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Spatial distribution, pollution level, and health risk of Pb in the finer dust of residential areas: a case study of Xi'an, northwest China

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Abstract The spatial distribution, pollution level, and exposure risk of Pb in the finer dust (particle size < 63 μm) of residential areas in Xi'an, northwest China were investigated in this study. Geographical information systems and geodetector methods were used to analyze the spatial variability of Pb content in the finer dust of Xi'an and its forming mechanism. The enrichment factor was used to assess the extent of Pb pollution, and the hazard index was used to evaluate the health risks to children and adults exposed to Pb. The results showed that the average content of Pb in the finer dust of residential areas in Xi'an was 99.9 mg kg^{-1}. In the Xi'an urban area, a higher Pb content was mainly found in the finer dust near the Second Ring Road of Xi'an City, and the Pb content in the old town of Xi'an City was relatively lower than that near the Second Ring Road. The results of geodetector analysis indicate that the spatial variability of Pb in the finer dust of the Xi'an urban area was primarily controlled by the interaction among vehicle emissions, daily behavior of residents, and industrial emissions. Pb in the finer dust from residential areas in all districts showed moderate enrichment. The non-cancer risks of Pb in the finer dust were within the safe range for both children and adults. However, the prolonged exposure risk of Pb in the finer dust of residential areas should be considered for children.

Keywords Residential area · Dust · Pb · Spatial distribution · Geodetector · Health risk

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Introduction

Dust pollution in urban areas is ubiquitous and affects human health. Dust usually receives heavy metals from various human sources (Han et al., 2020; Lu et al., 2014a,b). Owing to the toxicity and non-biodegradability of heavy metals, as well as the suspensibility and easy mobility of dust, the pollution, risk, and sources of heavy metals in urban dust have been investigated in numerous cities worldwide in recent decades (Bourliva et al., 2016; Guven, 2019; Kolakkandi et al., 2020; Lu et al., 2014a; Rehman et al., 2020; Wahab et al., 2020). The results indicate that urban dust generally has elevated levels of heavy metal contents, such as Pb, Cd, Cr, Hg, Cu, and Zn,

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owing to the influence of anthropogenic activities (Guven, 2019; Han & Lu, 2017; Kolakkandi et al., 2020; Lu et al., 2014a; Rehman et al., 2020; Wahab et al., 2020; Zhao et al., 2016; Zhou et al., 2015). Among heavy metals, Pb has become the primary focus as it can damage the nervous system, hematopoietic system, digestive system, kidney, and genital system (Pan et al., 2018). Several studies on heavy metal pollution and risk have shown that Pb pollution in urban dust is very common (Evans et al., 1992; Lu et al., 2017a,b; Pan et al., 2018), and elevated Pb content in urban dust is principally caused by vehicle emissions (Cui et al., 2020; Han et al., 2006; Yu et al., 2021; Zhao et al., 2019), nonferrous metal smelting (Wang et al., 2021), coal combustion (Yu et al., 2016), and the aging of buildings and urban facilities (Chen et al., 2014b; Yu et al., 2021).

Owing to the diverse sources and migration of urban dust, the Pb content in urban dust is related to land use types and human activities (Lu et al., 2017b; Pan et al., 2018; Wang et al., 2016b; Wei et al., 2015). Generally, in a city, different types of land use and human activities appear in various functional areas, resulting in spatial differences in pollutant concentrations in urban dust, including Pb (Lee & Dong, 2011; Li et al., 2017a; Lu et al., 2017b; Mihankhah et al., 2020; Wang et al., 2016b, 2020; Wei et al., 2015). As a common type of urban functional area, residential areas are the main places of activity for urban residents, particularly elderly people, children, and pregnant women (Lee & Dong, 2011). Heavy metals, including Pb, in urban dust from residential areas, are more easily exposed to inhabitants through skin contact, ingestion, and inhalation because inhabitants often spend more than half a day in their residential communities. Considering the toxicity of Pb and the daily routines of residents, it is essential to investigate Pb pollution and risk in surface dust from residential areas to protect residents' health.

Given the harmful impacts of Pb on human health, the content, source, distribution, pollution level, ecological risk, and health risk of Pb in dust from different functional areas, including residential areas, have been investigated in many cities over the past decades (Li et al., 2017a; Lu et al., 2017b; Mihankhah et al., 2020; Pan et al., 2018; Wang et al., 2016b, 2020; Wei et al., 2015). In fact, some studies of Chinese cities indicate that the content of Pb in dust in residential areas is higher than that in other functional areas (Li et al., 2017a; Pan et al., 2018; Wang et al., 2019a, 2020). For example, Pan et al. (2018) found that the content of Pb in surface dust from residential areas (161.0 mg kg^{-1}) was obviously higher than that from the traffic areas (74.8 mg kg^{-1}), park areas (147.4 mg kg^{-1}), and educational areas (119.6 mg kg^{-1}) in Xi'an; Wang et al. (2019a) found that the content of Pb in dust in residential areas (471.87 mg kg^{-1}) was higher than that in the commercial areas (207.44 mg kg^{-1}), industrial areas (302.87 mg kg^{-1}), and parks and green areas (145.52 mg kg^{-1}) in Shanghai. The higher Pb content of dust in residential areas compared to other functional areas, which is considered to be caused by resident activities such as decorating buildings and residential burning (Pan et al., 2018), implies that residential areas have a higher Pb exposure risk than other functional areas. Nevertheless, the above-mentioned results and conclusions regarding Pb content and risk in dust were mainly derived from the study of bulk samples of urban dust. Urban dust is composed of particles of different sizes. Urban dust particles of different sizes have different movement approaches, heavy metal contents, and environmental risks (Han et al., 2008, 2016). Dust particles with grain sizes less than 63 μm (finer dust) are more easily re-suspended into the atmosphere than larger particles by traffic, wind, and pedestrian flow, and these particles can be transported over long distances (Lu et al., 2017b). Finer dust particles often accumulate more heavy metals because of their greater surface area (Lu et al., 2017b) and adhere more easily to human skin than coarser dust particles (Han et al., 2014; Lu et al., 2017b; Shi & Lu, 2018). Therefore, finer dust has a greater health risk and more serious environmental hazards. However, research on Pb pollution in finer dust has been limited. Considering the toxicity of Pb, the daily routines of residents, the environmental risk of the finer dust, and the aforementioned research status, it is imperative to investigate the pollution and health risks of Pb in finer dust from residential areas.

Xi'an is a new first-tier city in China. In the past two decades of rapid urbanization and industrialization, Xi'an has faced many environmental problems and heavy metal pollution from atmospheric particles, urban road dust, soil, and aquatic sediments (Han et al., 2006, 2008; Shi & Lu, 2018; Chen et al., 2011, 2012, 2013, 2014a, b, 2016; Chen & Lu, 2018, 2019; Pan et al., 2017; Lei et al., 2008). Our group has investigated the pollution levels, spatial distribution, sources, and exposure risks of heavy metals in the surface bulk dust of Xi'an (Chen & Lu, 2018, 2019; Chen et al., 2014a,b, 2016; Lu et al., 2014b; Pan et al., 2017, 2018). We also explored the degree of accumulation, ecological health risks, and sources of Pb and other heavy metals in the finer dust from residential areas and other functional areas of Xi'an (Lu et al., 2017b; Shi & Lu, 2018), and preliminarily found that finer dust from residential areas has higher Pb content than that from other functional areas. In previous studies involving Pb pollution in the finer dust in Xi'an (Lu et al., 2017b; Shi & Lu, 2018), the investigated residential area number and the number of collected dust samples are limited (2 and 10, respectively). The pollution characteristics and health risk of Pb in the finer dust of residential areas in Xi'an as well as the spatial distribution and factors affecting the Pb content in the finer dust of the Xi'an urban area need to be further studied in detail.

The purposes of this research were (1) to measure the content of Pb in the finer dust from the residential area of Xi'an; (2) to analyze the spatial variability and the influence of human and natural factors on Pb content in the finer dust of the Xi'an urban area; and (3) to assess the pollution level and exposure risk of Pb in the finer dust from the residential area of Xi'an. The results would provide scientific evidence for the protection of resident health and environmental management of Pb pollution in urban areas.

Materials and methodologies

Study area

Xi'an (33°39'–34°45'N, 107°40'–109°49'E) is located in the hinterland of the Guanzhong Plain. The built-up area of the city is 369 km^2, with a resident population of 8.434 million (Chen & Lu, 2018). Xi'an has a warm temperate semi-humid continental monsoon climate, with an annual average rainfall of 500–700 mm and an annual average temperature of about 13–15 °C (Lu et al., 2014b, 2017b). There are many rivers and artificial lakes in the city, such as the Weihe, Chanhe, and Bahe rivers (XAMBS, 2019). The study area, an area bordered by the Third Ring Road of Xi'an (Fig. 1), covers all areas of Beilin District, Xincheng District and Lianhu District, and some areas of Yanta District (101.6 km^2), Weiyang District (117.4985 km^2), and Baqiao District (27.2 km^2), as obtained using LocaSpace Viewer 4.0 software based on Google Earth Image.

Sampling and analytical procedures

In the field sampling process, GPS was used to record the actual coordinates of the sampling sites. A total of 47 finer dust samples were collected from residential areas in the Third Ring Road of the Xi'an urban area (Fig. 1), including Baqiao District, Beilin District, Lianhu District, Weiyang District, Xincheng District, and Yanta District (Table 1). The location, scale, completion time, and spatial distribution of residential areas in Xi'an were considered in the residential areas investigated. A mixed dust sample with a weight of approximately 600–800 g was collected by sweeping with a brush and plastic dustpan from 15 to 20 impermeable ground sites, such as hardened pavement, cement road, playground, and parking lot in each residential area. In the laboratory, finer dust (particle size < 63 μm) was obtained by sieving the dust using a 63 μm nylon mesh, and the Pb content in the samples was determined using an X-ray fluorescence spectrometer (XRF) (Lu et al., 2017b; Shi & Lu, 2018). During the experiment, standard reference materials (GSD12 and GSS1, purchased from the Center of National Standard Reference Material of China) and 5% repeated samples (three repeated samples) were used for quality control. The analysis error was within 5%.

Spatial analysis method and geodetector

The spatial distribution of Pb in dust from Xi'an was analyzed based on the content data of Pb in the finer dust samples from the residential areas using the geostatistics method. Before geostatistical analysis, the sample data were generally tested for normal distribution. The kurtosis, skewness, and Kolmogorov–Smirnov (K–S) tests are commonly used in normal distribution tests. The kriging method in ArcGIS 10.6 software was used to explore the spatial distribution of Pb in the finer dust in the Third Ring Road of Xi'an. Cross-validation technology was used to compare the interpolation methods. First, the known points are divided into two sets of samples, one of

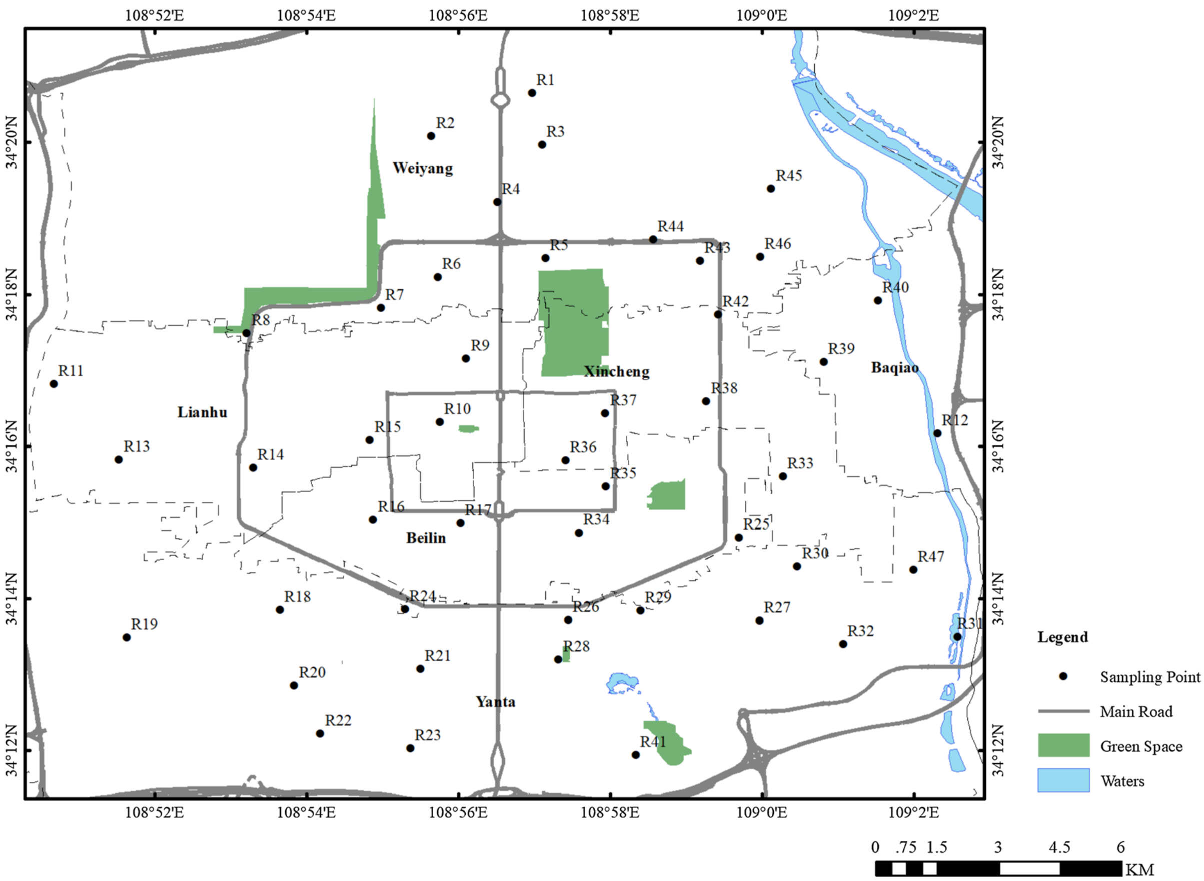

Fig. 1 Sketch map of the finer dust sampling sites in residential areas of Xi'an City

Table 1 Statistics of Pb content (mg kg^{-1}) in the finer dust from 6 districts and whole urban area of Xi'an City

District	Sample number (N)	Min	Max	Mean	SD	CV(%)
Baqiao District	3	63.0	143.6	100.5	40.5	40.4
Beilin District	5	81.6	158.6	118.3	33.3	28.2
Lianhu District	6	69.7	121.8	89.8	20.0	22.4
Weiyang District	13	51.5	166.0	105.8	39.0	36.9
Xincheng District	5	91.3	160.7	112.6	29.0	25.8
Yanta District	15	30.6	157.1	88.4	37.7	42.8
Xi'an urban area	47	30.6	166.0	99.9	35.1	35.1

Min minimum; *Max* maximum; *SD* standard deviation; *CV* coefficient of variation

which is used for modeling each interpolation method, and the other set of samples is used to test the accuracy of the model. The root mean square (RMS) derived from the test sample was used for comparison. The smaller the RMS value, the better the interpolation effect. The equation to derive RMS is as follows (Phillips et al., 1992; Carroll & Cressie 1996; Zimmerman et al., 1999):

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{N} \{z(x_i) - \hat{z}(x_i)\}^2}{N}} \quad (1)$$

where $z(x_i)$ is the known value, $\hat{z}(x_i)$ is the predicted value, and N is the number of samples in the dataset.

The geodetector, proposed by Wang et al. (2010) was used to analyze the factors influencing the spatial variability of Pb in the finer dust in the Third Ring Road of Xi'an. Previous studies have indicated that the content level and spatial distribution of heavy metals in street dust and urban surface dust are controlled by natural factors (such as landform, wind direction, vegetative cover, and precipitation) and human factors (such as population density, industrial activities, and vehicle emissions) (Acosta et al., 2015; Kolakkandi et al., 2020; Lu et al., 2014a, 2017a). Among natural factors, vegetation can intercept atmospheric dust to a certain extent (Castanheiro et al., 2020; Li et al., 2020) and precipitation can wash atmospheric particulates (Li et al., 2020; Zhang et al., 2008), thereby affecting the pollutant content in surface dust. Among the human factors, Acosta et al. (2015) investigated the influence of population density (PD) on the concentration and speciation of metals in street dust from urban areas and found that the contents of anthropogenic source metals, such as Zn, Pb, and Cu, in street dust from Murcia city with high PD (498 persons per km^2) were obviously higher than those in street dust from Totana city with medium PD (106 persons per km^2) and Abaran city with low PD (27.7 persons per km^2). Gross domestic product (GDP), mainly contributed by industrial production, can indirectly reflect industrial pollution, which is an important source of heavy metals in urban dust (Li et al., 2017b). Consequently, GDP, PD, normalized difference vegetation index (NDVI), and annual average precipitation (AAP) were considered in the geodetector method. The spatial data of GDP were obtained by comprehensively considering multiple factors, such as night light brightness and land use types. The multifactor weight distribution method was applied to achieve GDP spatialization (Ma et al., 2012). NDVI data were obtained from satellite remote sensing images, such as SPOT/VEGETATION and MODIS (Wang et al., 2019b). AAP data were obtained from the Resource and Environment Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). PD data were obtained using a multi-source data fusion model to spatially disseminate regional population data (Yang et al., 2002). The spatial distributions of the four factors considered in this study are shown in Fig. S1.

Geodetector is a novel tool to explore the factors influencing geographical phenomena or geographical temporal and spatial distribution differences. A factor detector and an interaction detector in a geodetector (Wang et al., 2010) were used to determine the individual and interactive influences of natural and human factors on the spatial distribution of Pb in finer dust. The main methods and principles of the geodetector are as follows (Wang & Xu, 2017; Wang et al., 2010, 2016a):

Differentiation of dependent variable and single-factor detection: The spatially stratified heterogeneity of the geographical variable Y (for example, Pb in this study) was measured to explore how factor X (PD, GDP, NDVI, AAP) explains the spatial pattern of Y, which is measured by the q-value calculated as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{\mathrm{SSW}}{\mathrm{SST}} \quad (2)$$

where $h = 1, 2, \ldots, L$ represents the stratification of factor X or variable Y; N_h and N represent the number of units in the stratum h and the whole area, respectively; σ_h^2 and σ^2 are the variances of the Y-value of the stratum h and the whole area, respectively; and SST and SSW are the total sum of squares and sum of squares, respectively. The range of the q-value is [0,1]; the larger the value of q, the more obvious the spatially stratified heterogeneity of Y. The q value indicates that X explains $100 \times q\%$ of Y. If the stratification is generated by the independent variable X, the larger the value of q, the stronger the explanatory power of the independent variable X to attribute Y.

Interaction detection: The basic principle is that after X_1 and X_2 intersect to form a new stratum, the q $(X_1 \cap X_2)$ of the new stratum to the dependent variable Y is calculated, and the size relationship among q (X_1), q (X_2), q $(X_1 \cap X_2)$ is subsequently compared.

Pb pollution and health risk evaluation method

The pollution level of Pb in the finer dust from residential areas in Xi'an was assessed using the enrichment factor (EF). The EF is calculated using the following equation (Bergamaschi et al., 2002; Eivazzadeh et al., 2019; Hejami et al., 2020; Lu et al., 2009a,b; Yadav et al., 2019; Zhang et al., 2018):

$$\mathrm{EF} = \frac{(C_{\mathrm{Pb}}/C_{\mathrm{ref}})_{\mathrm{Sample}}}{(C_{\mathrm{Pb}}/C_{\mathrm{ref}})_{\mathrm{Background}}} \quad (3)$$

where C_{Pb} is the Pb content and C_{ref} is the content of the reference element. In this study, to calculate the EF of Pb in the investigated dust samples, Al was used as the reference element due to its low occurrence variability (Chen et al., 2014b; Lu et al., 2009a; Pan et al., 2018; Shi & Lu, 2018). The five pollution levels were divided as listed in Supplementary Material (Table S1) based on the *EF* values (Yadav et al., 2019; Zhang et al., 2018).

The exposure risk of Pb in the finer dust to children and adults was evaluated using the soil health risk model of the US EPA (USEPA, 1989, 2011). The health hazard of Pb exposure to humans mainly causes chronic non-carcinogenic risks. The dose of Pb to humans via three exposure paths (i.e., ingestion, inhalation, and dermal contact) was calculated using Eqs. (3–5) (Yadav et al., 2019; Zheng et al., 2010):

$$D_{\mathrm{ing}} = \frac{C \times \mathrm{IngR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times 10^{-6} \quad (4)$$

$$D_{\mathrm{inh}} = \frac{C \times \mathrm{InhR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{PEF} \times \mathrm{BW} \times \mathrm{AT}} \quad (5)$$

$$D_{\mathrm{dermal}} = \frac{C \times \mathrm{SA} \times \mathrm{SL} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times 10^{-6} \quad (6)$$

where D is the dose due to ingestion (D_{ing}), inhalation (D_{inh}), and dermal contact (D_{dermal}) of Pb in the finer dust. The definition and value of each exposure parameter are provided in Supplementary Material (Table S2) (MEP, 2013, 2014, 2016; USEPA, 2001, 2011). The non-carcinogenic risk of each exposure route is described by the hazard quotient (HQ), which is the exposure dose divided by the reference dose, and the total non-carcinogenic risk of Pb in finer dust to individual exposed population is described by the hazard index (HI), which is the sum of HQ (Cui et al., 2020; Pan et al., 2018; Yadav et al., 2019; Zheng et al., 2010).

Statistical analysis

Statistical analysis, including minimum (Min), maximum (Max), mean, coefficient of variation (CV), and standard deviation (SD), was conducted to obtain the basic statistical information of Pb contents in the finer dust of residential areas in Xi'an City. One-way analysis of variance was used to determine the significance of Pb content in the finer dust of residential areas in six different administrative regions of the Xi'an urban area. IBM SPSS 22.0 was used for statistical analysis.

Results and discussion

Pb content in the finer dust of Xi'an residential areas

Table 1 lists descriptive statistics of Pb content in the finer dust from residential areas in different districts of Xi'an. Overall, the Pb concentration in finer dust ranged from 30.6 to 166.0 mg kg^{-1}, with a mean of 99.9 mg kg^{-1}. The average contents of Pb in Baqiao, Beilin, Lianhu, Weiyang, Xincheng, and Yanta were 100.5, 118.3, 89.8, 105.8, 112.6, and 88.4 mg kg^{-1}, which were 4.7-, 5.5-, 4.1-, 4.9-, 5.2-, and 4.1-fold higher than the background values of Shaanxi surface soil (21.4 mg kg^{-1}), respectively (CNEMC, 1990). Based on one-way ANOVA, there were no significant differences ($p > 0.05$) in the average contents of Pb in all districts, indicating that similar human activities are performed in all districts, such as traffic emissions and resident activities. As shown in Table 1, the CV of Pb in the finer dust of Xi'an residential areas is 35.1%, indicating moderate variability (Pan et al., 2017). The large CV value of Pb reflects the heterogeneity of Pb in the environment and indicates the influence and contribution of human activity sources to the Pb content in the finer dust of Xi'an residential areas.

We compared the Pb content in the finer dust of residential areas in Xi'an with those of previous studies on heavy metal pollution in the finer road dust in other cities (Table S3). Shi and Lu reported that the mean content of Pb in the finer dust (< 63 μm) from various functional areas of Xi'an City was 97.4 mg kg^{-1} (Shi & Lu, 2018), and the minimum was 23.5 mg kg^{-1}. Such finding indicates that the concentration of Pb in the finer dust from the residential area of the Xi'an urban area is similar to that in the whole city of Xi'an. Zhou et al. reported that the average Pb content in finer road dust (< 63 μm) in Huludao city is 2099 mg kg^{-1} (Zhou et al., 2015), which is 21-fold higher than the content of Pb in the finer dust of residential areas in Xi'an. Huludao city has the largest zinc smelter in Asia, known as the Huludao Zinc Smelter, which causes extreme Pb content in the finer road dust in Huludao. In Saeedi's research, finer road dust samples were collected near pollution sources, such as electric heating plants and some industrial sources; thus, the mean content of Pb in the finer road dust in Tehran (257 mg kg^{-1}) (Saeedi et al., 2012) is higher than Pb in finer dust of residential area of Xi'an. In brief, the content of Pb in the finer dust of residential areas in Xi'an is not high compared to other cities. The difference in Pb content in finer dust from different cities is thought to be associated with local human activities and pollution sources.

Spatial distribution characteristics and driving factors

Based on the normal distribution test results, the Pb content in finer dust in residential areas is close to the normal distribution (kurtosis = -0.837, skewness = 0.187, the significance level of the Kolmogorov–Smirnov test for normality = 0.20); thus, the ordinary kriging method was used to explore the spatial distribution of Pb in the finer dust in Xi'an. Table S4 presents the semi-variogram model. The circular model with the smallest RMS value was deemed appropriate for all the direct semi-variograms. Table S4 lists the best-fit model parameters. The Nugget/Sill ratio of Pb in finer dust in Xi'an was greater than 75%, indicating that the variable has weak spatial dependence, which implies that Pb in the finer dust in Xi'an is mainly affected by human factors. Figure 2 displays the spatial distribution of Pb in the finer dust collected in the Xi'an urban area. As shown in Fig. 2, the high-value areas of Pb were mainly concentrated in the east of Xincheng District and Beilin District, north of Yanta District, southeast and southwest of Weiyang District, and northwest of Lianhu District. The samples with high Pb content were principally distributed in the east, south, and northwest of the Second Ring Road, and the Pb content in the finer dust in the old town of Xi'an City (inside the Xi'an Circumvallation) was lower than that near the Second Ring Road. Compared with the old town of Xi'an City, the residential areas around the Second Ring Road are mainly new. Among these new communities, some have aboveground parking lots. Traffic emissions and house decorations, such as gasoline burning, the use of Pb-containing paint, polyvinyl chloride (PVC) window materials, and household anti-theft rods (Xie et al., 2019), might serve as the main sources of Pb pollution in the finer dust of the residential areas around the Second Ring Road of Xi'an City. Therefore, to reduce Pb pollution in residential areas, the use of Pb-containing materials should be reduced or forbidden in construction and renovation activities, and vehicle emissions should also be controlled.

The relative impacts of natural and human factors on the spatial distribution of Pb in the finer dust in the Third Ring Road of Xi'an were detected using a geodetector; the results are presented in Table 2. As shown in Table 2, the interpretation value of each factor on the spatial difference of Pb in the finer dust decreased in the order of PD (21.97%) > GDP (12.16%) > AAP (10.13%) > NDVI (2.18%). Among the four factors, PD had the largest interpretation value for spatial variability of Pb in the finer dust, while NDVI had the smallest interpretation value. The spatial distribution of Pb in the finer dust (Fig. 2) and the spatial distribution of PD, GDP, AAP, and NDVI in the study area (Fig. S1) can further explain this result. Figure S1 shows that the high PD values were located in the east between the Circumvallation and the Second Ring Road, and the northwest of the Second Ring Road, which are similar to the high-value areas of Pb in the finer dust in the Xi'an urban area (Fig. 2). Acosta et al. (2015) found a similar result; that is, increasing population density could increase heavy metal concentrations in street dust. The area with high PD often has large amounts of vehicles and intensive human activities, such as residents' daily consumption and living, municipal waste pile up, etc. (Chen et al., 2011; Pan et al., 2018), which may release Pb into the environment. GDP has a submaximal interpretation value for the spatial variability of Pb in the finer dust, reflecting the influence of industrial emissions, such as coal-fired power generation, on Pb spatial variability in finer dust. The interactive influences ($PD \cap NDVI$, $PD \cap AAP$, $PD \cap GDP$, $NDVI \cap AAP$, $NDVI \cap GDP$, and $AAP \cap GDP$) of the individual factors (PD, NDVI, AAP, and GDP) on the spatial distribution of Pb in the finer dust in the Third Ring Road of Xi'an were detected using the interaction detector of geodetector. The results, which are presented in Table 2, indicate that the interpretation values of the interactive influences of the individual factors were greater than their sum effects (i.e., the interactive influences of all individual factors are enhanced in a nonlinear manner). The interpretation values of the interactive influences among individual factors descend in the order of $PD \cap GDP$ (60.61%) > $PD \cap NDVI$ (49.68%) > $PD \cap AAP$ (45.55%) > $NDVI \cap AAP$ (41.65%) > $NDVI \cap GDP$ (40.62%) > $AAP \cap GDP$

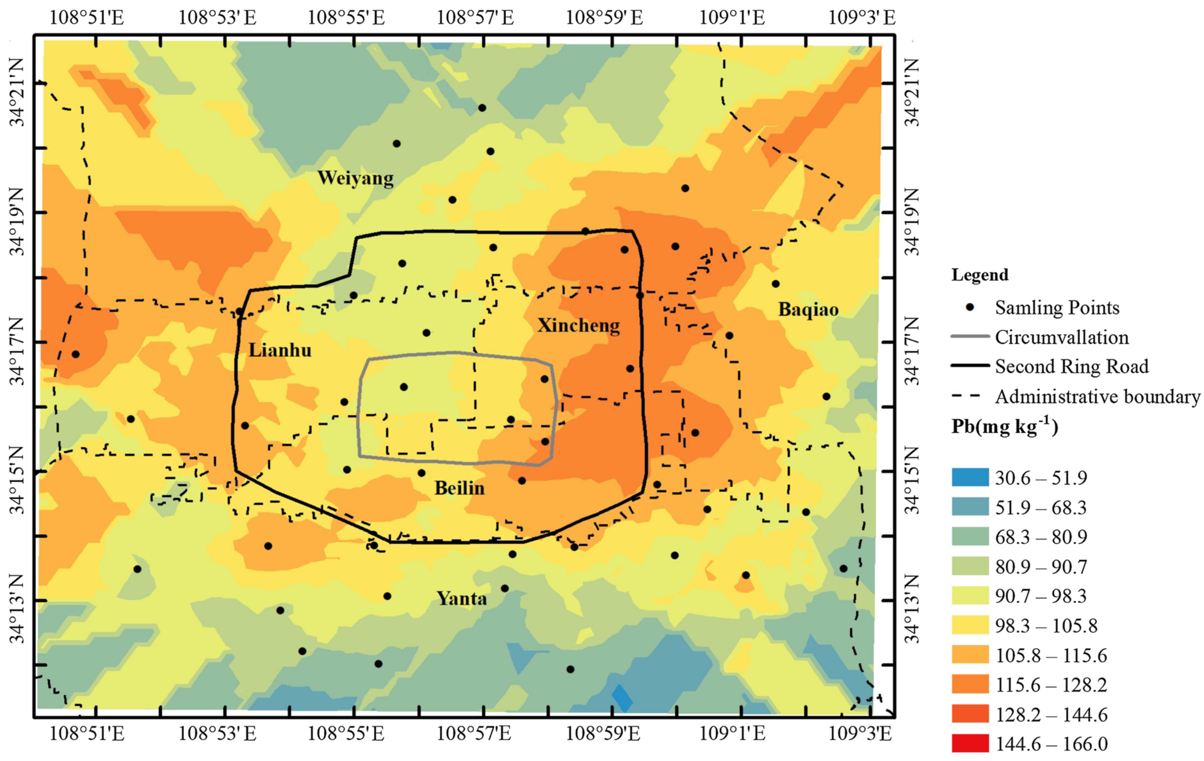

Fig. 2 Spatial distribution of Pb content in the finer dust in Xi'an urban area

Table 2 Interpretation value (%) of natural and human factors on the spatial difference of Pb in the finer dust

Influence factor	PD	NDVI	AAP	GDP
PD	21.97			
NDVI	49.68	2.18		
AAP	45.55	41.65	10.13	
GDP	60.61	40.62	39.27	12.16

PD population density; *NDVI* normalized difference vegetation index; *AAP* annual average precipitation; *GDP* gross domestic production

(39.27%) (Table 2), indicating that the spatial variability of Pb in the finer dust in Xi'an urban area was mainly controlled by the interaction of vehicle emission, residents' daily behavior, and industrial emission. Consequently, in addition to the above-mentioned measures for Pb pollution control, the management of solid waste and the control of industrial emissions, such as coal-fired emissions, should be strengthened.

Pollution level of Pb

Figure 3 presents the *EF* values of Pb in the finer dust from the residential areas of Xi'an. The *EF* value of Pb in the finer dust was between 0.81 and 5.76, with an average of 3.15. Figure 3 shows that 78.4% of the *EF* values of Pb ranged from 2 to 5, indicating moderate enrichment, while 4.2% of the *EF* values of Pb were in

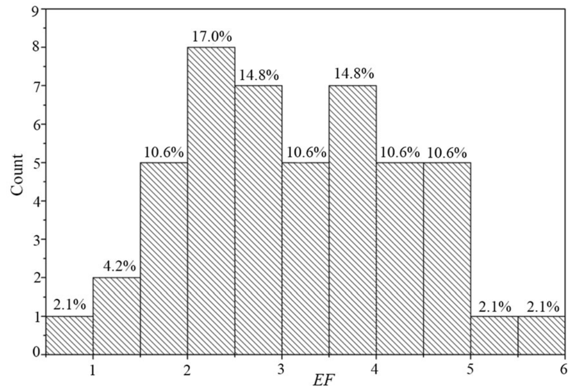

Fig. 3 *EF* histogram of Pb in the finer dust in Xi'an residential area

the range of 5–6, depicting high enrichment. The mean *EF* values of Pb in the finer dust from residential areas in Baqiao, Beilin, Lianhu, Weiyang, Xincheng, and Yanta Districts were 3.18, 3.62, 3.00, 3.49, 3.45, and 2.62 (Table S5, Supplementary Materials), existing in the range of 2–5. Such finding indicates that Pb was moderately enriched in the finer dust in the six administrative districts of Xi'an City. Although the mean pollution levels of Pb in the six administrative districts were the same, the means and ranges of the *EF* of Pb in all districts still have a certain difference (Table S5, Supplementary Materials). Table S5 clearly shows that the relative magnitude of the mean *EF* in the six districts is consistent with the PD and GDP values of the six districts. Combined with the results of geodetector analysis, the difference in *EF* value for Pb in the six districts might be caused by the discrepancy in vehicle emissions, daily behavior of residents, and industrial emissions in various districts.

Based on the *EF* values of Pb in the finer dust samples from the investigated residential areas, the spatial distribution of the *EF* of Pb in the finer dust in the entire area was obtained. Because the *EF* of Pb in finer dust in residential areas is close to the normal distribution (kurtosis = -0.612, skewness = 0.153, the significance level of the Kolmogorov–Smirnov test for normality = 0.20), the ordinary kriging method was used to explore the spatial distribution of the *EF* of Pb in the finer dust in Xi'an. As shown in Table S4, the circular model with the smallest RMS value was deemed appropriate for all direct semi-variograms. Table S4 lists the best-fit model parameters. The Nugget/Sill ratio of the *EF* of Pb in finer dust in Xi'an was between 25 and 75%, indicating that the variable has moderate spatial dependence. As demonstrated in Fig. 4, the higher *EF* values of Pb were mainly distributed in Xincheng, the middle of Lianhu, south of Weiyang, east of Beilin, north and west of Baqiao, and north of Yanta. *EF* values of 5–6 were mainly distributed in the southeast and southwest of Weiyang while *EF* values of 4–5 were principally distributed along the Second Ring Road. The *EF* values of Pb in $>$ 95% of the investigation area ranged from 2 to 6, indicating moderate enrichment to high enrichment. Hence, Pb enrichment and pollution in the finer dust in Xi'an urban areas were more serious, which should be monitored by the local government.

Health risk of Pb in the finer dust in the Xi'an residential areas

The results of the assessment regarding the HI for Pb exposure via the finer dust in residential areas in Xi'an are listed in Table 3. As shown in Table 3, for children and adults, the HI values were less than 1 in the six districts, decreasing in the order of Beilin $>$ Xincheng $>$ Weiyang $>$ Baqiao $>$ Lianhu $>$ Yanta, which ultimately demonstrates that there is no serious exposure risk. Although urban surface dust can accumulate in the body via ingestion, inhalation, and skin contact absorption, our study shows that digestive intake is the primary route of entry for Pb in finer dust for both children and adults. This result is consistent with that of previous studies (Chen et al., 2014a; Hejami et al., 2020; Pan et al., 2018). The exposure risk of Pb in the finer dust from the residential areas of Xi'an for children (HI = 7.38E-02) was obviously higher than that for adults (HI = 1.58E-02), approaching five times. Consequently, health hazards (such as impairment of the nervous system, hematopoietic system, digestive system, kidney and genital system, and intellectual development retardation) owing to prolonged exposure to Pb in the finer dust of residential areas should be considered for children.

Conclusions

The content of Pb in the finer dust retrieved from the residential area in Xi'an was 4.7-fold higher than the local soil background value. The high-value areas of Pb content in finer dust from the Xi'an urban area were mainly distributed around the Second Ring Road, and the Pb content in the old town of Xi'an city was lower than that near the Second Ring Road. The spatial variability of Pb content in the Xi'an urban area was mainly controlled by the interaction among vehicle emissions, daily residential behavior, and industrial emissions. The pollution level of Pb in the finer dust was moderately to highly enriched in more than 95% of the study area. To reduce Pb pollution in residential areas, the use of Pb-containing materials should be reduced or forbidden in construction and renovation activities, and the control of vehicle emissions and industrial emissions, such as coal-fired emissions, as well as the management of solid waste should be strengthened. The health risk assessment of Pb in the

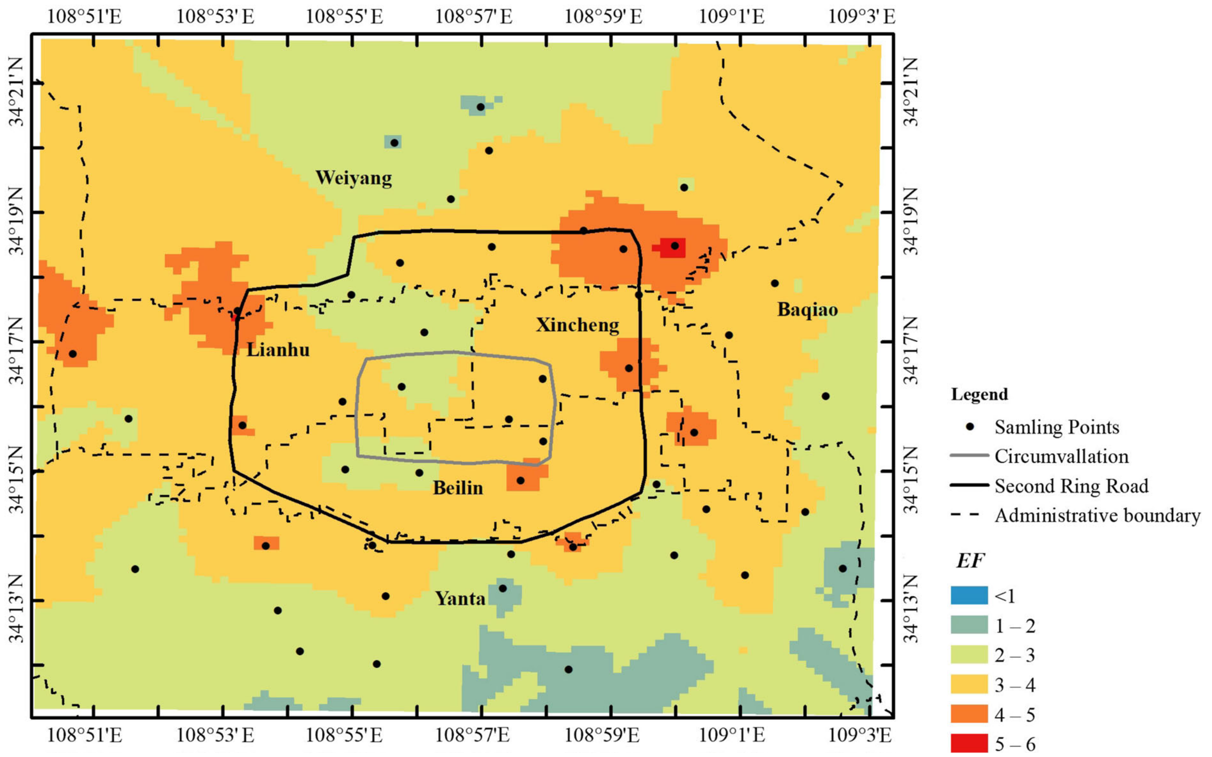

Fig. 4 Spatial distribution of *EF* in the finer dust in Xi'an urban area

Table 3 Individual non-carcinogenic risks from exposure to Pb in the finer dust of residential area in Xi'an City

District	Population	*C* (95% UCL, mg kg^{-1})	HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI
Baqiao District	Adults	133.6	1.77E-02	6.84E-06	1.41E-03	1.91E-02
	Children	133.6	8.29E-02	1.02E-06	6.56E-03	8.94E-02
Beilin District	Adults	159.7	2.12E-02	8.18E-06	1.69E-03	2.29E-02
	Children	159.7	9.91E-02	1.22E-06	7.85E-03	1.07E-01
Lianhu District	Adults	110.8	1.47E-02	5.67E-06	1.17E-03	1.59E-02
	Children	110.8	6.87E-02	8.48E-07	5.44E-03	7.42E-02
Weiyang District	Adults	129.3	1.71E-02	6.62E-06	1.37E-03	1.85E-02
	Children	129.3	8.02E-02	9.90E-07	6.35E-03	8.66E-02
Xincheng District	Adults	148.6	1.97E-02	7.61E-06	1.57E-03	2.13E-02
	Children	148.6	9.22E-02	1.14E-06	7.30E-03	9.95E-02
Yanta District	Adults	109.2	1.45E-02	5.59E-06	1.15E-03	1.56E-02
	Children	109.2	6.77E-02	8.36E-07	5.36E-03	7.31E-02
Xi'an urban area	Adults	110.2	1.46E-02	5.64E-06	1.16E-03	1.58E-02
	Children	110.2	6.84E-02	8.44E-07	5.41E-03	7.38E-02

finer dust of residential areas indicated that there is no significant non-cancer risk at present to children and adults. Nevertheless, owing to the ubiquitous Pb pollution in the study area, the strong toxicity of Pb, and the sensitivity of children to Pb pollution, investigations and management of Pb emission sources should be carried out in the future. Further, the prolonged exposure risk of Pb to children through the finer dust in residential areas should be a persistent concern.

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Authors contributions BY was involved in conceptualization, methodology, experimental execution, data analysis, writing the original draft, and doing the revision; XL had contributed to conceptualization, methodology, supervision, writing, reviewing, and editing; XF had contributed to data analysis and software; PF, LZ, and YY had contributed to investigation and visualization; and LW had contributed to methodology, writing, reviewing, and editing, and software. All authors approved final version of the manuscript for publication.

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Data availability The authors declare that the data and material have free access.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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