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ORIGINAL PAPER

Heavy metals in paired samples of hair and nails in China: occurrence, sources and health risk assessment

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Abstract The occurrence of heavy metals including chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd) and lead (Pb) was investigated in paired samples of hair and nails collected from 121 volunteers in 16 cities, China. Results showed that the mean concentrations of Zn, Cu, As, Pb, Cr, Ni and Cd were 205, 18.0, 7.79, 6.18, 3.54, 2.02, 0.533 μg g^{-1} in hair and 103, 8.09, 0.760, 7.27, 6.07, 8.81, 0.485 μg g^{-1} in nails, respectively. The concentrations of Zn, Ni, Cr, Cd and Pb were positively correlated in paired samples of hair and nails, whereas a negative correlation was found for Cu and As between hair and nails. Higher concentrations of heavy metals were found in northern China than southern China. The multivariate analysis of variance revealed that dwelling environment was the dominant factor influencing the levels of Cd in hair ($p < 0.05$), while age was the dominant factor influencing the levels of Cr in nails ($p < 0.05$). Moreover, industrial pollution and smoking were also the important factors leading to the accumulation of heavy metals in human body. Principal component analysis (PCA) showed that industrial pollution and decoration material immersion were the main factors for the high concentrations of Cr and Ni in hair, accounting for 62.9% of the total variation; As in hair was dominantly related to groundwater pollution. The concentrations of heavy metals were within the recommended ranges in nails from this study. However, the mean levels of Cr, Ni and As in hair exceeded their recommended reference values, indicating potential health risks from heavy metals for residents in China.

Keywords Heavy metals · Hair · Nails · Source apportionment · Risk assessment

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Introduction

Heavy metals are a kind of inorganic contaminants that are widely found in various environments. In recent years, with the gradual acceleration of industrial development and urbanization, heavy metals generated by human activities have caused serious environmental pollution (Abdullah et al., 2015; Malik et al., 2010). Organisms can enrich metals, some of which could be converted into more toxic organometallic compounds. Metals can enter human body through inhalation, ingestion and dermal contact, causing certain harm to human health, which is closely related to the occurrence of carcinogenic, teratogenic and mutagenic diseases (Chen et al., 2022; Cui et al., 2022; Peng et al., 2022).

It is reported that higher concentrations of copper (Cu), arsenic (As), cadmium (Cd) and lower concentrations of zinc (Zn) in the maternal hair are positively correlated with the risk of fetal congenital heart disease (Hu et al., 2014; Jin et al., 2016). Lead (Pb) has a half-life period of 4 years in the human body, which is particularly destructive to children's nervous system, kidney, circulation and reproductive system (Needleman, 2009). Cd has a half-life period of 6.2 to 18 years, which is neurotoxic and nephrotoxic to the human body (Thomas et al., 2009). It is reported that chromium (Cr) can promote the occurrence of diabetic complications (Zhou et al., 2019). Inorganic As is easily absorbed by the human body in the gastrointestinal tract with an absorption rate of up to 95% (Agency for Toxic Substances & Disease Registry, 2007). Cu and Zn are essential elements in the human body; however, excessive levels of Cu and Zn can still lead to human diseases (Pan & Li, 2015). Similarly, low concentration of nickel (Ni) will contribute to maintain human physiological function; however, high doses of Ni intake can lead to chronic bronchitis and allergic reactions (Agency for Toxic Substances & Disease Registry, 2005).

To study the exposure of metals to human body, a large number of studies have been conducted to explore the reliable biological indicators that represent the overall levels of elements in human body (Pan & Li, 2015; Zheng et al., 2021). The biological indicators are widely used to study the exposure of heavy metals to humans include hair, blood, urine, nails, teeth and breast milk (Dursun et al., 2016; Kuang et al., 2020; Mehra & Juneja, 2005; Qin et al., 2021; Salvatore et al., 2019; Sani & Abdullahi, 2017). Recent studies indicate hair and nails are frequently employed to analyze the levels of heavy metals in human body (Salcedo-Bellido et al., 2021; Waseem & Arshad, 2016; Zheng et al., 2021). Compared to other bioindicators, hair and nails are cheaper and easier to collect, transport and store. The levels of heavy metals in hair and nails can reflect the exposure information of human body for a long time (Samanta et al., 2004).

There are many factors influencing the concentrations of metals in human hair and nails, such as age, gender, time and pathway of exposure, occupation and life style (Fiłon et al., 2020; Hernández-Pellón & Fernández-Olmo, 2019; Kempson & Lombi, 2011; Lotah et al., 2021; Zheng et al., 2021). Previous studies evaluated the contents of trace metals in scalp hair of patients with gastric cancer and healthy people to measure the possible relationship between them, revealing that the contents of most metals were significantly influenced by gender, life and eating habits (Afzal et al., 2019; Janbabai et al., 2017). Zheng et al. (2021) determined 6 heavy metals in the hair of 1202 metropolitan residents from mainland China and found that gender was an important factor influencing the levels of elements. Sukumar and Subramanian (2007) suggested that occupation (farmer and rural businessman) and life style (smoking and non-smoking) were the main influencing factors on the levels of elements in paired hair and fingernails from New Delhi. Lotah et al. (2021) found that significantly higher levels of manganese (Mn) in smoker's hair than non-smoker's hair, and people exposed to second-hand smoke had significantly higher levels of Cd in their hair and Ni in their nails. Markiv et al. (2022) found that there were significant differences in contents of metals in hair of different genders in the vicinity of ferromanganese alloy factories, showing higher concentrations of Mn, Cu, Zn, Cd and Pb in female hair. Ilyas et al. (2015) found that the levels of Cd and Pb in nails of smokers were significantly higher than those of the non-smokers, suggesting that smoking habits had a significant impact on the levels of Cd and Pb in nails.

Recent studies have focused on concentrations of heavy metals in hair or nails from the residents in big cities (Qin et al., 2021) or regions with high endemic diseases (Zhang et al., 2018), rich in minerals (Adewumi et al., 2019; Wei et al., 2013), or polluted by waste recycling (Wang et al., 2009; Zheng et al., 2011). However, few studies investigated the occurrence of heavy metals in paired samples of hair and nails of residents from small cities and rural areas. Hair and nails have similar chemical components because they are appendages of skin (Samanta et al., 2004). However, few studies reported the correlation of heavy metals between hair and nail. Hence, it is of great significance to investigate the contents of heavy metals in paired samples of hair and nails from these areas in China and explore the correlations between heavy metals in hair and nails.

This study aims to investigate the levels and spatial distribution of heavy metals including Cu, Zn, Cd, Pb, Cr, Ni and As in hair and nails of residents from small cities and rural areas of China; to identify the correlations of heavy metals in paired samples of hair and nails; to explore the main influencing factors on levels of heavy metals in hair and nails; and to assess nutritional and bodily status of heavy metals.

Materials and method

Sample collection and preparation

121 paired samples of scalp hair and fingernails were collected from 16 cities or rural areas in 8 provinces of China in August 2020. These cities or rural areas are distributed in Northeast China (Changchun and Siping), North China (Cangzhou and Baotou), Central China (Zhengzhou and Puyang), East China (Yantai, Laoling, Zouping, Taizhou, Huzhou, Lu'an and Chuzhou) and Southwest China (Chengdu, Nanchong and Ya'an) (Fig. 1). Given the economically developed and densely populated East China, more sampling sites were selected than other sampling regions. Of all the paired samples, there were 48 males and 73 females. The ages of the volunteers ranged from 15 to 75 (age of 15–35, $n=61$; age of 36–56, $n=45$; age of >56, $n=15$). All the volunteers were in good health with no known infectious diseases or obvious occupational exposures. Table S1 lists the detailed information on all the volunteers.

Before sampling, each volunteer was assured of living locally for more than three years and was offered an informed consent. Meanwhile, each volunteer was required to complete a questionnaire including age, gender, geographical information and dwelling environment to assess the factors influencing the concentrations of heavy metals in hair and nails. Each hair sample was not dyed and scalded within a month before sampling. Each nail sample was not used with nail care products for one month prior to the sampling.

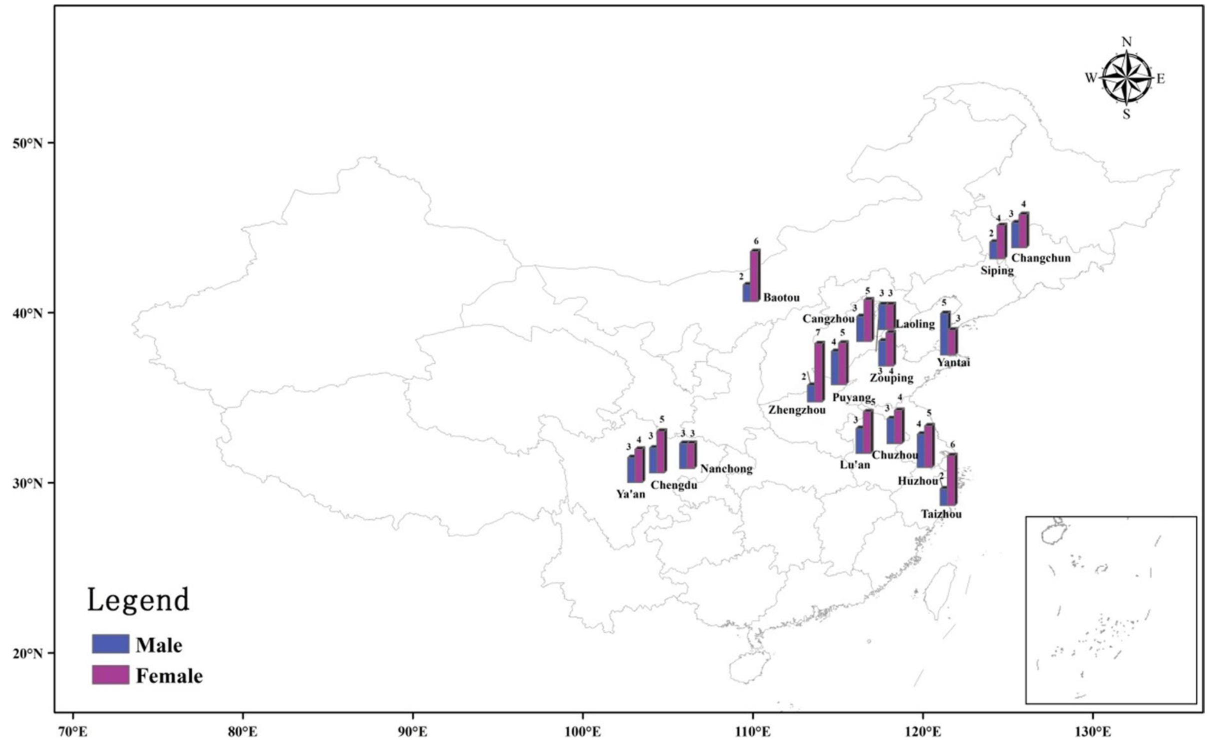

Fig. 1 Sampling sites and quantity regional distribution

The newly grown hair behind the ear (about 2 cm) and fingernails were cut off using a disinfected stainless steel scissor, sealed in a polyethylene bag, and then transported back to the laboratory. The hair and nails samples were first washed with acetone, then washed with ultrapure water for three times and then rinsed with acetone again to remove grease and dust (Zheng et al., 2021). The treated hair and nail samples were placed in an oven at 60 °C to constant weight and stored in clean polyethylene bags.

Sample digestion and analysis

The procedures for digestion were based on the methodologies described in detail previously (Zheng et al., 2011). Briefly, exactly 0.1 g of hair sample or 0.5 g of nail sample were added into polytetrafluoroethylene (PTFE) microwave digestion containers with 4 mL of 65% HNO_3 and 2 mL 30% H_2O_2 (guaranteed reagent grade, Nanjing Chemical Reagent Co. Ltd., China). The samples of hair and nails were digested by a microwave digestion system (APL MD6M model, Chengdu, China). The digestion program is shown as follows: start at room temperature, ramp to 120 °C within 15 min and maintain for 20 min, ramp to 190 °C within 10 min and hold for 40 min. After digestion, the digest was cooled to room temperature and diluted to 25 mL with deionized water. The solution was filtered using a 10 mL of disposable sterile syringe (Jiangsu Changcheng Medical Instrument Co., Ltd., China) with a 0.45 μm of filter membrane. The concentrations of Cr, Ni, Cu, Zn, As, Cd, Pb in the filtrate were analyzed using an inductively coupled plasma mass spectrometry (ICP-MS) (Perkin Elmer, 350D, USA). The measurement conditions and related parameters of the instrument are shown in Table S2.

Quality control and quality assurance

To ensure the accuracy of analysis, the certified reference materials (CRMs) (GBW07601) were used as the quality control samples that were purchased from National Center for Standard Substances of China (Beijing, China). The target metals were determined with the recoveries of the CRMs ranging from 83 to 96%. An instrumental blank was simultaneously analyzed with a batch of 5 hair and nail samples. The target metals were not detected or detected in negligible concentration in the instrumental blanks. Ge74 was selected as the internal standard in the determination of Cu, Zn, Ni, Cr; Bi209 and Y89 were identified as the internal standard in the measurement of Pb and As, respectively. Cd was analyzed using In115 as internal standard. The limit of detection (LOD) and limit of quantification (LOQ) were determined with a signal-to-noise ratio of 3 and 10 at the lowest concentration of the calibration curve. Table S3 lists LODs, LOQs and recoveries for all the target metals.

Statistical analysis

Kolmogorov–Smirnov test was used to determine whether the data conform to the normal distribution. Multivariate analysis of variance (MNOVA) was employed using the software IBM SPSS 20.0 to explore the factors influencing the contents of metals in hair and nails. Principal component analysis (PCA) was conducted using Origin 2018 software packages to identify the sources of heavy metals.

Results and discussion

Concentrations and spatial distribution of heavy metals

The descriptive statistics analysis of concentrations of Cr, Ni, Cu, Zn, As, Cd and Pb in hair and nails are shown in Fig. S1. The average concentrations of heavy metals (μg g^{-1}) in hair decreased in the order of Zn (205 ± 101) > Cu (18.0 ± 5.91) > As (7.79 ± 8.15) > Pb (6.18 ± 4.86) > Cr (3.54 ± 5.70) > Ni (2.02 ± 1.95) > Cd (0.533 ± 0.545). The average concentrations of heavy metals (μg g^{-1}) in nails decreased in the order of Zn (103 ± 23.5) > Ni (8.81 ± 7.65) > Cu (8.09 ± 2.55) > Pb (7.27 ± 4.53) > Cr (6.07 ± 4.32) > As (0.760 ± 0.580) > Cd (0.485 ± 0.280).

As shown in Fig. 2, the average concentrations of heavy metals varied greatly in different regions. Relatively higher concentrations of heavy metals in hair and nails were found in northern provinces (Jilin, Hebei, Shandong, Henan and Inner Mongolia) than those in southern provinces (Anhui, Sichuan, Zhejiang), which are consistent with the spatial distribution of heavy metals in indoor dust and soil (Liu et al., 2021a, 2021b). Previous studies indicated that

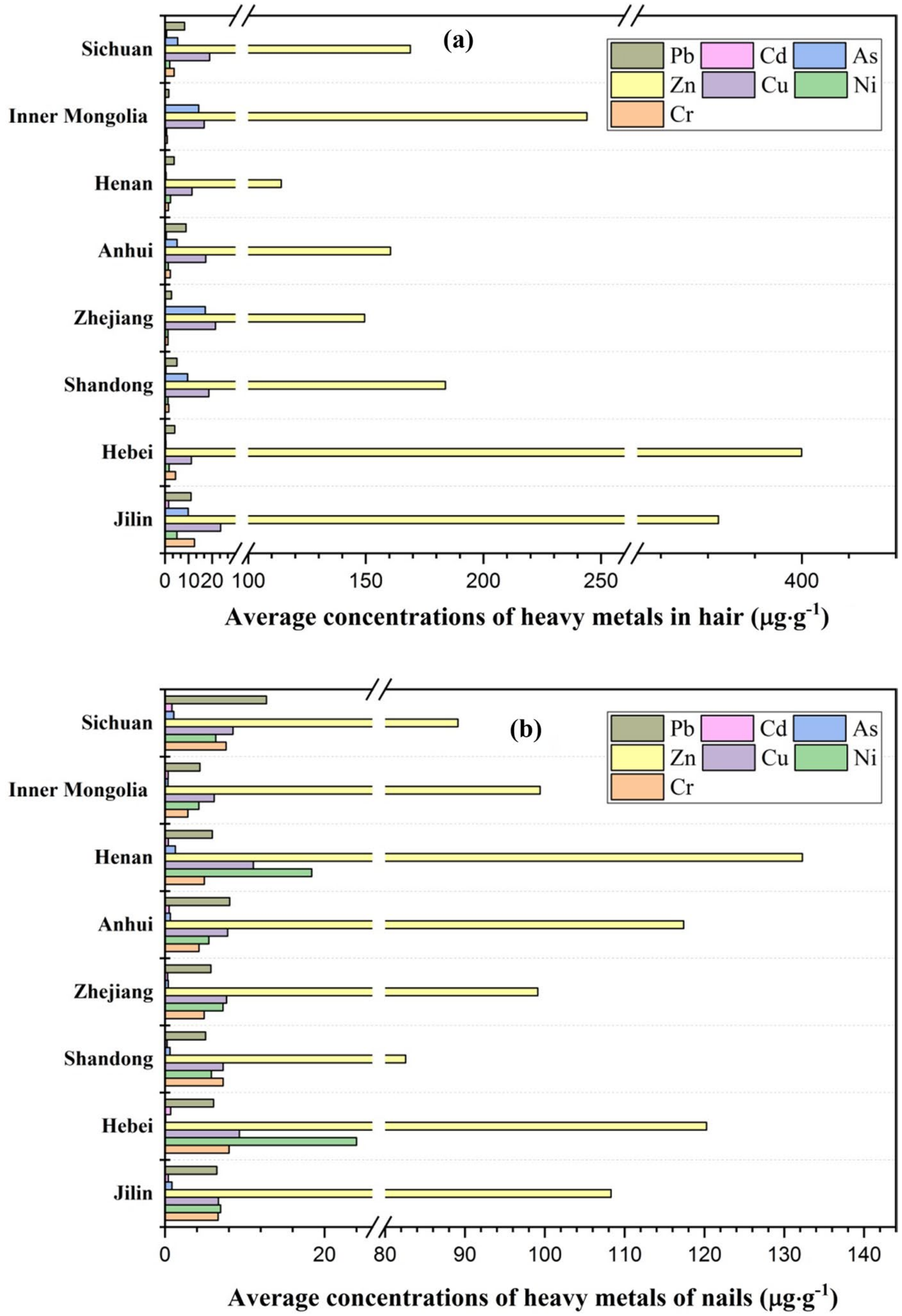

Fig. 2 Spatial distribution of heavy metals in hair (**a**) and nails (**b**) from China

air pollution in northern China was more serious than in the south, which was related to the local vehicle exhaust and industrial emissions (Sun et al., 2019; Zhu et al., 2018). The average concentrations (μg g^{-1}) of Cr (12.5), Ni (5.10), Cu (23.6), Cd (1.54) and Pb (11.1) in hair from Jilin Province are higher than those from the other provinces, indicating that the residents in Jilin Province may be influenced by the airborne PM from coal emission during the heating period (Liu et al., 2021c). Previous studies reported that coal and biomass combustion contributed a lot to atmospheric particulate matter pollution in winter (Ai et al., 2021; Liu et al., 2021c). Jilin Province is located in Northeast China where coal and biomass are usually used for cooking and heating. The heavy metals in $PM_{2.5}$ and PM_{10} generated by combustion are more likely to accumulate in human tissues (Hsu et al., 2019; Li et al., 2021).

A comparison between the levels of heavy metals in this study and those in other studies is summarized in Table 1. The concentrations of Cu and Zn were comparable with those in other regions. The concentrations of As in hair are about 1–2 orders of magnitude higher than those in other studies. Previous studies showed that As was extremely abundant in the alluvial layers that make up the main groundwater aquifers in more than 70 countries, leading to high concentrations of As in hair of the residents (Goswami et al., 2014; Gunduz et al., 2016; Rasool et al., 2016; Rehman et al., 2019; Winkel et al., 2008). As-contaminated groundwater is used to drink, cook, wash clothes and hair, leading to the accumulation of As in human hair (Ferreccio et al., 2000; Islam et al., 2012; Sharma et al., 2014; Wongsasuluk et al., 2018). Previous studies showed that high concentrations of As were found in the groundwater aquifers in some

Table 1 Concentrations of heavy metals in this study compared with those in other areas (μg g^{-1})

	Study region	Cr	Ni	Cu	Zn	As	Cd	Pb	References
Hair	16 cities in China	3.54 ± 5.70	2.02 ± 1.95	18.0 ± 5.91	205 ± 101	7.79 ± 8.15	0.533 ± 0.545	6.18 ± 4.86	This study
	Taizhou, China	/	1.09	39.8	/	/	0.518	49.5	Wang et al. (2009)
	West Bengal, India	/	1.59	14.8	152	/	0.400	8.03	Samanta et al. (2004)
	New Delhi, India	1.80 ± 0.300	3.80 ± 0.500	37.5 ± 3.00	146 ± 11.0	/	0.500 ± 0.0600	9.20 ± 2.00	Sukumar and Subramanian (2007)
	Pakistan	2.22 ± 1.74		12.5 ± 5.24	260 ± 153	/	0.860 ± 0.600	10.3 ± 7.01	Ilyas et al. (2015)
	Copperbelt, Zambian	1.20 ± 0.210	1.30 ± 0.230	38.0 ± 6.90	137 ± 21.1	/	0.300 ± 0.0200	4.30 ± 1.95	Nakaona et al. (2020)
	Northern, Sweden	0.167 ± 0.118	0.430 ± 0.400	25.0 ± 21.0	142 ± 29.0	0.0850 ± 0.0540	0.0580 ± 0.0560	0.960 ± 0.850	Rodushkin and Axelsson (2000)
	South-west, Poland	0.568 ± 1.04	0.838 ± 1.13	12.4 ± 12.1	156 ± 74.5	0.0440 ± 0.110	0.114 ± 0.140	1.05 ± 1.39	Chojnacka et al. (2005)
	Autonomous Community of Madrid, Spain	/	0.0350	12.5	161	/	0.0300	0.273	González-Muñoz et al. (2008)
Nail	16 cities in China	6.07 ± 4.32	8.81 ± 7.65	8.09 ± 2.55	103 ± 23.5	0.760 ± 0.580	0.485 ± 0.280	7.27 ± 4.53	This study
	New Delhi, India	1.20 ± 0.200	4.80 ± 1.00	50.5 ± 7.00	176 ± 16.0	/	1.10 ± 0.300	15.3 ± 2.50	Sukumar and Subramanian (2007)
	Dizajabaad, Zanjan province, Iran	/	18.2	/	68.5	15.5	1.18	7.27	Parizanganeh et al. (2014)
	Pakistan	10.5 ± 7.74	/	12.0 ± 7.75	141 ± 59.8	/	8.00 ± 5.35	39.6 ± 31.9	Ilyas et al. (2015)
	Copperbelt, Zambian	0.600 ± 0.0800	1.70 ± 0.140	29.6 ± 4.80	172 ± 27.4	/	0.100 ± 0.00200	4.80 ± 0.530	Nakaona et al. (2020)

"/" means that data are not available

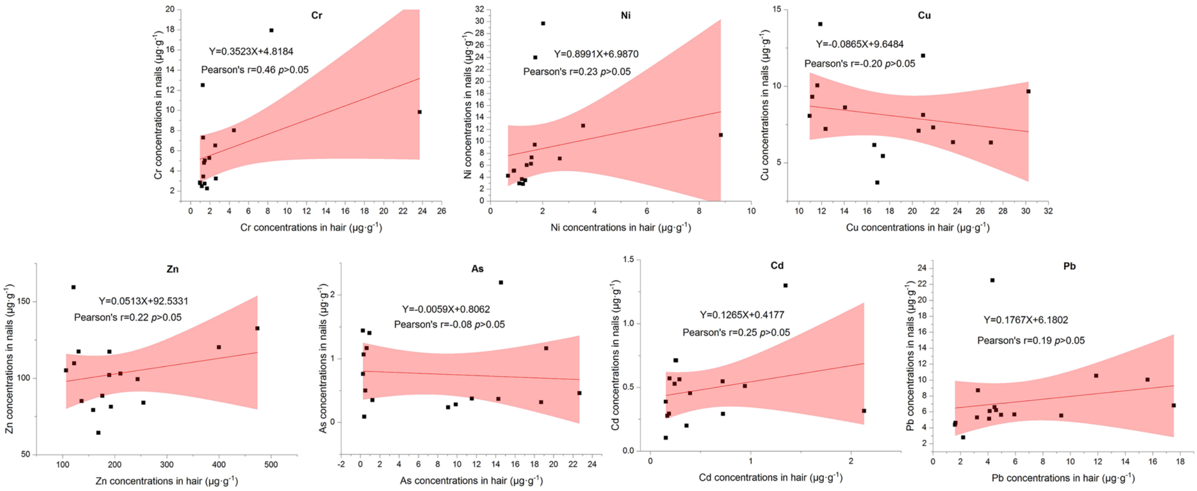

Fig. 3 Correlations between concentrations of heavy metals in paired samples of hair and nails

rural areas of China (Qiao et al., 2019; Wang & Li, 2022). Chen et al. (2021) reported high levels of As in groundwater in the Songnen Plain of Jilin Province. Hence, the high concentrations of As in this study may be related to local groundwater pollution. The concentrations of Ni, Cr and Cd observed in this study were comparable to some Asian and African cities (Ilyas et al., 2015; Nakaona et al., 2020; Samanta et al., 2004; Sukumar & Subramanian, 2007). However, the levels of Ni, Cr and Cd in hair in Asian residents were two orders of magnitude higher than those in Europe (Chojnacka et al., 2005; González-Muñoz et al., 2008; Rodushkin & Axelsson, 2000), indicating that the concentration of Ni, Cr and Cd in hair was greatly influenced by environmental exposure. Similarly, the levels of Pb in hair of residents from Asian countries were approximately one order of magnitude higher than those from Europe. Wang et al. (2009) found that the levels of Pb in hair of electronic waste recycling area residents were significantly higher than those in nonoccupationally exposed residents, indicating that the levels of Pb in hair were significantly influenced by occupational exposures.

In this study, the mean concentrations of all heavy metals except Zn in nails were lower than those in Dizajabaad, Iran, near a mining area (Parizanganeh et al., 2014). The concentrations of Cu, Zn, Cd and Pb in nails from this study were lower than those from New Delhi, whereas the concentrations of Cr and Ni were higher than those from New Delhi (Sukumar & Subramanian, 2007). This is mainly due to the differences in ages and living environments of the volunteers (Bai et al., 2020).

Hair and nails are considered to accumulate trace elements in a similar way due to their similar chemical compositions (Samanta et al., 2004). In this study, the concentrations of Zn, Cu and As in hair were significantly higher than those in nails ($p < 0.05$), while the concentrations of Cr and Ni in hair were lower than those in nails ($p < 0.05$). No significant difference was found in concentrations of Pb and Cd in hair and nails. This is mainly due to the different nutritional status and environmental factors of the volunteers, leading to the large difference in the concentrations of elements in the nail and hair samples (Samanta et al., 2004).

In view of the marked similarity in composition between hair and nails, the correlations between the contents of metals in hair and nails would be expected. Figure 3 shows the relationships between the contents of heavy metals in paired samples of hair and nails. There were no statistically significant correlations ($p > 0.05$) in the contents of heavy metals. Previous study elucidated that the concentrations of toxic elements were positively correlated in hair and nails (Vance et al., 1988). In this study, it was observed that the positive correlations in the levels of Cr, Ni, Cd and Pb in hair and nails, which was consist with the conclusion by Sukumar and Subramanian (2007). Besides, Zn was also found to be positively correlated between hair and nails in this study. Conversely, there was a negative correlation between Cu and As contents in hair and nails, suggesting that Cu and As are more likely to be concentrated in hair than nails (Adewumi et al., 2019; Hashim et al., 2013; Rujiralai et al., 2018). Harland et al. (2022) indicated that cysteine residues promoted the stabilization of keratin in mammalian hair and intermolecular sulfhydryl bonds maintained elasticity in hair. Cu and As have a strong affinity with sulfhydryl bonds, leading to high concentrations of Cu and As in hair (Zeng & Zhang, 2020).

Influencing factors on the levels of heavy metals

The distribution of heavy metals in hair and nails stratified by age and sex is shown in Fig. 4. The concentrations of Cr in nails were significantly influenced by age ($p < 0.05$) (Table S4). High levels of Cr (15.2) in nails were found in volunteers over 56 years old. Moreover, the mean concentrations (μg g^{-1}) of Ni (9.32), Cu (9.15), Cd (0.748) and Pb (7.57) in nails in > 56 years group were higher than those of Ni (7.76), Cu (7.68), Cd (0.457) and Pb (6.27) in 15–35 years group. However, the concentrations of heavy metals in hair were not affected by age in this study ($p > 0.05$) (Table S5). Previous studies reported that the half-life of metals, body's metabolic capacity, diet and geographical environment were important contributors to heavy metals in hair and nails (Cao et al., 2010; González-Muñoz et al., 2008; Pereira et al., 2004). Thus, the decline in physical function and long-term accumulation in older people may be the main reason for the high concentrations of heavy metals in nails.

Previous studies have reported that gender was an important factor influencing the concentrations of heavy metals in hair and nails (Qin et al., 2021; Zheng et al., 2021; Zhu et al., 2018). However, no significant differences in the concentrations of heavy metals in hair and nails were found in volunteers of different genders in this study (Tables S6 and S7). Previous studies indicated that living habits and occupations of urban and rural people may be the factors affecting the contents of heavy metals in hair and nails (Li et al., 2012; Qin et al., 2021). This study found no significant differences in levels of heavy metals in hair and nails of volunteers from urban and rural areas (Tables S8 and S9).

In China, most of the village houses and public rental houses have a long living age and are simply decorated, while private buildings are mostly built in recent years and beautifully decorated (Qin et al., 2021). The dwelling environment may have an impact on trace elements in the human body. Chen et al. (2012) found that heavy metals entered the body by touching decoration materials and placing hands in the mouth and nose. The decorative materials of walls and floors were painted by coating containing Pb, Cr and Ni (Duarte et al., 2010). The present study found that the dwelling environment had a significant impact on the contents of Cd in hair ($p < 0.05$, Table S10), which was consistent with the conclusion from the previous study (Qin et al., 2021). This study found significantly higher levels of Pb, Cr and Cd in hair of the residents from private houses than those from public rental houses or village houses. However, no significant differences were found in the concentrations of heavy metals in nails ($p > 0.05$, Table S11).

Table S1 summarizes the information influencing the concentrations of heavy metals in volunteers, including GDP, PM_{10}, $PM_{2.5}$, vehicle ownership, and industrial pollution. Previous study showed that concentrations of heavy metals in the environment were highly correlated with atmospheric particulate matter, smelting industry, transportation and vehicle ownership (Malik et al., 2010). The concentrations of heavy metals in atmospheric particulate matter were significantly related to human health by respiration and inhalation (Chen et al., 2017). The present study found that PM_{10} was an important factor influencing the concentrations of As and Pb in nails ($p < 0.05$, Table S12). However, PM_{10} was not the main factor influencing the levels of heavy metals in hair ($p > 0.05$, Table S13). Similarly, $PM_{2.5}$, GDP, vehicle ownership and industrial pollution were not the main factors influencing the concentrations of heavy metals in hair and nails ($p > 0.05$, Tables S14–S21). Nevertheless, the mean concentrations of Cr, Ni, Cu, Zn, Cd and Pb in hair exposed to industrial areas were higher than those in non-industrial areas (Table S22), indicating that industrial pollution played an important role in accumulation of metals in human body.

Previous study showed that smoking was an important factor influencing the levels of heavy metals in hair and nails (Sukumar & Subramanian, 2007). In this study, no significant differences were found in the concentrations of heavy metals in paired samples of

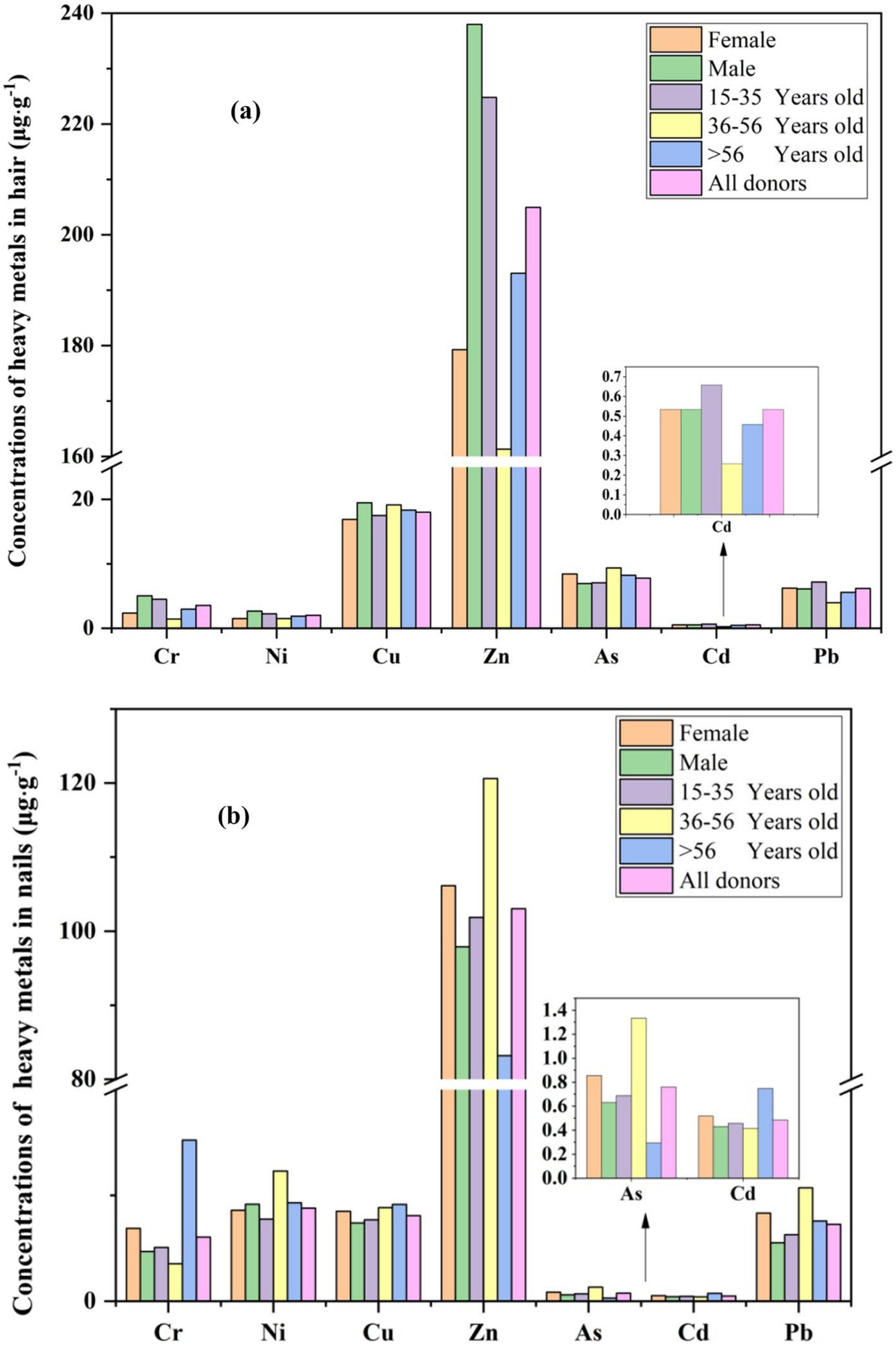

Fig. 4 Mean concentrations of heavy metals in hair (**a**) and nails (**b**) stratified by ages and genders

hair and nails ($p > 0.05$) (Tables S23 and S24). However, the mean concentrations of all the selected metals in hair samples from smoking people were higher than those from non-smoking people (Table S25). The mean concentration of Cr in the hair of smokers was about three times as high as that of non-smokers. The mean concentrations of Ni and Pb in the hair of smokers were about twice as high as those of non-smokers. In addition, the average concentrations of Cr, Cu, Zn and Cd in the nails of smokers were higher than those in non-smokers (Table S25). Generally, smoking as an important factor had a much greater impact on contents of heavy metals in hair than nails.

Source apportionment of heavy metals

PCA was performed to identify the most possible sources of heavy metals in hair and nails. Results showed that the primary three factors (62.9%, 18.7% and 10.8%) accounted for 92.4% of the total variances in hair (Fig. 5). Factor 1 was dominated by Cr, Ni and Cd; factor 2 was dominated by As; factor 3 was dominated by Zn. A comparison was conducted between the mean concentrations of heavy metals and their corresponding recommended values (Table S26). The mean concentrations of Cr and Ni in hair were about one order of magnitude higher than their recommended values. Some studies showed that respiration was the main route for the human body to ingest Ni, which was mainly derived from the emissions from smelting industry and automobile (Chen et al., 2017; Huang et al., 2018; Liu et al., 2021c; Sun et al., 2009; Valko et al., 2006). Cr may be originated from decoration and dust pollution (Chen et al., 2012; Cheng et al., 2018). Hence, factor 1 could be considered as a mixture of human activity sources that related to industrial pollution emission and decoration material immersion. The average concentration of As in this study was about 50 times higher than the recommended value, indicating that As in hair was primarily derived from the exposure to environmental pollution. Therefore, factor 2 was attributed to the exposure to groundwater pollution. It is well known that Zn is an essential trace element in human body (Cai et al., 2005; Dlugaszek, 2019; Kumakli et al., 2017), which was within the recommended ranges. Hence, factor 3 could be considered as natural sources in hair.

Considering that the value of Kaiser–Meyer–Olkin (KMO) was 0.473, the concentrations of heavy metals in nails were not suitable for PCA. The concentrations of all the investigated heavy metals in nails were lower than the recommended values (Table S26). Therefore, the sources of heavy metals in nails were possibly normal dietary intakes. The accumulation characteristics of metals may be the main reason for relatively low concentrations of metals in fingernails.

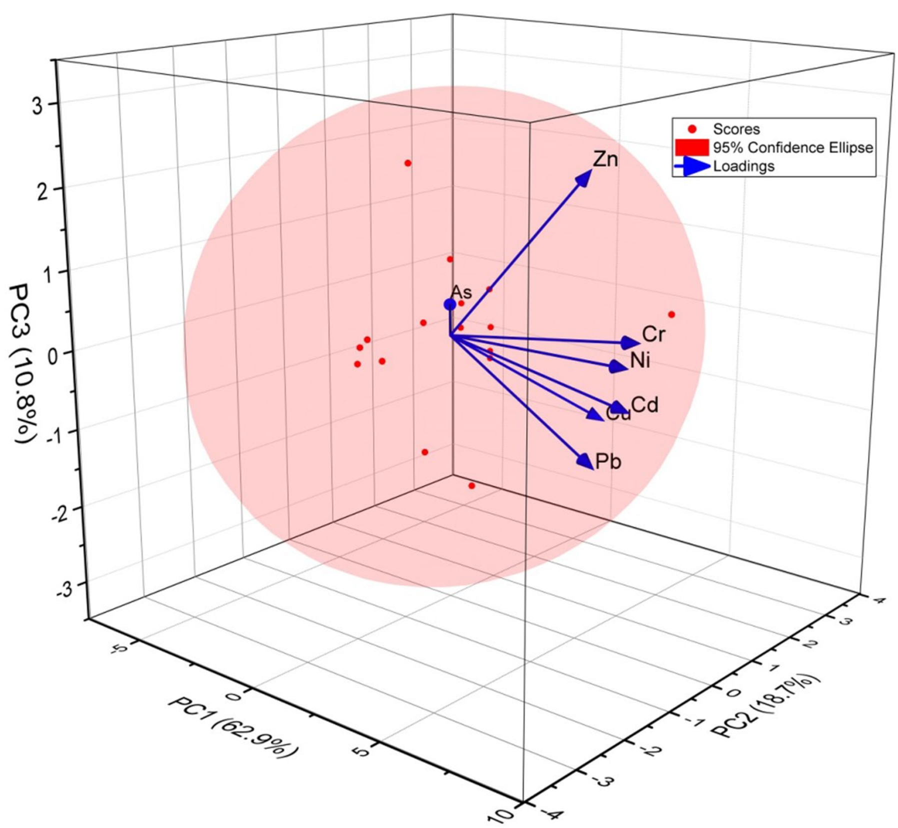

Fig. 5 Principal component analysis (PCA) results for the first three principal components loading in hair

Health risk assessment

The contents of Cu, Zn and Pb in hair and nails are within the recommended ranges. Cu and Zn are essential elements for maintaining human health and involved in all aspects of human life. Pb is a toxic metal for human body. Lin et al. (2021) indicated that early Pb exposure was related to a variety of neurodegenerative diseases. Moreover, the mean concentrations of Cr, Ni, As and Cd in nails are lower than their reference values.

However, high concentrations of Cr, Ni and As were found in hair in this study. Cr, Ni and As are common carcinogens. The mean concentrations of Cr, Ni and As were about 12, 3 and 52 times higher than their reference values, respectively. Cr(VI) and Cr(V) can be produced from Fenton reaction and destroy DNA structure through catalytic decomposition, resulting in carcinogenesis and mutagenesis (Kasprzak, 2002; Zhitkovich, 2005). Valko et al (2006) proposed that Ni might alter gene expression, interfere with DNA repair processes and lead to the occurrence of tumors. Studies showed that As might lead to skin, bladder, kidney, lung and vascular-related diseases by inhibiting the activity of various enzymes and causing DNA mutations through external triggers (Chakraborti et al., 2002; Waalkes et al., 2004). As mentioned above, long-term exposure to environmental pollution caused that the concentrations of Cr, Ni and As in hair of volunteers significantly exceeded the standards, suggesting that residents may be at potential risks of cancer from these metals.

Limitation of this study

In this study, one limitation is the insufficient quantity of paired samples of hair and nails. The sampling area does not involve Northwest and South China. The other limitation is relatively simple information in the questionnaire for volunteers. For example, it only includes smoking habits, without information on smoking frequency and types of cigarettes. Residential housing types are only roughly divided into three types, however, detailed information on the decoration materials and history is not available. Therefore, further studies should be conducted to understand the contents and correlations between heavy metals in human hair and nails.

Conclusions

The present study was conducted to investigate the levels and distribution of heavy metals in paired samples of hair and nails from 16 cities in China. High concentrations of heavy metals were observed in hair compared with other studies. Zn and a few toxic metals including Cr, Cd, Ni and Pb were positively correlated in paired samples of hair and nails, while Cu and As were found to be negatively correlated between hair and nails. Dwelling environment was the main factor influencing the level of Cd in hair. Concentrations of As and Pb in nails were significantly influenced by PM_{10}. The accumulation of Cr in nails was positively related with the age of volunteers. In addition, smoking was an important factor influencing the heavy metals in hair of the volunteers. Health risk assessment showed that the contents of Cr, Ni and As in hair significantly exceeded their reference values, indicating the absence of carcinogenic risks. This study provides new information on the occurrence of heavy metals in hair and nails from residents in China.

Author's contribution LL and BL wrote the manuscript; they took an active part in experimental research. YY and WD checked the manuscript and made statistical adjustments. LG and YH determined the elements.

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Data availability All data generated or analyzed during this study are included in this published article and its Supplementary Information file.

Declarations

Conflict of interest The authors declare no conflict of interests.

Ethics approval and consent to participate The ethical approval was obtained from the Institutional Ethics Committee of Changchun Normal University (China) to the commencement of the study. All authors confirm ethical responsibilities. The preliminary content of this study strictly follows the *Helsinki Manifesto* and the *International Ethical Guidelines for Biomedical Research Involving Humans*. The informed consent has been strictly acquired during the implementation of this study.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participants signed informed consent regarding publishing their data.

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