Contamination characteristics, mass concentration, and source analysis of metal elements in PM$_{2.5}$ in Lanzhou, China

Yingquan Li$^{1,2}$, Baowei Zhao$^{1,*}$, Kaixiang Duan$^1$, Juexian Cai$^{1,2,3}$, Wujiang Niu$^4$, and Xiao Dong$^{2,3}$

PM$_{2.5}$ and its bound metals pose a serious threat to human health. Understanding their contamination characteristics and source could provide implication for controlling their spreading and ensuring air quality. In this article, 1,600 of PM$_{2.5}$ samples were collected from 5 urban sites in Lanzhou, China. The contamination characteristics of PM$_{2.5}$, its relationship with meteorological factors, and the source of its bound metals were studied based on multiple linear regression analysis, enrichment factor (EF), principal component analysis and correlation analysis. The outcomes show that the PM$_{2.5}$ concentrations in winter ($0.117$ mg/m$^3$) and spring ($0.083$ mg/m$^3$) are higher than those in summer ($0.043$ mg/m$^3$) and autumn ($0.048$ mg/m$^3$). The influence degree of meteorological factors on PM$_{2.5}$ concentration is in the order of wind speed > atmospheric pressure > temperature > humidity. The major source of Fe and Cu in PM$_{2.5}$ is construction dust, Pb and As is industrial, and Hg is coal combustion. In addition, Cd, V, Co, and Mn are mainly derived from dust produced by weathering of soil or rock. In general, the spatiotemporal distribution of PM$_{2.5}$ and its bound metals are different, which is closely related to geographical location, source, and meteorological factors. The results in this article could provide support for the scientific formulation to prevent air pollution in Lanzhou.

Keywords: PM$_{2.5}$, Contamination characteristics, Meteorological factors, Metal source analysis, Lanzhou

1. Introduction

In recent years, PM$_{2.5}$ has become one of the dominant air contaminants in many cities. PM$_{2.5}$ particles are very small and can enter the alveoli through the trachea and bronchi, then circulate in the blood (Brook, 2008; Wang et al., 2013). PM$_{2.5}$ can cause damage to the body, especially when the individual immune defense ability is low or the pathogenic microorganisms occur (Shi et al., 2016). At the same time, it has large specific surface area and easily accumulates numerous toxic and hazardous materials (Cheng et al., 2016). Heavy metals are the important parts of PM$_{2.5}$, which are easy to accumulate on the surface of fine particles (Talbi et al., 2018). Contamination of PM$_{2.5}$ with excessive heavy metals could threaten the ecological environment and human health (Xu et al., 2013), which has attracted worldwide attention (Baumgartner et al., 2014). Therefore, carrying out research on atmospheric PM$_{2.5}$ and its bound metals is significant to improve environmental quality and protect human health.

In the last few years, scholars have done a lot of researches on PM$_{2.5}$ and its bound metals. The main research methods include health risk assessment model for risk analysis (Huang et al., 2018), enrichment factor (EF; Zhang et al., 2018), principal component analysis (PCA; Terrouche et al., 2016), correlation analysis (Soleimani et al., 2018), and positive matrix factorization (Amato and Hopke, 2012) for determining the element origin. The main research directions include the spatiotemporal change characteristics of PM$_{2.5}$ and its relevance with meteorological factors (Huang et al., 2015), the levels of PM$_{2.5}$ in city (Zhang and Cao, 2015) and school (Khadijja et al., 2019), the latent risk of heavy metals and polycyclic aromatic hydrocarbons (PAHs) in PM$_{2.5}$ (Gao et al., 2016), and features, origins, and health risk assessment of heavy metals (Li et al., 2016). However, there are still some deficiencies in the current understanding of the spatiotemporal changes of PM$_{2.5}$. Related researches mainly focus on the issues on a large scale. There are few studies on the spatiotemporal patterns of PM$_{2.5}$ levels based on the neighborhood scale (Xu and Zhang, 2020). In fact, there are significant differences in PM$_{2.5}$ concentrations within
cities (Merbitz et al., 2012). According to the difference of the PM$_{2.5}$ concentration at neighborhood level in the cities, the spatiotemporal pattern of urban PM$_{2.5}$ concentration can be further investigated to provide targeted control measures (Dai et al., 2020). In addition, higher spatiotemporal resolution is needed to better understand urban air quality issues (Zhang and Cao, 2015).

Lanzhou is a river valley city located in the west of the Loess Plateau. It is surrounded by mountains, which makes it difficult for atmospheric particles to diffuse, and leads to high concentrations of PM$_{2.5}$. In addition to the smoke and dust from industry, traffic, and construction, the external input of desert dust from the surrounding area are contributing to the increase in particulate pollution in Lanzhou. Due to the special terrain, the PM$_{2.5}$ pollution pattern in Lanzhou may be different from that in other regions (Tshehla and Wright, 2019; Sun et al., 2019; Yu et al., 2019; Wang et al., 2020). The results of a study by Yu et al. (2012) showed that heavy metals in particles in Lanzhou presented seasonal and regional distribution and exhibited unacceptable carcinogenic risk in winter, where only 6 metals (Zn, Ni, Cu, Pb, Cr, and Cd) were concerned. Thus, the study on PM$_{2.5}$ bound metals is not comprehensive enough. The research findings by Qiu et al. (2016) indicated that coal combustion emissions, dust, and secondary aerosol were the major origins of particulate pollution in Lanzhou. However, in their study, there were only 3 sampling points. The results cannot fully explain the pollution situation in Lanzhou. Therefore, in the present study, PM$_{2.5}$ real-time monitoring data were obtained in a whole year at 5 sites in Lanzhou City. On the basis of multiple linear regression analysis (MLRA), EF, CA, and PCA, the aims of this research are as follows: (1) to assign the spatiotemporal distribution of PM$_{2.5}$ and its bound metals, (2) to dissect the relevance between PM$_{2.5}$ concentrations and meteorological factors, and (3) to predict the origins of metals.

2. Materials and methods
2.1. Study area and sample collection
As revealed in Figure 1, surrounded by mountains, Lanzhou City, the capital of Gansu Province, with a gross area of 13,085.6 km$^2$, is located in the valley basin of Yellow River. The terrain of Lanzhou City is higher in the southwest and lower in the northeast. The climate is temperate continental with an annual average temperature of 10.3°C. The dominant wind direction is northeastern with a frequency of 37.1%. The days of calm wind is observed as 60%. Especially in winter, the quiet wind frequency in the atmospheric boundary layer height is even up to 87% (Feng and Wang, 2012). The average annual precipitation is 327 mm, primarily occurring from June to September. Temperature inversion is serious in Lanzhou, with about 80% days of the year experiencing temperature inversion, and the lower atmosphere is usually in a stable state (Chu et al., 2008).

In 2018, the automatic monitoring sampler (U.S. MaiTe One, Class III EPA EQPM-0308-170) was used to simultaneously collect PM$_{2.5}$ samples at 5 air monitoring stations in Lanzhou. The stations from east to west are Lanzhou University Campus Station (LZU), Biological Products Institute (BPI), Railway Design Institute (RDI), Staff and Worker Hospital (SWH) in Qilike District, and Lanyuan Hotel (LYH) in Xigu District. LZU is 30 km away from Lanzhou City, which is taken as the control point in this study. The other 4 sampling points are located in the main urban area, with a distance of 10–20 km away, as shown in Figure 1. The samples were collected at 1-h interval, and the flow rate of sampling was 16.7 L min$^{-1}$. The filter membrane was made of fiberglass with a diameter of 11.5 mm.

January, April, July, and September were selected to represent winter, spring, summer, and autumn, respectively. Samples of 10 days (every 3 days as an interval) were selected for monthly analysis, and those of 8 h (every 3 hours as an interval) were selected for daily analysis. A total of 8 sample filter membranes were taken in a day; 320 samples were collected from each sampling point, and a total of 1,600 samples were collected. The weather was clear, and there was no rain during the sampling period. The sampling height at LZU is 4 m (above ground level), and the other sampling heights are between 12 m and 15 m (above ground level). In addition, the atmospheric temperature (°C), barometric pressure (kPa), average daily wind speed (m s$^{-1}$), and relative humidity (%) at the 5 stations were provided by the China Meteorological Administration at the same time. The average atmospheric temperature in January, April, July, and September was −5.3, 12.1, 22.4, and 16.3°C. The average wind speed in January, April, July, and September was 0.3, 1.2, 1.1, and 0.7 m s$^{-1}$. The average atmospheric humidity in January, April, July, and September was 49.7, 21.6, 72.6, and 50.8%. The average atmospheric pressure in January, April, July, and September was 844.9, 819.3, 817.2, and 843.4 hPa.

2.2. Determination of PM$_{2.5}$ and metal concentrations
All chemicals were of analytical grade purity. Milli-Q water (CSR-1-10, > 18.2 MΩ cm, Beijing ASTK Technology Development Co., Ltd., Beijing, China) was used for the preparation of solutions. PM$_{2.5}$ concentration was computed by subtracting the weight of the filter membrane before and after sampling (HJ 618–2011; Ministry of Ecology and Environment of the People’s Republic of China, 2011). For metal analysis, the filter membrane was treated with 10 mL of HNO$_3$-HCl mixed solution (55.5 mL of HNO$_3$ and 167.5 mL of HCl were added to 500 mL of water, with a constant volume up to 1 L) in a closed Teflon vessel and was digested for 15 min in an Automatic Digestion Instrument (Politech DigestLinc ST60 Beijing Polytech Instrument Co., Ltd. Beijing, China) with the temperature of 200°C. The digested samples were then transferred into a Teflon beaker, cooled for 20 min, diluted to 50 mL with Milli-Q water, and measured after filtration. Meanwhile, blank filter membrane was used as control (HJ 657–2013; Ministry of Ecology and Environment of the People’s Republic of China, 2013). Atomic Fluorescence Spectrometer (AFS-930, Beijing Jitian Company, Beijing, China) was used to determine the concentration of Hg and As. 10 mL of digestion solution was transferred to a colorimetric tube, 0.5 mL of HCl was added, and then Hg concentration
was tested on the spectrometer (GB/T 22105.1–2008; General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China, Standardization Administration of the People’s Republic of China, 2008a). Another 10 mL of digestion solution was transferred to a colorimetric tube with 0.5 mL of HCl and 1 mL 10% of CH₄N₂S. The solution was mixed and left for 20 min. Then, As concentration was determined on the spectrometer (GB/T 22105.2–2008; General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China, Standardization Administration of the People’s Republic of China, 2008b). Inductively Coupled Plasma Mass Spectrometer (ICP-MS X series II, American Thermo Fisher Scientific (China) Co., Ltd. Shanghai, China) was used to survey the metals, such as Mn, V, Fe, Co, Pb, Cu, Sh, and Cd (HJ 657–2013; Ministry of Ecology and Environment of the People’s Republic of China, 2013). The setting parameters of instrument are shown in Table S1 and quality control parameters are shown in Table S2. The detection limit of elements ranged from 0.0002 to 0.058 mg/m³, and the recovery rates were from 86.10% to 123.0%.

2.3. Modeling relevance between PM$_{2.5}$ concentrations and meteorological factors

First, the relevance between PM$_{2.5}$ concentrations and meteorological factors was evaluated by CA. Then, MLRA was used to illustrate the confounding effect of the variables. The meteorological variables and PM$_{2.5}$ concentration were used as the independent variables and the dependent variable, respectively (Amos et al., 2010). The CA and MLRA were adopted to establish the mathematical model for the relevance between PM$_{2.5}$ concentrations and meteorological factors. In this study, PM$_{2.5}$ monitoring values at LYH site in January were selected to study the relationship with meteorological factors. The main reason is that the LYH site is located in an urban–rural combination zone with the predominance of many heavy
industries and construction sites. A severe level of air pollution was observed, especially in winter due to PM$_{2.5}$ in LYH site as compared to other regions.

2.4. Source analysis of metals

EF can reflect the interference degree caused by human activities (Zhang et al., 2018). Comparing the measured value of elements in sample with its background value, the enrichment degree is calculated to determine the contribution level of the content of metals by human activities. The calculation formula is as follows:

$$EF = \left( \frac{C_i}{C_{ref}} \right)_{\text{annual}} \left( \frac{C_i}{C_{ref}} \right)_{\text{crustal}},$$

where $C_i$ refers to the concentration of an element being studied, and $C_{ref}$ refers to the reference element concentration. The data were calculated based on soil background values (Wu, 1994). As for reference elements, they usually refer to the ones abundantly existing in the Earth's crust, with little man-made pollution, better chemical stability, and lower volatility, such as Al, Fe, Sc, and Ba (Gao et al., 1992). Fe is chosen as the reference element in this article. According to the value of EF, the elements can be separated into 3 groups. When the EF value of an element is less than 10, it can be considered as a nonenriched component. The element mainly derived from the crust or soil, which was mainly caused by the dust blown into the atmosphere and by the weathering of soil or rock. If the EF value is greater than 10 but less than 100, it indicates that the element in the particulate matter partly derived from anthropogenic activities and partly from crustal materials. If the EF value is greater than 100, the element can be considered to be enriched, and it is mainly derived from various kinds of pollution caused by anthropogenic activities (Odabasi et al., 2002; Ma et al., 2014; Zhang et al., 2018).

The degree of correlation between the measured variables and the commonality of their sources was characterized by CA. The influencing factors of each indicator were determined by PCA. The principle of this method is to synthesize and summarize common factors from global variable data according to the correlation between the components, calculate the load of each factor, and then infer the type of possible pollution source based on the size of the factor load and the characteristic elements of the pollution source. SPSS 22.0 software (IBM) was used for PCA and CA analysis.

3. Results and discussion

3.1. Spatiotemporal distribution characteristics of PM$_{2.5}$

The concentration profiles of PM$_{2.5}$ are revealed in Figure 2. The average annual concentration of PM$_{2.5}$ in Lanzhou is 0.073 mg m$^{-3}$ and ranges from 0.049 to 0.089 mg m$^{-3}$ at

![Figure 2. The seasonal average concentrations of PM$_{2.5}$ at the sampling sites. * represents extreme outliers; the positions of the upper and lower edges of the rectangular box correspond to the upper and lower quartiles of the data, respectively; the line segments inside the rectangular box represent the median of the data, and the squares inside the rectangular box represent the mean of the data. DOI: https://doi.org/10.1525/elementa.2020.00125.f2](https://doi.org/10.1525/elementa.2020.00125.f2)
The concentrations of PM$_{2.5}$ were obviously related to wind speed, temperature, and air pressure but had no significant correlation with atmospheric humidity. The order of correlation extent is wind speed > atmospheric pressure > temperature > humidity. It is negatively related to wind speed and atmospheric pressure while positively related to temperature and humidity. Therefore, PM$_{2.5}$ concentrations were less influenced by atmospheric humidity, mainly affected by wind speed, and to a certain extent also affected by atmospheric pressure and temperature. The influence of wind speed, atmospheric pressure, and temperature on PM$_{2.5}$ concentration has been confirmed by many scholars (Li et al., 2013; Huang et al., 2015), while the influence of humidity on PM$_{2.5}$ concentration is very weak, which may be related to the seasonal changes. Chen et al. (2016) reported that relative humidity was negatively correlated with ABLH. The decrease in ground wind speed was unfavorable for the development of ABLH, and the ABLH was found to be generally positively correlated with sea-level pressure (Xiang et al., 2018). Therefore, the PM$_{2.5}$ concentration must be related to meteorological factors, and it is necessary to explore the relationship between them.

3.2. Modeling relevance between PM$_{2.5}$ concentrations and meteorological factors

The relationship and correlation coefficients between PM$_{2.5}$ concentrations and meteorological factors are described in Figure 3 and Table 1, respectively.

Each station. All of the values exceed the secondary standard (0.035 mg m$^{-3}$) specified by China government (Ambient Air Quality Standards in China, GB 3095–2012).

In the light of the daily average secondary mass concentration limit (0.075 mg m$^{-3}$; GB3095–2012, China), the exceeding rates of daily average PM$_{2.5}$ concentration are different at the same sampling sites in the 4 seasons. The rates are 44.3%, 26.6%, 11.3%, and 67.5% at BPI; 28.8%, 3.8%, 7.5%, and 85.0% at RDI; 50.0%, 14.1%, 15.2%, and 86.25% at SWH; 45.0%, 9.1%, 18.75%, and 86.25% at LYH; and 20.0%, 1.3%, 0%, and 63.8% at LZU, respectively. In general, the seasonal average concentration of PM$_{2.5}$ in Lanzhou is in the order of winter (0.117) > spring (0.083) > autumn (0.048) > summer (0.043 mg m$^{-3}$). In recent years, with the intensification of urbanization, the velocity of near-surface airflow has decreased significantly. The percentage of slight wind and calm wind days in Lanzhou accounts for 60% of the whole. Especially in winter, the quiet wind frequency is as high as 87% (Feng and Wang, 2012), and the diffusion rate of the tiny particles slows down with the wind speed decreasing. In addition, temperature inversion is relatively serious in Lanzhou, with about 80% days of the year experiencing temperature inversion (Chu et al., 2008), which seriously obstructs air convection and goes against the diffusion of tiny particles. In addition, the boundary layer height of atmosphere (ABLH) is negatively correlated with PM concentration (Pan et al., 2019) and affected by meteorological factors. Studies have shown that relative humidity was negatively correlated with ABLH. The decrease in ground wind speed was unfavorable for the development of ABLH, and the ABLH was found to be generally positively correlated with sea-level pressure (Xiang et al., 2018). Therefore, the PM$_{2.5}$ concentration must be related to meteorological factors, and it is necessary to explore the relationship between them.

Figure 3. Relationship between PM$_{2.5}$ concentrations and meteorological factors. Data from LYH in January. DOI: https://doi.org/10.1525/elementa.2020.00125.f3
had a strong negative association with PM$_{2.5}$ concentration in summer but no correlation in other seasons. PM$_{2.5}$ concentration is positively correlated with temperature. The reason is that the decrease of temperature in winter is often accompanied by strong cold air activity, which breaks the stable state of atmosphere, and high temperature helps to produce more secondary particles in photochemical activity (Li et al., 2013). The correlation between PM$_{2.5}$ concentration and humidity is positive. Studies have shown that high humidity facilitates the absorption of semi-volatile substances by aerosols (Hu et al., 2008), and promotes magnanimous gaseous pollutants such as CO, O$_3$, SO$_2$, and NO$_x$ to produce more secondary PM$_{2.5}$ (Olivares et al., 2007). Despite the positive sign, the correlation between PM$_{2.5}$ concentration and humidity is slight. Wind speed has long been considered as a key factor affecting pollutants diffusion (Chaloulakou et al., 2003). Obviously, the increase in wind is beneficial to PM$_{2.5}$ diffusion. High pressure usually causes low wind speed, limiting the spread of pollutants in the air (Hussein et al., 2005). This conflicts with the observed negative correlation between barometric pressure and PM$_{2.5}$ concentration. However, the high atmospheric pressure is often accompanied with strong cold air, that is, strong wind, which favors air pollution dispersion. This enhances dust resuspension and leads to decreased PM$_{2.5}$ mass concentration (Harrison et al., 2001).

In order to control the confounding effect of the research variables, MLRA was conducted, which can reflect the relevance between dependent variables and multiple independent variables (Du et al., 2020). MLRA is a statistical analysis method that can analyze the influence of multiple factors on an observed variable through the observation of a large number of samples to determine “multiple causes and one effect.” Regarding PM$_{2.5}$ content as the dependent variable and temperature, humidity, wind direction, and atmospheric pressure as the independent variables, the regression equation was obtained with 0.775 of $R^2$ value, which indicates a good fitting degree. The regression equation is as follows:

$$Y = -0.0219 + 0.0211X_1 + 0.0082X_2 - 0.0488X_3 - 0.0001X_4,$$

where $Y$ is PM$_{2.5}$ concentration (mg·m$^{-3}$), $X_1$ is atmospheric temperature ($^\circ$C), $X_2$ is atmospheric humidity (% RH), $X_3$ is wind speed (m·s$^{-1}$), and $X_4$ is barometric pressure (kPa). The fitting value is calculated with this equation and compared with the measured data to determine the fitting extend, as shown in Figure 4.
As revealed in Figure 4, the variation trend of the fitting value and the original monitored value is similar. Due to the complex correlation between meteorological factors and PM$_{2.5}$ concentrations and the diversity of meteorological factors, some fitting values are different from the actual monitored values. However, on the whole, the equation is sufficient to illustrate the relationship between PM$_{2.5}$ concentrations and meteorological factors, which can be used to establish a model to forecast the change of PM$_{2.5}$ concentrations.

3.3. Spatiotemporal distribution features of metals in PM$_{2.5}$

The spatiotemporal distribution features of metal mass concentration in PM$_{2.5}$ are illustrated in Figure 5. The metal concentrations show a significant seasonal distribution, and the overall pattern is winter > spring > summer > autumn. This is consistent with the seasonal distribution of PM$_{2.5}$ concentration above. In addition, the annual average concentration of metals at each sampling site is in the order of BPI (0.064) > RDI (0.062) ≈ SWH (0.062) > LYH (0.050) > LZU (0.039 µg·m$^{-3}$). Metals exhibit different seasonal and spatial variations, which may be related to their different sources. These metals mainly originated from nature (mineral dust) and anthropogenic activities (industrial, burning, transportation, household waste, etc.; McKenzie et al., 2009; Götze et al., 2016; Hu et al., 2018).

3.4. Source analysis of metals

For the sake of further exploring pollution features of PM$_{2.5}$, the sources of its bound metals were analyzed. EF of elements in atmospheric aerosols can be used to evaluate natural and anthropogenic sources of elements. The EF values of metals in PM$_{2.5}$ are shown in Figure 6.

The average EF values of metals are in the order of Cu (113.0) > Pb (98.86) > Hg (13.13) > Cd (2.118) > Sb (1.252) > Fe (1.000) > As (0.672) > V (0.238) > Co (0.018) > Mn (0.004). The EF value is greater than 100 for Cu, which indicates that Cu is subject to anthropogenic pollution.
The EF values of Pb and Hg are between 10 and 100, which indicates that these 2 elements are partly caused by anthropogenic pollution and partly by soil or rock. The EF values of Cd, Sb, As, V, Co, and Mn are less than 10, which means that these elements are mainly derived from dust generated by the weathering of soil or rock.

The correlation among metals in the PM$_{2.5}$ in Lanzhou is exhibited in **Table 2**. The closer the correlation coefficient is to 1, the more likely the 2 variables are derived from the same source of pollution (Wang et al., 2018). There is a good correlation among V, Mn, Fe, Cu, and Co, and the correlation coefficients are between 0.505 and 0.803, indicating that they might derive from the same source. A strong correlation is observed for the pair of Pb–As (0.704), suggesting their common emitting source. The correlation of each metal element with Hg and Cd is not significant, suggesting that Hg and Cd might come from different sources.

**Table 2.** Correlation coefficients among different metals in PM$_{2.5}$ (Pearson’s $R^2$). DOI: https://doi.org/10.1525/elementa.2020.00125.t2

|     | V   | Mn  | Fe  | Co  | Pb  | Cu  | Cd  | Sb  | As  | Hg  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| V   | 1   |     |     |     |     |     |     |     |     |     |
| Mn  | 0.505* | 1   |     |     |     |     |     |     |     |     |
| Fe  | 0.692** | 0.660** | 1   |     |     |     |     |     |     |     |
| Co  | 0.769** | 0.756** | 0.807** | 1 |     |     |     |     |     |     |
| Pb  | 0.767** | 0.364 | 0.492* | 0.701** | 1 |     |     |     |     |     |
| Cu  | 0.736** | 0.600** | 0.803** | 0.728** | 0.539** | 1 |     |     |     |     |
| Cd  | -0.076 | 0.113 | -0.270 | 0.024 | -0.039 | -0.052 | 1 |     |     |     |
| Sb  | 0.508* | 0.200 | 0.360 | 0.513* | 0.352 | 0.153 | -0.186 | 1 |     |     |
| As  | 0.610** | 0.110 | 0.328 | 0.483* | 0.704** | 0.328 | 0.115 | -0.277 | 1 |     |
| Hg  | 0.020 | -0.059 | -0.113 | -0.049 | 0.004 | -0.035 | -0.059 | -0.060 | -0.099 | 1 |

* and ** denote that the correlation is significant when the confidence (2-tailed test) is 0.01 and 0.05, respectively.
The results of PCA of metals are shown in Table 3. It is necessary to check the suitability of the data used for PCA by Kaiser–Meyer–Olkin (KMO) and Bartlett’s test of sphericity. The values of KMO and Bartlett’s test of sphericity in this study were 0.757 and 0, respectively, indicating that PCA is applicable (Varol, 2011). Four principal components are extracted in the light of the eigenvalue greater than 1, and 4 factors (RPC1, RPC2, RPC3, and RPC4) were obtained after maximum variance orthogonal rotation, and explain the data variance of 39.04%, 23.54%, 10.96%, and 9.369%, respectively. The cumulative variance contribution rate is 82.91%.

Indicators with higher loading on the same principal component may have homology. The load of Mn, Fe, and Cu in RPC1 is relatively large (≥0.856), and it is also a significant positive correlation between Fe and Cu (Table 2), which might derive from the same pollution source, since Fe and Cu are widely used in building materials. As the EF value of Mn is less than 10, it can be considered that RPC1 represents ground dust, which includes soil and building dust (Terrouche et al., 2016; Liu et al., 2017). The load of Pb and As in RPC2 is larger (≥0.828). The source of Pb could be gasoline combustion, and the potential sources of As could be industrial activities and charcoal combustion (Soleimani et al., 2018). Since Pb has not been added to the gasoline throughout the Lanzhou City for many years, and there is no evidence of charcoal combustion throughout the city, the main potential sources of Pb and As could be industrial activities. The load of Cd in RPC3 is relatively large (0.948). Since the EF value of Cd is less than 10, the RPC3 can be considered as the natural source. There is a larger load of Hg in the RPC4 (0.986). Hg is mainly derived from coal consumption, and coal-fired power plant is a prominent source of Hg (Zhang et al., 2017).

4. Conclusions
PM2.5 concentrations in winter and spring are higher than those in summer and autumn. The meteorological factors influencing on PM2.5 are wind speed > atmospheric pressure > temperature > humidity. The relevance between PM2.5 concentrations and weather factors was illustrated using MLRA, and the corresponding model could forecast the change of PM2.5 concentration. The temporal variation of the concentration of metals in PM2.5 was similar to those of PM2.5 concentration. The spatial distribution of metals in PM2.5 was BRI (0.862) > RDI (0.802) > SWH (0.774) > LYH (0.741) > LZU (0.411 μg·m⁻³). Metal distribution showed different seasonal and spatial variations, which is related to different sources of them. The major source of Fe and Cu in PM2.5 is construction dust, Pb and As is industrial, and Hg is coal combustion. In addition, Cd, V, Co, and Mn in PM2.5 are mainly derived from dust produced by the weathering of soil or rock. In general, geographical location, source, and meteorological factors are the main reasons for the differences in spatiotemporal distribution of PM2.5 and its bound metals. The results of this study provide guidance for controlling of emissions and prevention of air pollution in Lanzhou City.

Data accessibility statement
All relevant data are available in the supplementary materials.

Supplemental files
The supplemental files for this article can be found as follows:

Figure S1. The instrument details and schematic diagram of PM2.5 sampler in this study, the particle was detected by β-ray attenuation principle.

Table S1. The setting parameters of instrument.

---

Table 3. The results of PCA for metals in PM2.5. DOI: https://doi.org/10.1525/elementa.2020.00125.t3

| Elements | PC1 | PC2 | PC3 | PC4 | RPC1 | RPC2 | RPC3 | RPC4 |
|----------|-----|-----|-----|-----|------|------|------|------|
| V        | 0.906 | -0.185 | -0.063 | 0.122 | 0.638 | 0.673 | -0.099 | 0.068 |
| Mn       | 0.716 | 0.515 | 0.004 | -0.025 | 0.869 | 0.021 | 0.143 | -0.058 |
| Fe       | 0.871 | 0.156 | 0.271 | -0.180 | 0.856 | 0.224 | -0.310 | -0.096 |
| Co       | 0.931 | 0.071 | -0.078 | 0.010 | 0.795 | 0.493 | -0.009 | -0.050 |
| Pb       | 0.763 | -0.371 | -0.277 | 0.201 | 0.382 | 0.828 | 0.032 | 0.070 |
| Cu       | 0.849 | 0.271 | 0.084 | 0.047 | 0.861 | 0.246 | -0.026 | 0.041 |
| Cd       | -0.103 | 0.455 | -0.789 | 0.254 | 0.013 | -0.009 | 0.948 | -0.069 |
| Sb       | 0.491 | -0.407 | 0.118 | -0.209 | 0.216 | 0.474 | -0.412 | -0.152 |
| As       | -0.561 | 0.616 | 0.346 | -0.071 | -0.076 | 0.898 | 0.046 | 0.063 |
| Hg       | -0.064 | -0.039 | 0.396 | 0.901 | -0.028 | -0.026 | -0.028 | 0.986 |
| EV       | 5.024 | 1.402 | 1.299 | 1.024 | 39.04 | 23.54 | 10.96 | 9.369 |
| VC/%     | 51.34 | 12.40 | 9.964 | 9.225 | 39.04 | 23.54 | 10.96 | 9.369 |

PC = principal component; RPC = rotated principal component; EV = eigenvalue; VC = variance contribution rate (%).
Table S2. Quality control in metal determination process.

Table S3. The concentration of atmospheric PM$_{2.5}$ in Lanzhou (mg·m$^{-3}$). This is the original data of Figure 2 in the manuscript. LZU = Lanzhou University; BPI = Biological Products Institute; RDI = Railway Design Institute; SWH = Staff and Works Hospital; LYH = Lanyuan Hotel.

Table S4. The concentration of bound heavy metals in atmospheric PM$_{2.5}$ in Lanzhou (μg·m$^{-3}$). This is the original data of Figure 5 and Figure 6 in the manuscript.

Funding
This research was financially supported by the Major Special Projects of the Ministry of Science and Technology of China (2016YFC020600), the Young Scholars Science Foundation of Lanzhou Jiaotong University (20180333), and the Talent Innovation and Entrepreneurship Projects of Lanzhou (2018-RC-84).

Competing interests
The authors have no competing interests to declare.

Author contributions
Conception and research design: YL, BZ, WN.
Acquisition of data: YL, XD, JC.
Analysis and interpretation of data: YL, KD.
Drafting the article: YL, KD.
Critical revision of article: YL, BZ.
Final article approval: BZ.

References
Amato, F, Hopke, PK., 2012. Source apportionment of the ambient PM$_{2.5}$ across St. Louis using constrained positive matrix factorization. Atmospheric Environment 46: 329–337. DOI: http://dx.doi.org/10.1016/j.atmosenv.2011.09.062.

Amos, PKT, Loretta, JM, Daniel, JJ. 2010. Correlations between fine particulate matter (PM$_{2.5}$) and meteorological variables in the United States: Implications for the sensitivity of PM$_{2.5}$ to climate change. Atmospheric Environment 44(32): 3976–3984. DOI: http://dx.doi.org/10.1016/j.atmosenv.2010.06.060.

Baumgartner, J, Zhang, YX, Schauer, JJ, Huang, W, Wang, YQ, Ezzati, M. 2014. Highway proximity and black carbon from cookstoves as a risk factor for higher blood pressure in rural China. Proceedings of the National Academy of Sciences 111: 13229–13234. DOI: http://dx.doi.org/10.1073/pnas.1317176111.

Brook, RD. 2008. Cardiovascular effects of air pollution. Clinical Science 115: 175–187. DOI: http://dx.doi.org/10.1042/CS20070444.

Chaloulakou, A, Kassomenos, P, Spyrellis, N, Demokritou, P, Kourtrakis, P. 2003. Measurements of PM$_{10}$ and PM$_{2.5}$ particle concentrations in Athens, Greece. Atmospheric Research 70: 649–660. DOI: http://dx.doi.org/10.1016/S0169-8095(02)00898-1.

Chen, T, He, J, Lu, X, She, J, Guan, Z. 2016. Spatial and temporal variations of pm$_{2.5}$ and its relation to meteorological factors in the urban area of Nanjing, China. International Journal of Environmental Research and Public Health 13(9): 921. DOI: http://dx.doi.org/10.3390/ijerph13090921.

Cheng, Z, Luo, LN, Wang, SX, Wang, YG, Sharma, S, Shimadera, H, Wang, XL, Bressi, M, de Miranda, RM, Jiang, JK, Zhou, W, Fajardo, O, Yan, NQ, Hao, JM. 2016. Status and characteristics of ambient PM$_{2.5}$ pollution in global megacities. Environmental International 89–90: 212–221. DOI: http://dx.doi.org/10.1016/j.envint.2016.02.003.

Chu, PC, Chen, YC, Lu, SH, Li, ZC, Lu, YQ. 2018. Particulate air pollution in Lanzhou China. Environmental International 34: 698–713. DOI: http://dx.doi.org/10.1016/j.envint.2017.12.013.

Dai, F, Chen, M, Yang, B. 2020. Spatiotemporal variations of PM$_{2.5}$ concentration at the neighborhood level in five Chinese megacities. Atmospheric Pollution Research. DOI: http://dx.doi.org/10.1016/j.apr.2020.03.010.

Du, Z, Hu, YG, Buttar, NA. 2020. Analysis of mechanical properties for tea stem using grey relational analysis coupled with multiple linear regression. Scientia Horticulturae 260: 108886. DOI: http://dx.doi.org/10.1016/j.scienta.2019.108886.

Feng, XY, Wang, SG. 2012. Influence of different weather events on concentrations of particulate matter with different sizes in Lanzhou, China. Journal of Environmental Sciences 24: 665–674. DOI: http://dx.doi.org/10.1016/S1001-0742(11)60807-3.

Gao, Y, Arimoto, R, Duce, RA, Lee, DS, Zhou, MY, 1992. Input of atmospheric trace elements and mineral matter to the Yellow Sea during the spring of a low-dust year. Journal of Geophysical Research: Atmospheres 97: 3767–3777. DOI: http://dx.doi.org/10.1029/91JD02686.

Gao, Y, Guo, XY, Ji, HB, Li, C, Ding, HJ, Brikii, M, Tang, L, Zhang, Y. 2016. Potential threat of heavy metals and PAHs in PM$_{2.5}$ in different urban functional areas of Beijing. Atmospheric Research 178–179: 6–16. DOI: http://dx.doi.org/10.1016/j.atmosres.2016.03.015.

General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China, Standardization Administration of the People’s Republic of China. 2008a. Soil quality—Analysis of total mercury, arsenic and lead contents—Atomic fluorescence spectrometry—Part 1: Analysis of total mercury contents in soils (GB/T 22105.1-2008). Beijing: China Standards Press. Available at https://www.doc88.com/p-1893004122523.html. Accessed 1 October 2008.

General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China, Standardization Administration of the People’s Republic of China. 2008b. Soil quality—Analysis of total mercury, arsenic and lead contents—Atomic fluorescence spectrometry—Part 2: Analysis of total arsenic contents in soils (GB/T 22105.2-2008). Beijing, China: China Standards Press. Available at https://www.doc88.com/p-9079120192943.html. Accessed 1 January 2008.
Götze, R, Boldrin, A, Scheutz, C, Astrup, TF. 2016. Physico-chemical characterisation of material fractions in household waste: Overview of data in literature. Waste Management 49: 3–14. DOI: http://dx.doi.org/10.1016/j.wasman.2016.01.008.

Harrison, RM, Yin, J, Mark, D, Stedman, J, Appleby, RS, Booker, J, Moorcroft, S. 2001. Studies of the coarse particle (2.5-10 μm) component in UK urban atmospheres. Atmospheric Environment 35: 3667–3679. DOI: http://dx.doi.org/10.1016/S1352-2310(00)00526-4.

Hu, B, Zhao, R, Chen, S, Yue, Z, Jin, B, Li, Y, Shi, Z. 2018. Heavy metal pollution delineation based on uncertainty in a coastal industrial city in the Yangtze River Delta, China. International Journal of Environmental Research and Public Health 15(4): 710. DOI: http://dx.doi.org/10.3390/ijerph15040710.

Hu, XM, Zhang, Y, Jacobson, MZ, Chan, CK. 2008. Coupling and evaluating gas/particle mass transfer treatments for aerosol simulation and forecast. Journal of Geophysical Research: Atmospheres 113: D111208. DOI: http://dx.doi.org/10.1029/2007JD009588.

Huang, FF, Li, X, Wang, C, Xu, Q, Wang, W, Luo, YX, Tao, LX, Gao, Q, Guo, J, Chen, SP, Cao, K, Liu, L, Gao, N, Liu, XT, Yang, K, Yan, AS, Guo, XH. 2015. PM$_{2.5}$ spatiotemporal variations and the relationship with meteorological Factors during 2013-2014 in Beijing, China. PLoS One 10: e0141642. DOI: http://dx.doi.org/10.1371/journal.pone.0141642.

Huang, H, Jiang, Y, Xu, XY, Cao, XD. 2018. In vitro bioaccessibility and health risk assessment of heavy metals in atmospheric particulate matters from three different functional areas of Shanghai, China. Science of the Total Environment 610–611: 546–554. DOI: http://dx.doi.org/10.1016/j.scitotenv.2017.08.074.

Hussein, T, Karppinen, A, Kukkonen, J, Harkonen, J, Aalto, PF, Hameri, K, Kerminen, KV, Kulmala, M. 2006. Meteorological dependence of size-fractionated number concentrations of urban aerosol particles. Atmospheric Environment 40: 1427–1440. DOI: http://dx.doi.org/10.1016/j.atmosenv.2005.10.061.

Khadidja, N, Mhamed, M, Lazreg, B, Heilmeier, H, Kharytonov, M. 2019. Quantification of mass concentrations aerosols PM$_{2.5}$ in primary schools. A case study: Tiaret City (Algeria). Environmental Research, Engineering and Management 75: 47–59. DOI: http://dx.doi.org/10.5755/j01.erem.75.2.21601.

Li, JJ, Wang, GH, Wang, XM, Cao, JJ, Sun, T, Cheng, CL, Meng, JJ, Hu, TF, Liu, SX. 2013. Abundance, composition and source of atmospheric PM$_{2.5}$ at a remote site in the Tibetan Plateau, China. Tellus B 65: 20281. DOI: http://dx.doi.org/10.3402/tellusb.v65i0.20281.

Li, YP, Zhang, ZS, Liu, HF, Zhou, H, Fan, ZY, Lin, M, Wu, DL, Xia, BC. 2016. Characteristics, sources and health risk assessment of toxic heavy metals in PM$_{2.5}$ at a megacity of southwest China. Environmental Geochemistry and Health 38: 353–362. DOI: http://dx.doi.org/10.1007/s10653-015-9722-z.

Liu, K, Shang, Q, Wan, C, Song, P, Ma, C, Cao, L. 2017. Characteristics and sources of heavy metals in PM$_2.5$ during a typical haze episode in rural and urban areas in Taiyuan, China. Atmospheric Environment 91: 2. DOI: http://dx.doi.org/10.1016/j.atmosenv.2016.03.057.

Ma, X, Ren, XQ, Liu, JJ, Liu, Y. 2014. Study on distribution and source apportionment of heavy metals in atmospheric particulate matter in Gansu, Ningxia and Inner Mongolia sections of the yellow river of China. Applied Mechanics and Materials 675–677: 363–366. DOI: http://dx.doi.org/10.4028/www.scientric.net/AMM.675-677.363.

Mckenzie, ER, Money, JE, Green, PG, Young, TM. 2009. Metals associated with stormwater-relevant brake and tire samples. Science of the Total Environment 407(22): 5855–5860. DOI: http://dx.doi.org/10.1016/j.scitotenv.2009.07.018.

Ministry of Ecology and Environment of the People’s Republic of China. 2011. Determination of atmospheric articles PM$_{10}$ and PM$_{2.5}$ in ambient air by gravimetric method (HJ 618–2001). Beijing, China: China Environmental Press. Available at http://www.doc88.com/p-6641339537692.html. Accessed 1 November 2011.

Ministry of Ecology and Environment of the People’s Republic of China. 2013. Ambient air and stationary source emission – Determination of metals in ambient particulate matter – Inductively coupled plasma/mass spectrometry (ICP-MS) (HJ 657–2013). Beijing, China: China Environmental Press. Available at http://www.doc88.com/p-1052907669719.html. Accessed 1 September 2013.

Odashi, M, Muezzinoğlu A, Bozlaker, A. 2002. Ambient concentrations and dry deposition fluxes of trace elements in Izmir, Turkey. Atmospheric Environment 36(38): 5841–5851. DOI: http://dx.doi.org/10.1016/s1352-2310(02)00644-1.

Olivares, G, Johansson, C, Ström, J, Hannson, HC. 2007. The role of ambient temperature for particle number concentrations in a street canyon. Atmospheric Environment 41: 2145–2155. DOI: http://dx.doi.org/10.1016/j.atmosenv.2006.10.068.

Pan, L, Xu, J, Tie, X, Mao, X, Gao, W, Chang, L. 2019. Long-term measurements of Planetary Boundary Layer height and interactions with PM$_{2.5}$ in Shang- hai, China. Atmospheric Pollution Research 10(3): 989–996. DOI: http://dx.doi.org/10.1016/j.apr.2019.01.007.

Qiu, XH, Duan, L, Gao, J, Wang, SL, Chai, FH, Hu, J, Yun, YR. 2016. Chemical composition and source apportionment of PM$_{10}$ and PM$_{2.5}$ in different functional areas of Lanzhou, China. Journal of...
Environmental Sciences 40: 75–83. doi: http://dx.doi.org/10.1016/j.jes.2015.10.021.
Shi, J.J., Chen, R.J., Yang, C.Y., Lin, Z.J., Cai, J., Xia, Y.J., Wang, C.C., Li, H.C., Johnson, N., Xu, X.H., Zhao, Z.H., Kan, H.D. 2016. Association between fine particulate matter chemical constituents and airway inflammation: A panel study among healthy adults in China. Environmental Research 150: 264–268. doi: http://dx.doi.org/10.1016/j.envres.2016.06.022.

Soleimani, M., Amini, N., Sadeghian, B., Wang, D., Fang, L. 2018. Heavy metals and their source identification in particulate matter (PM2.5) in Isfahan City, Iran. Journal of Environmental Sciences 72: 166–175. DOI: http://dx.doi.org/10.1016/j.jes.2018.01.002.

Sun, R.G., Fan, L., Chen, Z. 2019. Temporal and spatial distribution characteristics of atmospheric PM2.5 concentrations in Guiyang, China. Nature Environment & Pollution Technology 18: 663–671.

Talbi, A., Kerchich, Y., Kerbachi, R., Boughedaoui, M. 2018. Assessment of annual air pollution levels with PM1, PM2.5, PM10 and associated heavy metals in Algiers. Environmental Pollution 232: 252–263. DOI: http://dx.doi.org/10.1016/j.envpol.2017.09.041.

Terrouche, A., Ali-Khodja, H., Kemmouche, A., Bouziane, M., Derradj, A., Charron, A. 2016. Identification of sources of atmospheric particulate matter and trace metals in Constantine, Algeria. Air Quality, Atmosphere & Health 9(1): 69–82. DOI: http://dx.doi.org/10.1007/s11869-014-0308-1.

Tshehla, C., Wright, C.Y. 2019. Spatial variability of PM10, PM2.5 and PM chemical components in an industrialised rural area within a mountainous terrain. South African Journal of Science 115: 31–40. DOI: http://dx.doi.org/10.17159/sajs.2019.6174.

Varol, M. 2011. Assessment of heavy metal contamination in sediments of the Tigris River (Turkey) using pollution indices and multivariate statistical techniques. Journal of Hazardous Materials 195: 355–364. DOI: http://dx.doi.org/10.1016/j.jhazmat.2011.08.051.

Wang, J., Hu, Z.M., Chen, Y.Y., Chen, Z.L., Xu, S.Y. 2013. Contamination characteristics and possible sources of PM10 and PM2.5 in different functional areas of Shanghai, China. Atmospheric Environment 68: 221–229. DOI: http://dx.doi.org/10.1016/j.atmosenv.2012.10.070.

Wang, J., Zhang, X., Yang, Q., Zhang, K., Zheng, Y., Zhou, G. 2018. Pollution characteristics of atmospheric dustfall and heavy metals in a typical inland heavy industry city in China. Journal of Environmental Sciences. DOI: http://dx.doi.org/10.1016/j.jes.2018.05.031.
How to cite this article: Li, Y, Zhao, B, Duan, K, Cai, J, Niu, W, Dong, X. 2021. Contamination characteristics, mass concentration, and source analysis of metal elements in PM$_{2.5}$ in Lanzhou, China. *Elementa: Science of the Anthropocene* 9(1). DOI: https://doi.org/10.1525/elementa.2020.00125

**Domain Editor-in-Chief:** Detlev Helmig, Boulder AIR LLC, Boulder, CO, USA

**Associate Editor:** Md Firoz Khan, Department of Chemistry, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia

**Knowledge Domain:** Atmospheric Science

**Published:** September 03, 2021  **Accepted:** June 25, 2021  **Submitted:** August 29, 2020

**Copyright:** © 2021 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See http://creativecommons.org/licenses/by/4.0/.

*Elem Sci Anth* is a peer-reviewed open access journal published by University of California Press.