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Heavy Metals in Indoor Dust Across China: Occurrence, Sources and Health Risk Assessment

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Abstract

In this study, the occurrence of heavy metals including cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) was investigated in indoor dust samples collected from 33 urban and rural areas in 11 provinces, China. The concentrations of the selected heavy metals were determined by an inductively coupled plasma mass spectrometry. The mean concentrations of Zn (166 mg kg^{-1}), Pb (40.7 mg kg^{-1}), Cr (19.8 mg kg^{-1}), Cu (16.9 mg kg^{-1}), and Cd (2.29 mg kg^{-1}) in indoor dust are in low or moderate levels compared with other countries or regions. Cd was significantly enriched with the highest enrichment factor of 23.7, followed by Zn, Pb, Cu, and Cr, which were all lower than 3. The concentrations of Pb from Northern China (61.4 mg kg^{-1}) were significantly higher than those from Southern China (8.88 mg kg^{-1}). The concentrations of heavy metals in indoor dusts from rural areas were higher than those from urban areas except for Cu. The multivariate analysis of variance revealed that wall cover, fuel types, and air conditioning were dominant factors influencing the levels of heavy metals in indoor dust. Principal component analysis showed that outdoor dust and wall paint were main factors for the high concentrations of Cd, Pb, and Cr, accounting for 40.6% of the total contribution; traffic sources contributed to the high levels of Cu and Zn explained 20.6% of the total variance. The hazard indexes of selected heavy metals were less than 1 and carcinogenic risk value of Cr were between 1.01×10^{-6} and 1×10^{-4}, indicating minor noncarcinogenic and carcinogenic risks from heavy metals in indoor dust for residents in China. Pb contributed 72.0% and 86.9% to the sum of noncarcinogenic risk values of selected heavy metals for adults and children, respectively. The carcinogenic risk value of Cr was approximately 13-fold higher than that of Cd for both adults and children. Children endured higher risks from heavy metals in indoor dust compared with adults.

Indoor dust is a heterogeneous mixture of particles loading numerous pollutants. Particulate matter in indoor air is derived from outdoor air, in-and-out activity of residents, and indoor activities, including smoking and cooking (Koehler et al. 2018; Zhou et al. 2019a). Many studies have shown that adults spend ~ 90% of the time exposed to indoor atmosphere (Andrade and Dominski 2018; Barrio-Parra et al. 2018), leading to the increase of exposure to some pollutants in indoor air by ~ 1000-fold than those of outdoor exposure (Hwang et al. 2008). Children generally ingest more near-ground dust than adults due to their short stature, frequent hand-to-mouth behavior, and low tolerance to toxins (Acosta et al. 2009; Cao et al. 2020; He et al. 2009; Tepanosyan et al. 2017). Thus, an increasing public attention has been paid to indoor environment. Indoor air pollution ranks tenth among all risk factors for global disease burden analysis in 2015 (Cohen et al. 2017), and approximately 4.5 million people die of indoor air pollution globally each year (WHO 2018).

Heavy metals, such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn), adsorbed in indoor dust are easier to enter the human body by ingestion, dermal contact, and inhalation (Gu and Gao 2018; Lian et al. 2019) than those in other mediums, which eventually makes it an important threat to human health (Zhou et al. 2019b). Heavy metals in indoor dust come from a variety

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of sources, including soil dust, combustion, industrial, and traffic activities (Charlesworth et al. 2011; Othman et al. 2018). Heavy metals accumulated in the human body can cause a variety of diseases due to their nonbiodegradability (Lü et al. 2018; Staessen et al. 1994, 1999). Some heavy metals, such as Cd, Cr, and Pb, are highly toxic even at a low concentration (Kavcar et al. 2009; Saha and Zaman 2013), resulting the potential risk for heart disease, neurotoxicity, and immunological problems (Huang et al. 2012). It is therefore essential to study the concentrations of heavy metals in indoor dust and their health risks to human.

In recent years, some studies have been conducted on the contents of heavy metals in indoor dust from China (Bao et al. 2019; Cao et al. 2020; He et al. 2017; Zhou et al. 2019a, b). Higher levels of heavy metals were detected in dust samples collected in winter than in summer (Bao et al. 2019). Indoor human activities, such as smoking and cooking (Shi and Wang 2020; Zhou et al. 2019a), and outdoor sources, such as vehicle emission and corrosion of alloys (Cheng et al. 2018), are the main factors that contribute to the levels of heavy metals in indoor dust. However, the scope of these studies was relatively limited, because they usually focused on a single region or city. Because the exposure time of human body to indoor dust is much higher than that of outdoor dust, it is necessary to investigate the pollution characteristics of heavy metal in indoor dusts across China.

This study was designed to (1) investigate the levels, characteristics, and spatial distributions of heavy metals in indoor dusts in 11 provinces of China; (2) explore the main factors influencing the contents of heavy metals in indoor dust; and (3) estimate human exposure risks via dust ingestion.

Materials and Methods

Sample Collection and Storage

A total of 38 indoor dust samples were collected from 33 urban and rural areas in 11 provinces of China in August 2020 (Fig. 1). The selected provinces are mainly concentrated in the east of China with a developed industry and dense population. Each sample was combined with three to four subsamples that were collected from bedroom, living room, etc. The detailed information of each sampling site is listed in Table S1 based on a questionnaire from the resident volunteers. The indoor dust samples were collected by using a precleaned brush from floor surface. The wet areas were avoided during the sample collection to maintain

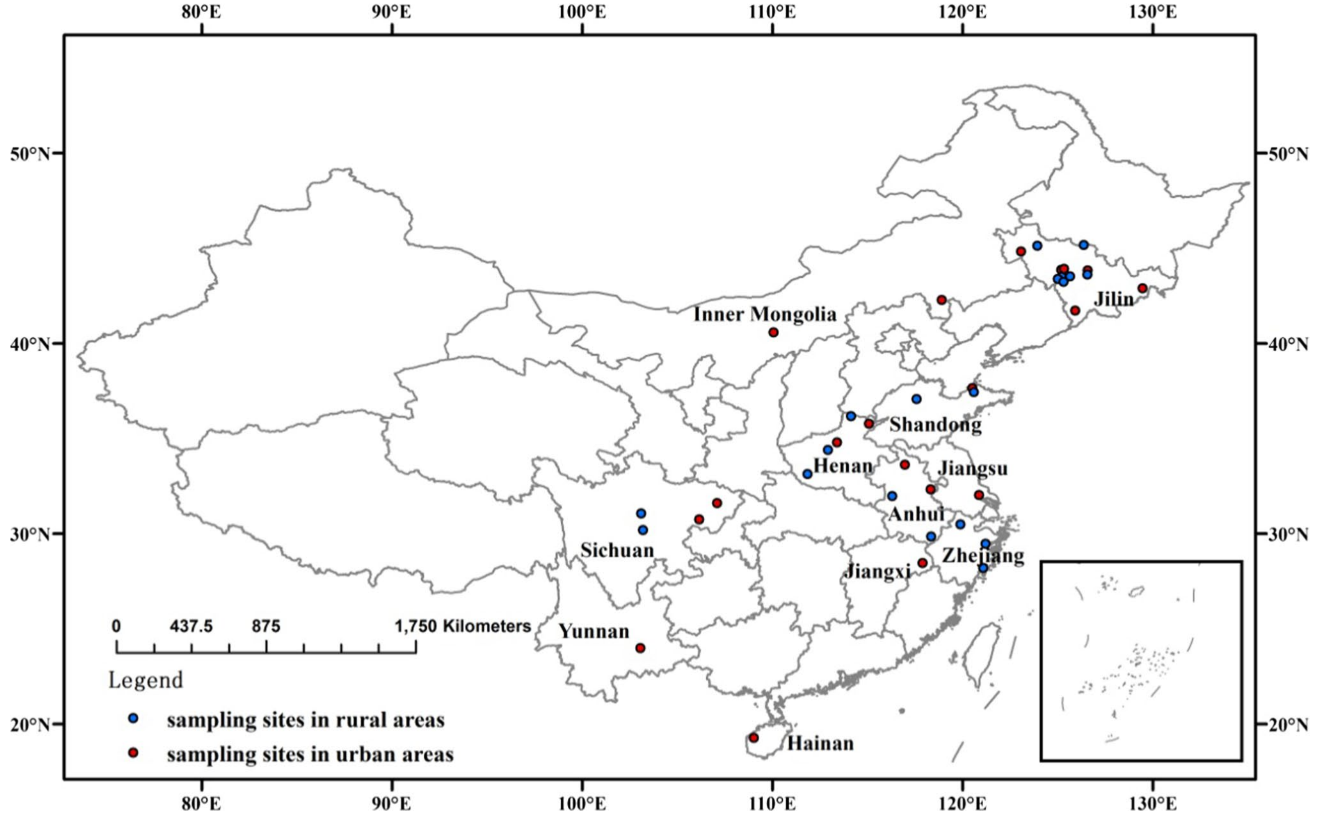

Fig. 1 Sampling sites located in 33 cities or rural areas in 11 provinces, China

the integrity of each sample. The indoor dust samples were wrapped with aluminum foils, sealed into clean polypropylene (PP) bags, and then mailed to the laboratory. On arrival at the laboratory, the dust samples were freeze-dried, homogenized, and then passed through a 0.15-mm sieve.

Analytical Methods

All of the dust samples were digested using an APL MD6M model microwave digestion system (Chengdu, China). Approximate 0.10 g of dust samples was weighed into a Teflon container capable of resisting high temperature and pressure. Then, 6 mL of 65% nitric acid, 2 mL of 36% hydrochloric acid, 2 mL of 40% hydrofluoric acid, and 2 mL of 30% hydrogen peroxide were added into the container (Bao et al. 2019). The temperature of digestion was gradually increased to 180 °C from room temperature and kept for 40 min. After digestion, the extracts were passed through a 0.45-μm filter membrane and then diluted to 25 mL with deionized water. The concentrations of heavy metals were analyzed by an inductively coupled plasma mass spectrometry (ICP-MS) (Perkin Elmer, 350D).

Quality Assurance and Quality Control (QA/QC)

The certified reference materials GBW07408 (GSS-8) were used to conduct the precision and accuracy of the analysis. Every ten dust samples combined with an instrument blank were simultaneously analyzed in triplicate. Cr, Cu, Zn, and Mn were determined by using Ge 74 as internal standard, and Pb was analyzed by using Bi 209 as internal standard with concentrations of standard solutions at 20 μg L^{-1}, 50 μg L^{-1}, 100 μg L^{-1}, 500 μg L^{-1}, 1000 μg L^{-1}, 2000 μg L^{-1}, 5000 μg L^{-1}, and 1000 μg L^{-1}. Cd was determined using In 115 as internal standard with concentrations of standard solutions at 2 μg L^{-1}, 5 μg L^{-1}, 10 μg L^{-1}, 20 μg L^{-1}, 50 μg L^{-1}, 100 μg L^{-1}, and 200 μg L^{-1}. The limit of quantification (LOQ) was determined with a signal-to-noise ratio of 10 at the lowest concentration of the calibration curve. LOQs and recoveries for the selected heavy metals are listed in Table S2.

Enrichment Factors

Enrichment factors (EFs) are widely used to distinguish between an anthropogenic source and a natural source of elements, as well as to assess the degree of anthropogenic influence. Previous studies employed EFs to explore the enrichment of elements in particulate matter of atmosphere (Khademi et al. 2019; Wei et al. 2010). EFs can be estimated by the following formula:

$$\mathrm{EF} = \frac{(C_i/C_n)_{\mathrm{sample}}}{(C_i/C_n)_{\mathrm{background}}} \tag{1}$$

where $(C_i/C_n)_{\mathrm{sample}}$ is the ratio of metal and the reference metal in dust sample. Considering Mn is ubiquitous in earth crust and rarely derived from anthropogenic sources, it is widely used as the reference metal (Han et al. 2006; Cheng et al. 2018; Bao et al. 2019). In this study, Mn was employed as the reference metal as it had the lowest mean coefficient of variation (9.86%). $(C_i/C_n)_{\mathrm{background}}$ is the ratio of metal and the reference metal in background area. The background values of Cd, Cr, Cu, Pb, Zn, and Mn were 0.097 mg kg^{-1}, 61.0 mg kg^{-1}, 22.6 mg kg^{-1}, 26.0 mg kg^{-1}, 74.2 mg kg^{-1}, and 583 mg kg^{-1} in China that were derived from China National Environmental Monitoring Center (CNEMC 1990).

Health Risk Assessment

The main pathways of exposure to heavy metals in indoor dust could be summarized as follows: (1) average daily intake through ingestion ($\mathrm{DI_{ing}}$); (2) average daily intake through inhalation ($\mathrm{DI_{inh}}$); and (3) average daily intake through dermal contact ($\mathrm{DI_d}$) (Du et al. 2013; Wei and Yang 2010). The average daily intake of heavy metals (Cu, Pb, and Zn) and the lifetime average daily index (LDI), which was employed to assess the cancer risk of two carcinogenic metals (Cd and Cr) through the three pathways, can be calculated by Eqs. (2)–(4):

$$\mathrm{DI_{ing}}(\mathrm{LDI_{ing}}) = C_{95\%\mathrm{UCL}} \times \frac{\mathrm{EF} \times \mathrm{ED} \times \mathrm{OSIR}}{\mathrm{AT} \times \mathrm{BW}} \times 10^{-6} \tag{2}$$

$$\mathrm{DI_{inh}}(\mathrm{LDI_{inh}}) = C_{95\%\mathrm{UCL}} \times \frac{\mathrm{EF} \times \mathrm{ED} \times \mathrm{DAIR}}{\mathrm{AT} \times \mathrm{BW} \times \mathrm{PEF}} \tag{3}$$

$$\mathrm{DI_d}(\mathrm{LDI_d}) = C_{95\%\mathrm{UCL}} \times \frac{\mathrm{EF} \times \mathrm{ED} \times \mathrm{SL} \times \mathrm{SA} \times \mathrm{ABS}}{\mathrm{AT} \times \mathrm{BW}} \times 10^{-6} \tag{4}$$

$C_{95\%\mathrm{UCL}}$ represents the upper confidence limit of heavy metal concentrations at $P = 95\%$ and can be calculated by Eq. (5):

$$C_{95\%\mathrm{UCL}} = \bar{x} + t_{1-a,n-1}\frac{s}{\sqrt{n}} \tag{5}$$

where $\bar{x}$ represents the mean concentration of individual heavy metal; n is the number of dust samples; $1-\alpha$ represents the confidence level; $n-1$ is the degree of freedom; s represents the standard deviation. The other parameters in Eq. (2)–(4) were described as follows: EF, exposure frequency (d a^{-1}); ED, exposure duration (a); OSIR, daily oral ingestion rate of particulates (mg d^{-1}); AT, average exposure time (d); BW, average body weight (kg); DAIR, daily air inhalation rate (m^3 day^{-1}); PEF, particulate emission factor (m^3 kg^{-1}); SL, adherence rate of particulates on skin (mg cm^{-2}); SA, the contact area of skin (cm^2 d^{-1}); ABS, skin absorption coefficient. The values of the parameters for adults and children in Eqs. (2)–(4) are listed in Table S3.

The hazard quotients (HQs) calculated by Eq. (6) were employed to estimate the noncarcinogenic risk of heavy metals in indoor dust. A hazard index (HI) is equal to the sum of HQ of a single contaminant by all the pathways of exposure, which is described as Eq. (7). Carcinogenic risk (CR) calculated by Eq. (8) is used to estimate the carcinogenic risk of heavy metals in indoor dust during a lifetime. The Eqs. (6)–(8) are shown as follows:

$$\mathrm{HQ}_{ij} = \frac{\mathrm{DI}_{ij}}{\mathrm{RfD}_{ij}} \tag{6}$$

$$\mathrm{HI}_i = \sum_{j=1}^{m} \mathrm{HI}_{ij} \tag{7}$$

$$\mathrm{CR}_i = \sum_{j=1}^{m} \mathrm{LDI}_{ij} \times \mathrm{SF}_{ij} \tag{8}$$

where i represents an individual metal; j is the exposure route; RfD_{ij} is the reference dose of heavy metal i by route j; SF_{ij} is the carcinogenic slope factor of heavy metal i by route j. The RfD and SF of each heavy metal are listed in Table S4 referring to Regional Screening Levels (US EPA 2010). The RfD for Pb was set as 25 μg kg^{-1} referring to the weekly Pb intake limit recommended by FAO/WHO due to no RfD for Pb provided by US EPA (Bao et al. 2019; Hu et al. 2011).

Statistical Analysis

The multivariate analysis of variance (MNOVA) was used to explore the influencing factors on the levels of heavy metals in indoor dust. The principal component analysis (PCA) was performed using the varimax rotation of Kaiser normalization to generate an interpretable results. SPSS 20.0 and Origin 2018 software packages were used to perform the statistical analysis.

Results and Discussion

Concentrations of Heavy Metals in Dust Samples

The concentrations of heavy metals in indoor dust samples are shown in Fig. 2. The mean contents of heavy metals (mg·kg^{-1}) ranked in the order of Zn (166) > Pb (40.7) > Cr (19.8) > Cu (16.9) > Cd (2.29), which is similr to those in previous studies in Hefei (Zhou et al. 2019b) and Lanzhou (Bao et al. 2019). No significant difference in the concentrations of Zn ($F = 1.98$, $P > 0.05$), Cr ($F = 0.081$, $P > 0.05$), Cu ($F = 2.80$, $P > 0.05$), and Cd ($F = 1.74$, $P > 0.05$) was found between northern provinces (Jilin, Inner Mongolia, Henan and Shandong) and southern provinces (Anhui, Hainan, Jiangsu, Jiangxi, Sichuan, Yunnan and Zhejiang) (Table S5). The mean concentration of Pb in northern provinces (61.4 mg kg^{-1}) was significantly higher than that in southern provinces (8.88 mg kg^{-1}) ($F = 5.35$, $P < 0.05$), which could be related to the more serious air pollution originated from vehicle exhaust in northern provinces of China (Sun et al. 2019). The order of mean EF values of the selected heavy metals was Cd > Zn > Pb > Cu > Cr. The mean EF value of Cd (23.7) was higher than 5, indicating that Cd in indoor dusts from 11 provinces in China was significantly enriched (Loska et al. 1997) and likely derived from anthropogenic activities (Han et al. 2006), which is consistent with the finding from a previous study (Ma et al. 2020). The mean EF values of Cu, Zn, Pb, and Cr were less than 3, suggesting that they were partly from ground particulate. The mean EF values of heavy metals in indoor dusts from rural areas were higher than those from urban areas, which may be related to the use of coal and straw as the fuel for home cooking in rural areas.

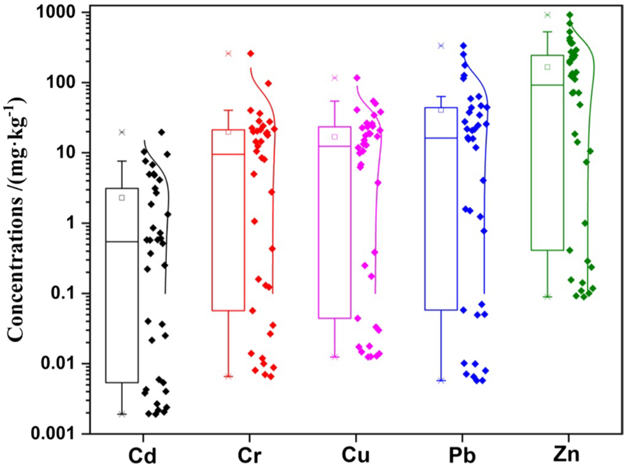

Fig. 2 Box plot of heavy metal concentrations in indoor dusts collected from 11 provinces of China ($n = 39$). Upper edge of box, median bar, and lower edge of box represent the 75th, 50th, and 25th percentiles, respectively. Upper and lower error bars indicate that values were in the nonoutlier range. Upper and lower limits of the whiskers show the maximum and minimum values. "☐" represents mean concentration of each heavy metal

A comparison of mean concentrations of heavy metals in household dust is shown in Fig. 3. Compared with the cities from Japan, Canada, Australia, Turkey, Egypt, and China, the concentrations of heavy metals in this study are at a low or moderate level. The highest mean concentration of Cd was observed in the samples at 4.88 mg kg^{-1} from

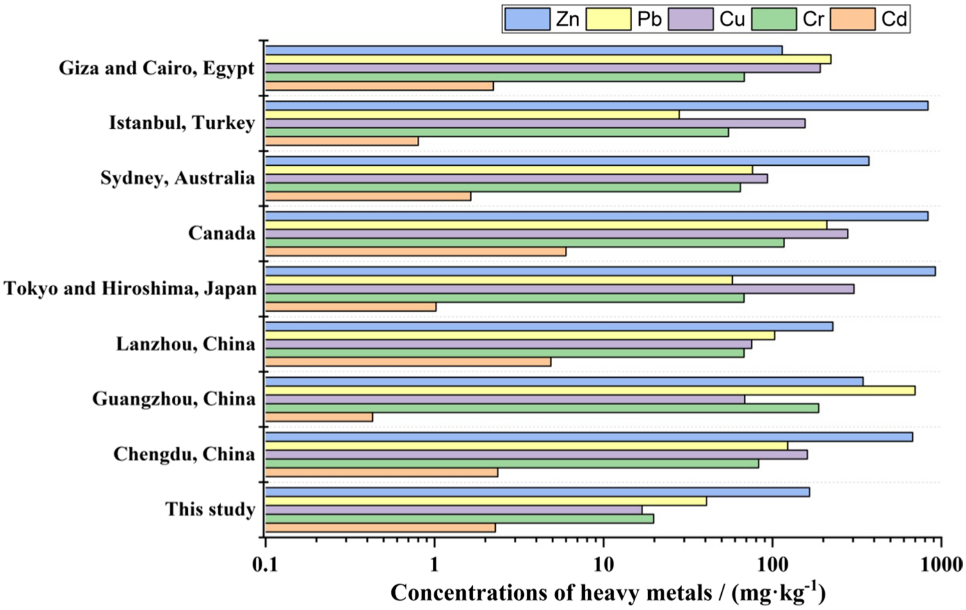

Fig. 3 Mean concentrations of Cu, Zn, Cd, Pb, and Cr in indoor dust from this study and other countries or cities. The data for Chengdu, China were from Cheng et al. (2018). The data for Guangzhou, China were from Huang et al. (2014a, b, c). The data for Lanzhou, China were from Bao et al. (2019). The data for Tokyo and Hiroshima, Japan were from Yoshinaga et al. (2014). The data for Canada were from Rasmussen et al. (2013). The data for Sydney, Australia were from Chattopadhyay et al. (2003). The data for Istanbul, Turkey were from Kurt-Karakus (2012). The data for Giza and Cairo, Egypt were from Hassan (2012)

Lanzhou, China (Bao et al. 2019). The concentrations of Cd in this study are comparable to those in Chengdu, China (Cheng et al. 2018) and Giza and Cairo, Egypt (Hassan 2012). Cu, Pb, and Cr were detected at the lowest levels in this study compared with other studies. The highest mean concentration of Cu was found in Tokyo and Hiroshima, Japan, at 304 mg kg^{-1} (Yoshinaga et al. 2014), which is 18-fold higher than that in this study. The highest mean concentrations of Pb and Cr were found in Guangzhou, China at 699 mg kg^{-1} and 188 mg kg^{-1} (Huang et al. 2014a, b, c), respectively, much higher than those in this study. High concentrations of Zn were found in Tokyo and Hiroshima, Japan at 920 mg kg^{-1} (Yoshinaga et al. 2014), Canada at 833 mg kg^{-1} (Rasmussen et al. 2013) and Istanbul, Turkey at 832 mg kg^{-1} (Kurt-Karakus 2012), which are > fivefold higher than that in this study.

Influencing Factors on the Levels of Heavy Metals

The household information collected at each sampling site is shown in Table S1. 47.4% of the samples were collected from cities and the others were from rural areas. The MNOVA revealed significant differences in the contents of Cd in the indoor dusts from urban and rural areas ($P < 0.05$, $F = 6.49$; Table S6). Moreover, the median concentrations of Cd (1.86 mg kg^{-1}), Cr (12.4 mg kg^{-1}), Cu (12.9 mg kg^{-1}), Pb (21.8 mg kg^{-1}), and Zn (128.5 mg g^{-1}) in rural indoor dusts were higher than those of Cd (0.370 mg kg^{-1}), Cr (8.04 mg kg^{-1}), Cu (10.6 mg kg^{-1}), Pb (11.9 mg kg^{-1}), and Zn (70.9 mg kg^{-1}) in urban indoor dusts. The liquefied gas, coal, and straw are commonly used as main fuels in rural areas in China. Previous studies reported that cooking is an important contributor to heavy metals in indoor dust (Kurt-Karakus 2012; Rasmussen et al. 2013). The fuels used in rural areas with a poor cleanliness would produce more by-products during combustion process, leading to the high levels of heavy metals in indoor dust.

A few studies have reported that the floor height level may influence the contents of heavy metals in indoor dust (Bao et al. 2019; Cheng et al. 2018). However, no statistical difference in the concentrations of heavy metals was observed in the floor level, floor cover, and age of building ($P > 0.05$; Table S7–S9). Some studies have observed that smoking is the main reason for the high contents of heavy metals in indoor dust due to the amount of heavy metals in cigarette (Bohlandt et al. 2012; Cheng et al. 2018; Rasmussen et al. 2013). However, in this study, smoking was not the main factor contributing to the increase of heavy metal content in indoor dust. Moreover, the contents of Zn in indoor environments without smoking were significantly higher than that with smoking in this study ($P < 0.05$, $F = 4.83$; Table S10), indicating that Zn in indoor dust was not originated from smoking. In addition, the number of occupants, pets, and sweeping frequency were not influencing the contents of heavy metals in indoor dust ($P > 0.05$; Tables S11–S13).

The present study found that the wall cover had important effects on heavy metals enriched in household dust, especially for Cd ($P < 0.05$, $F = 4.22$; Table S14), which is consistent with the previous study (Cheng et al. 2018). All the concentrations of heavy metals studied in the house painted by latex paint were significantly lower than those painted by lime, cement, wallpaper, etc. In this study, 36.8% of houses were painted by lime made by natural rocks containing calcium carbonate ($CaCO_3$). The heavy metal contents in natural rock are considerably higher than latex paint based on synthetic resin. Considering that the age of 86.8% houses were > 6 years, and the last paint time of 68.4% houses were > 5 years (Table S1), the flaking of paint off the wall may be an important contributor to the indoor dust.

Previous study has shown that cooking is the main source of polycyclic aromatic hydrocarbons (Wang et al. 2013). However, this study did not find a significant correlation between levels of heavy metals and fuel types or cooking frequency ($P > 0.05$; Tables S15 and S16). The median dust concentrations of Cd (5.00 mg kg^{-1}), Cr (21.2 mg kg^{-1}), Cu (17.6 mg kg^{-1}), Pb (43.9 mg kg^{-1}), and Zn (134.8 mg kg^{-1}) in household using liquefied gas were higher than those using other fuels, such as natural gas, coal gas, coal, and straw, etc., which may be related to the low purity of liquefied gas. In addition, the present study also found that air conditioning was the main factor influencing the contents of Pb in household dust (Table S17). The median dust concentration of Pb in houses without air conditioning was 31.0 mg kg^{-1}, which was significantly higher than that in air-conditioned houses (2.64 mg kg^{-1}). Similarly, the median dust concentrations of Cd (0.595 mg kg^{-1}), Cr (16.1 mg kg^{-1}), Cu (12.4 mg kg^{-1}), and Zn (130 mg kg^{-1}) in houses without air conditioning were higher than those of Cd (0.145 mg kg^{-1}), Cr (1.60 mg kg^{-1}), Cu (10.4 mg kg^{-1}), and Zn (29.2 mg kg^{-1}) in air-conditioned houses, indicating air conditioning will help to reduce the contents of heavy metals in indoor dust.

Source Apportionment of Heavy Metals

PCA was performed to identify the most probable sources of heavy metals in dust. Results showed that the first two factors (46.0% and 20.6%) accounted for 66.6% of the total variance (Fig. 4). Factor 1 was dominated by Cd, Cr, and Pb. Factor 2 was heavily weighted by Cu and Zn. The sources of heavy metals in household dust could be identified according to the results of PCA combined with EF values. Previous studies have reported that Cd in indoor dusts mainly originated from outdoor dusts such as erosion and wear of building materials and tires, use or discarding of Cd-batteries, and application of fertilizer containing Cd (Saeedi et al. 2012; Wei et al. 2010; Yildirim and Tokalioğlu 2016). Considering that the mean EF value of Cd was > 5, anthropogenic emissions may be the main source of Cd in indoor dust. Previous studies have demonstrated that Pb may originate from colored paint (Chattopadhyay et al. 2003; Tong and Lam 2000), vehicle fuel combustion, and corrosion of automobile parts (Adamiec et al. 2016; Cai et al. 2019). Cr was usually regarded as an indicator metal of natural sources (da Silva et al. 2016; Esmaeili et al. 2014; Huang et al. 2018; Jiang et al. 2020, 2021; Lu et al. 2012; Wang et al. 2021). The mean EF values of Pb (1.56) and Cr (1.32) were close to 1, indicating that Pb and Cr might be from natural source (Han et al. 2006; Cheng et al. 2018). Hence, Factor 1 could be related to outdoor dusts and wall paint and considered as a mixture of human activities and natural sources. It is well known that Cu and Zn are common elements in motor vehicles (Charlesworth et al. 2003; Yuen et al. 2012) and fuel and gas leakage (Hassan 2012). As mentioned above, factor 2 was attributed to traffic sources.

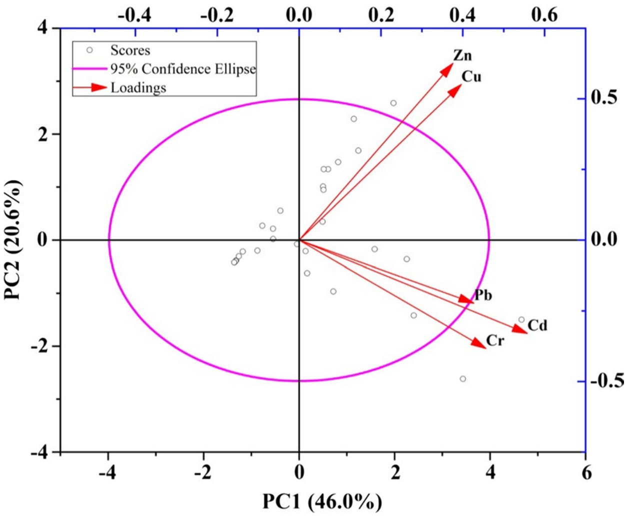

Fig. 4 Principal component analysis (PCA) results for the first two principal components loading

Health Risk Assessment

The results of DI and LDI of heavy metals in indoor dust samples are shown in Tables 1 and 2. Ingestion was the main pathway of exposure to heavy metals in indoor dust with dermal contact and inhalation serving as the second and third exposure pathway, which was consistent with the results of previous studies (Bao et al. 2019; Cheng et al. 2018; Jiang et al. 2021; Kurt-Karakus 2012). Considering that dust particles in large size are not readily resuspended, oral ingestion was confirmed to be the most important exposure pathway for human (Huang et al. 2014a; Wang et al. 2014). Moreover, the DI_{ing} values of heavy metals for adults were less than those for children, which could be explained by the fact that children are likely to rely more on hand-to-mouth contacts, such as eating with hands and finger sucking (Li et al. 2015; Wei et al. 2015). It is therefore necessary for children to wash their hands frequently to reduce health risk.

The HI and CR of heavy metals in indoor dust are shown in Fig. 5. The HI and CR values under the three exposure pathways for both adults and children were in the order of ingestion > dermal contact > inhalation. The risks of human health caused by heavy metals in indoor dust via ingestion were much greater than the other pathways. Pb was found to be the highest risk element for adults, followed by Cr, Cd, Zn, and Cu. Similarly, HIs caused by the studied

Table 1 Average daily intake (DI) to heavy metals in dust through three different exposure routes (mg (kg day)$^{-1}$)

DI	Cd	Cr	Cu	Pb	Zn
DI_{ing}					
Adults	6.11×10^{-6}	5.77×10^{-5}	4.09×10^{-5}	1.09×10^{-4}	3.98×10^{-4}
Children	4.36×10^{-5}	4.12×10^{-4}	2.92×10^{-4}	7.77×10^{-4}	2.84×10^{-3}
DI_{inh}					
Adults	6.71×10^{-10}	6.34×10^{-9}	4.49×10^{-9}	1.19×10^{-8}	4.37×10^{-8}
Children	1.24×10^{-9}	1.17×10^{-8}	8.29×10^{-9}	2.21×10^{-8}	8.08×10^{-8}
DI_{d}					
Adults	7.27×10^{-9}	6.87×10^{-8}	4.86×10^{-8}	1.30×10^{-7}	4.74×10^{-7}
Children	3.92×10^{-8}	3.71×10^{-7}	2.62×10^{-7}	6.99×10^{-7}	2.56×10^{-6}

Table 2 Lifetime average daily intake (LDI) of carcinogenic metal in dust through three different exposure routes (mg (kg day)$^{-1}$)

LDI	Cd	Cr
LDI_{ing}		
Adults	2.09×10^{-6}	1.98×10^{-5}
Children	3.74×10^{-6}	3.53×10^{-5}
LDI_{inh}		
Adults	2.30×10^{-10}	2.17×10^{-9}
Children	1.06×10^{-10}	1.00×10^{-9}
LDI_{d}		
Adults	2.49×10^{-9}	2.36×10^{-8}
Children	3.36×10^{-9}	3.18×10^{-8}

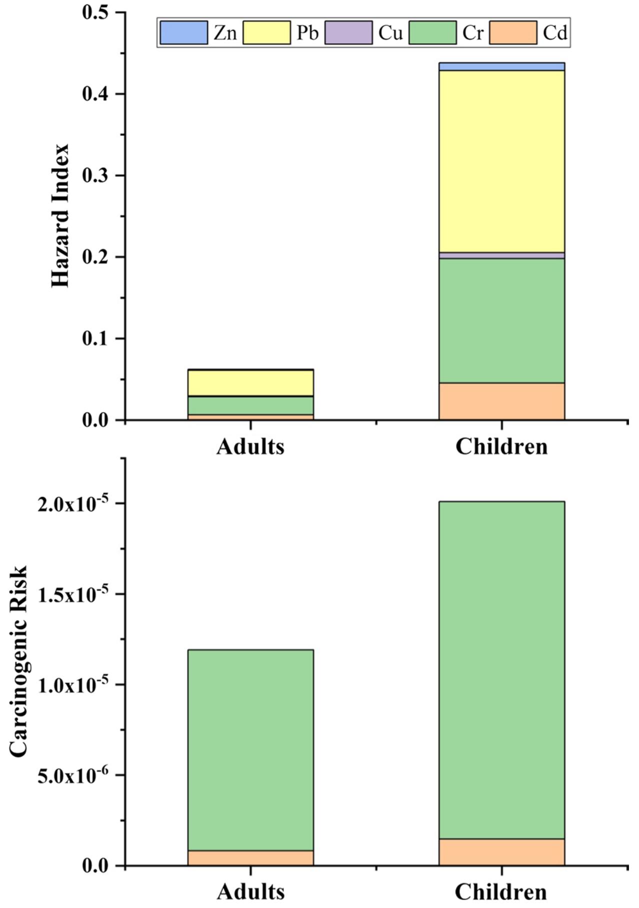

Fig. 5 Stacked column of hazard index and carcinogenic risk of heavy metals in dust samples

elements for children decreased in the following order: Pb > Cr > Zn > Cu > Cd. The contribution ratios of Pb to the sum of HI of all the selected heavy metals were 72.0% for adults and 86.9% for children, respectively. All HI values for both adults and children were less than 1, which was identified to be the critical value of noncarcinogenic effects (US EPA 2001), indicating that no significant noncarcinogenic effects would occur in residents. The HI value for children was approximately sevenfold higher than that for adults, suggesting that children have a higher risk from exposure to heavy metals in indoor dusts from 11 provinces of China.

In this study, Cd and Cr were selected to estimate the values of CR for adults and children. The carcinogenic risk value of Cr was approximately 13-fold higher than that of Cd for both adults and children. The carcinogenic risks for both adults and children ranging from 1×10^{-6} to 1×10^{-4} were established to be tolerable or acceptable carcinogenic risk ranges by US EPA (2001), indicating that the total carcinogenic risk for Cd and Cr was acceptable in 11 provinces of China. However, the total carcinogenic risk for children was 1.69-fold higher than that for adults, suggesting the carcinogenic risk exposure for children to heavy metals via indoor dust should not be ignored. Considering Cr and Pb mainly originated from natural sources with low EF values, these two metals in indoor dust from outdoor ground dust can pose a certain risk to human health.

Although both carcinogenic and non-carcinogenic risks caused by heavy metals in indoor dusts are acceptable for adults and children in 11 provinces of China, it is obvious that with increasing exposure frequencies and pathways, the health risks of heavy metals in indoor dust will increase. The maintaining of a clean indoor environment can help reduce the potential health risk.

Conclusions

The present study was conducted to investigate the occurrence of heavy metals in indoor dust from 11 provinces of China. Concentrations of heavy metals were in low or moderate level of major cities in the world. Wall cover, fuel, and air conditioning were three principal factors influencing the levels of heavy metals in indoor dust. Principal component analysis showed heavy metals in indoor dust were derived from outdoor dust, wall cover and traffic sources. Noncarcinogenic and carcinogenic risks of exposure to heavy metals were very low for adults and children in 11 provinces of China. This study provides new information on the occurrence of heavy metals in indoor dust from China and helps to implement risk assessment of heavy metals from various indoor environments.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00244-021-00849-9.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest related to this study.

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