals. The same results were concluded from dermal contact except V and Cr. Based on what was mentioned above, we can come to a conclusion that we must take measures to reduce the risk of V and As for children. The total non-carcinogenic risk values of the nine heavy metals through ingestion and dermal contact were 78.40 and 4.00, respectively, and the non-carcinogenic risk value through ingestion was almost 20 times higher than that of dermal contact, which should arouse widespread concern and effective measures to reduce the threat to children health.

The impact of the nine heavy metals through ingestion and inhalation for adults and children was relatively serious. Therefore, in addition to taking certain measures to reduce the harm of heavy metals to human, we should also take precautions in daily life to avoid the threat to human health. The same conclusion was drawn by Wang et al. (2016), who confirmed that the non-carcinogenic risk values through ingestion and dermal contact were similar and just over 1, and the impact for population was lower than that in this study. Fang et al. (2015) observed that the non-carcinogenic risk value of Mn for adults and children was the highest, and the risk decreases as the age increases. Lin et al. (2020) found that the average HQ was 2.10 for children and 0.70 for adults, indicating that apparent non-carcinogenic risk was found for children during the haze event. Wang et al. (2018) found that the non-carcinogenic risk values of adults and children showed the same trend in health risk assessment of PM<sub>2.5</sub> elements in Beijing; i.e., the non-carcinogenic risk value of single element was less than 1. Tofan et al. (2013) concluded that the HQ values for all the elements studied were far below threshold values for adults, indicating no risks from these elements for adults. However, the HQ values of Co, Cr, and Pb were > 0.1 for toddlers, suggesting potential health risk to toddlers.

**Table 5** The non-carcinogenic risk of heavy metals to adults and children in PM<sub>2.5</sub> from power plants through three routes

Heavy metal	HQ <sub>ing</sub>		HQ <sub>inh</sub>		HQ <sub>dermal</sub>		HI	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children
As	4.90	45.70	$7.18 \times 10^{-4}$	$1.27 \times 10^{-3}$	1.43	$3.12 \times 10^{-1}$	6.33	46.00
Cd	$4.27 \times 10^{-2}$	$3.99 \times 10^{-1}$	$6.29 \times 10^{-6}$	$1.11 \times 10^{-5}$	$1.71 \times 10^{-2}$	$1.12 \times 10^{-1}$	$5.98 \times 10^{-2}$	$5.11 \times 10^{-1}$
Cu	$4.77 \times 10^{-2}$	$4.45 \times 10^{-1}$	$6.98 \times 10^{-6}$	$1.24 \times 10^{-5}$	$6.34 \times 10^{-4}$	$4.15 \times 10^{-3}$	$4.83 \times 10^{-2}$	$4.49 \times 10^{-1}$
Cr	1.11	10.40	$1.72 \times 10^{-2}$	$3.05 \times 10^{-2}$	$2.22 \times 10^{-1}$	1.46	1.35	11.90
Mn	$3.73 \times 10^{-1}$	3.48	$2.43 \times 10^{-1}$	$4.30 \times 10^{-1}$	$3.80 \times 10^{-2}$	$2.49 \times 10^{-1}$	$6.54 \times 10^{-1}$	41.60
Pb	$6.16 \times 10^{-1}$	5.75	$9.01 \times 10^{-5}$	$1.60 \times 10^{-4}$	$1.64 \times 10^{-2}$	$1.07 \times 10^{-1}$	$6.33 \times 10^{-1}$	58.60
Ni	$1.51 \times 10^{-1}$	1.41	$2.15 \times 10^{-5}$	$3.82 \times 10^{-5}$	$2.23 \times 10^{-3}$	$1.46 \times 10^{-2}$	$1.53 \times 10^{-1}$	14.20
V	$6.62 \times 10^{-1}$	6.18	$9.73 \times 10^{-5}$	$1.73 \times 10^{-4}$	$2.64 \times 10^{-1}$	1.73	$9.26 \times 10^{-1}$	79.10
Zn	$1.08 \times 10^{-1}$	1.00	$1.58 \times 10^{-5}$	$2.81 \times 10^{-5}$	$2.15 \times 10^{-3}$	$1.41 \times 10^{-2}$	$1.10 \times 10^{-1}$	10.20
Σ	8.01	78.40	$2.61 \times 10^{-1}$	$4.62 \times 10^{-1}$	1.99	4.00	10.30	79.20

**Table 6** Carcinogenic risk value of heavy metals in PM<sub>2.5</sub> from coal dust (R)

Heavy metal	As	Cd	Cr	Ni	Σ
Children (R)	$5.79 \times 10^{-6}$	$7.02 \times 10^{-8}$	$3.66 \times 10^{-5}$	$6.61 \times 10^{-7}$	$4.31 \times 10^{-5}$
Adults (R)	$3.26 \times 10^{-6}$	$3.96 \times 10^{-8}$	$2.06 \times 10^{-5}$	$3.73 \times 10^{-7}$	$2.43 \times 10^{-5}$

### Carcinogenic risk assessment

The carcinogenic risk of As, Cd, Cr, and Ni through inhalation was calculated using the exposure reported by EPA (Zhang and Lu 2015). The results are shown in Table 6.

The acceptable risk level in most countries, such as the USA and Europe, was  $1.00 \times 10^{-6}$  (Hu et al. 2013). Table 6 indicates that the carcinogenic R of As is the highest and the values for children and adults were  $2.06 \times 10^{-5}$  and  $3.66 \times 10^{-5}$ , respectively. Followed by As, the carcinogenic R values for adults and children were  $5.79 \times 10^{-6}$  and  $3.26 \times 10^{-6}$ , respectively. Both the carcinogenic R values for adults and children are above the acceptable level ( $1.0 \times 10^{-6}$ ), indicating the health of the population will be affected. The carcinogenic R values of Ni in children and adults were higher than Cd; however, the carcinogenic R values of Ni and Cd are relatively lower than the acceptable level. In addition, the carcinogenic R values of all heavy metals for children were relatively higher than those for adults, which indicates that children were more sensitive to heavy metals than adults and attention should be paid to children's health. The risk of all heavy metals for children and adults was negligibly reported by Wang et al. (2016), who studied the carcinogenic risk of heavy metals in PM<sub>2.5</sub> during heating season in Taiyuan. The total CR value in Linfen during the haze event was  $2.91 \times 10^{-5}$  for children and  $7.75 \times 10^{-5}$  for adults, and the cancer risk of each element for adults was higher than that of children (Lin et al. 2020).

### Uncertainty analysis

The uncertainty of health risk assessment was related to the uncertainty of exposure parameters (Hu et al. 2013). It is crucial to select the exposure parameters in health risk assessment; due to the limited research on exposure parameters in China, the parameters selected in this paper have been adjusted on the basis of existing parameters (Chen et al. 2016), and it will influence the results. For example, the inhalation rate (In) of children was 7.5 in this study, while the recommended inhalation rate in the USA was 5. The larger parameter selection will lead to a higher carcinogenic risk. The carcinogenic risk of heavy metals through inhalation was studied in this paper, while other pathways and the interaction between pollutants will also lead to deviations in the results (Cui 2018). Except for climatic conditions, meteorological factors and pollution sources will also affect the content of heavy metals in

PM<sub>2.5</sub>. In addition to the concentration, the shape, valence, and particle size of heavy metals have an impact on human health (Wang 2017). Therefore, the adequacy of health risk assessment using health risk models deserves further discussion. In this study, the ashes under dust catcher of typical power plants in Fuxin were collected, and other power plants such as Shengming Thermal Power Plant were not considered. The results cannot fully express the impact of heavy metals on human health, which also indirectly affects the health risk values of heavy metals.

Zhang et al. (2017) found that the health risk value of PM<sub>2.5</sub> was greater than PM<sub>10</sub>, and PM<sub>2.5</sub> was more harmful to human than PM<sub>10</sub>. This study only discussed the effects of PM<sub>2.5</sub> on human health, and the effects of other particles need further investigation.

### Conclusion

The major components of coal dust are Ca, Al, Fe, EC, OC, NH<sub>4</sub><sup>+</sup>, SO<sub>4</sub><sup>2-</sup>, Ca<sup>2+</sup>, Na, Mg, K, Ti, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, Na<sup>+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, and OC, while other components are relatively low. The source profile of PM<sub>2.5</sub> in Fuxin power plant is different from other areas except for Fushun. The enrichment factor of heavy metals in PM<sub>2.5</sub> of power plant was less than 1, the value of Cd was the highest ( $3.97 \times 10^{-3}$ ), and Ti was the lowest ( $0.67 \times 10^{-3}$ ). Ti, Pb, Ni, Cu, V, Mn, and Cr were heavily polluted in PM<sub>2.5</sub>, while Cd and Zn were severely polluted.

Some specific measures should be adopted to reduce environmental exposure risks to heavy metals to protect human health, especially As and Cr. The total carcinogenic risk of heavy metals in PM<sub>2.5</sub> for children was higher than that for adults. As, Cr, V, Pb, Mn, Ni, and Zn were the main metals for children's health, and As and Pb were the main non-carcinogenic factors for adults.

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## Compliance with ethical standards

**Conflicts of interests** The authors declare that they have no competing interests.

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