

Effects of Metallic Components in Ambient PM_{2.5} on Pediatric Respiratory Diseases in Shijiazhuang

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Research Article

Keywords: PM_{2.5}, Metal composition, Children, Respiratory diseases, Mixed exposure

Posted Date: May 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9565618/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

Short-term effects of ambient PM_{2.5} on children's respiratory health are a major concern, yet evidence on individual and combined exposure to its metal components remains limited, especially in typical industrial cities.

Methods

Based on daily data on pediatric respiratory outpatient visits, concentrations of 12 PM_{2.5}-bound metals, and meteorological variables in Shijiazhuang from 2020 to 2023, a generalized additive model was used to assess short-term lag effects of individual metals, and a quantile g-computation model was applied to evaluate the joint effect of metal mixtures. Stratified analyses were further performed by sex and age.

Results

Multiple metals were significantly associated with increased risks of pediatric respiratory outpatient visits. Lead (Pb) and zinc (Zn) showed the strongest effects: at lag0-7 days, each interquartile range increment in Pb and Zn concentrations corresponded to increases of 13.188% (95%CI: 9.157%-17.369%) and 9.685% (95%CI: 5.612%-13.915%) in total visits, respectively. Pb had the strongest effect on acute upper respiratory infections (excess risk = 24.510%). Girls were more sensitive to Ca, Fe, K, and Zn, while Pb and Zn had a greater impact on children aged 7–14 years than on those aged 0–6 years. Combined exposure to eight metals was associated with a 3.059-fold (95%CI: 2.416–3.444) increase in outpatient risk per decile increase, with Pb and Cr contributing the highest weights.

Conclusions

Multiple PM_{2.5}-bound metals in Shijiazhuang significantly increase the risk of pediatric respiratory outpatient visits, with variations by disease subtype, sex, and age. Priority should be given to reducing Pb and Cr emissions and developing differentiated health protection strategies for school-aged children and girls.

1. Introduction

With the continuous advancement of industrialization and urbanization worldwide, air pollution has become a severe public health challenge[1]Extensive epidemiological evidence indicates that both short-term and long-term exposure to PM_{2.5} is significantly associated with an increased risk of multiple adverse health outcomes in populations, including outpatient visits, hospitalizations, and mortality[2–4]Respiratory diseases are a major global health burden[5]. PM_{2.5} is a critical environmental factor contributing to the incidence and mortality of respiratory diseases[6–8]. The health hazards of PM_{2.5} exhibit pronounced spatial heterogeneity,which may be closely related to regional variations in its chemical composition[9].Among the complex chemical constituents of PM_{2.5}, heavy metals and metalloids such as arsenic(As), cadmium(Cd), chromium(Cr), and lead(Pb)have garnered particular attention[10]. Epidemiological studies have suggested associations between exposure to these metallic components and the risk of cardiopulmonary diseases[11–13].

Children, with their underdeveloped respiratory systems and weaker immune functions, are particularly vulnerable to air pollution. The metallic components in PM_{2.5}exhibit specific associations with asthma onset[14]and symptom exacerbation[15]. While existing studies have predominantly focused on the health impacts of PM_{2.5} mass concentration,

systematic evaluations of the effects of its specific metallic components-particularly in typical industrial pollution areas-on children's health remain limited[16]. Therefore, conducting studies on the health effects of specific components in key regions holds significant practical importance.

This study used hospital visit data as an indicator of acute health effects, with Shijiazhuang City as the study area. Using daily data on pediatric respiratory disease outpatient visits, concentrations of metal and metalloid (hereinafter referred to as metals) components in $PM_{2.5}$, and meteorological variables from 2020 to 2023, we quantitatively assessed the impact of metallic components in ambient $PM_{2.5}$ on pediatric respiratory diseases, identified susceptible populations, and provided a scientific basis for future early warning of children's health risks and targeted air pollution prevention and control measures.

2. Materials and Methods

2.1 Study Area

Shijiazhuang City (37°27'–38°47'N, 113°30'–115°20'E) is situated in the south-central part of Hebei Province. It stands as one of the largest transportation hubs and industrial cities on the North China Plain[17], featuring a typical warm temperate continental monsoon climate. Although air quality has improved in recent years, pollution issues persist.

2.2 Data Sources

Daily outpatient visit data for pediatric respiratory diseases from January 1, 2020, to December 31, 2023, were obtained from Hebei Children's Hospital. Outpatient records were screened using the International Classification of Diseases, 10th Revision (ICD-10) codes (J00–J99 and R04–R09.3). Respiratory diseases were further categorized into: acute upper respiratory infections (J00–J06) (AURIs); influenza and pneumonia (J09–J18) (FLU&PN); and acute lower respiratory infections (J20–J22) (ALRIs). Daily average concentrations of metallic components in ambient $PM_{2.5}$ and routine air pollutant monitoring data in Shijiazhuang were obtained from the Shijiazhuang Environmental Forecasting and Prediction Center. Among these, 18 heavy metal components were determined using an XHAM-2000A atmospheric heavy metal analyzer, which employs a combined method of β -ray absorption and X-ray fluorescence spectrometry. Meteorological data, including daily average temperature (°C) and daily average relative humidity (%), were obtained from the Shijiazhuang Meteorological Service Center.

2.3 Data Quality Control

Systematic quality control was performed separately for outpatient data and environmental monitoring data. For outpatient data, cases with age >14 years and non-residents of urban Shijiazhuang were excluded. Duplicate records were removed based on patient demographic and clinical information. Due to equipment malfunctions or other factors, some metal component data were missing. Only metal elements with a missing rate $\leq 5\%$ were included in subsequent analyses. Ultimately, 12 metal elements were included: arsenic (As), barium (Ba), calcium (Ca), chromium (Cr), iron (Fe), mercury (Hg), potassium (K), manganese (Mn), lead (Pb), selenium (Se), vanadium (V), and zinc (Zn). For the remaining missing data on these metal components, multiple imputation[18] was employed to ensure data integrity and analytical reliability.

2.4 Basic Description

To characterize the distribution of pediatric respiratory disease outpatient visits, meteorological factors, air pollutants, and metal components in $PM_{2.5}$, the Kolmogorov–Smirnov normality test was first applied. The results indicated that none of these datasets followed a normal distribution. Therefore, the median, quartiles (P25, P75), minimum (Min), and maximum (Max) were used to describe their central tendency and dispersion. As all data collected in this study were non-

normally distributed, Spearman's rank correlation analysis was employed to examine correlations between PM_{2.5} mass concentration, metal component concentrations, and meteorological factors (daily average temperature and daily average relative humidity).

2.5 Effects of Exposure to Individual Metallic Components in Ambient PM_{2.5} on Pediatric Respiratory Diseases

2.5.1 Single-Metal Composition Model

A generalized additive model (GAM) with a Poisson distribution was employed to assess the short-term effects of individual metallic components in ambient PM_{2.5} on pediatric respiratory outpatient visits. Pediatric respiratory disease outpatient events are low-probability occurrences, and daily visit counts approximately follow a Poisson distribution; therefore, a Poisson link function was selected for the time series analysis. To control for potential confounding factors, the model incorporated the following variables: a natural cubic spline smoothing function to control for long-term temporal trends (with 7 degrees of freedom per year for time), as well as to adjust for the nonlinear effects of daily mean temperature and daily mean relative humidity (each with 3 degrees of freedom); a categorical variable for day of the week; and a binary variable indicating the COVID-19 pandemic control period to account for its impact on outpatient volume.

Based on the aforementioned control conditions, the model degrees of freedom were optimized using the Akaike information criterion (AIC). The final degrees of freedom for the time variable, daily mean temperature, and daily mean relative humidity were set to 5 per year, 3, and 3, respectively. Individual metallic components-Ca, Fe, K, Mn, and Zn-in ambient PM_{2.5} were sequentially incorporated into the model to assess their exposure-response relationships with pediatric respiratory disease outpatient visits in Shijiazhuang. The basic form of the model is as follows:

$$\text{Log}[E(Y_t)] = \beta Z_t + ns(\text{Time}, 5) + ns(TM, 3) + ns(RH, 3) + nCov + DOW + \alpha \quad (1)$$

In the formula :

$E(Y_t)$ -Expected Daily Outpatient Volume for Pediatric Respiratory Diseases on Day t

β -Exposure-Response Relationship Coefficient

Z_t -Concentrations of Metal Components in Atmospheric PM_{2.5} on Day t , $\mu\text{g}/\text{m}^3$

ns -natural spline smoothing function

Time - time variable

TM -Average daily temperature $^{\circ}\text{C}$

RH -daily average relative humidity%

$nCov$ -The Impact of the COVID-19 Pandemic

DOW -Day-of-the-week effect, for Monday through Sunday, dummy variables

α -Intercept, constant term

Referencing previous studies [19, 20], we incorporated both discrete lags (lag0 to lag7 days) and moving average lags (lag0-1 to lag0-7 days) to analyze the effects of exposure to different metallic components in ambient PM_{2.5} on pediatric

respiratory diseases. Specifically, lag0 represents exposure on the day of the outpatient visit, i.e., the concentration of each metallic component in ambient PM_{2.5} on that day; lag1 denotes the concentration on the previous day; and lag0-1 indicates the average concentration of each metallic component over the day of the visit and the preceding day, and so forth.

Based on the exposure-response coefficients (β) obtained from the GAM, we quantitatively assessed the percentage change in excess risk (ER) and its 95% confidence interval (CI) for pediatric respiratory disease outpatient visits associated with each interquartile range (IQR) increase in the concentration of each metallic component in ambient PM_{2.5}. Finally, the optimal lag period for each metallic component was determined based on the principle of maximizing the ER value.

2.5.2 Stratified analysis

Stratified analyses were conducted by gender (boys, girls) and age (0-6 years, 7-14 years). Using the optimal lag period determined from the single-metal component models, we analyzed the effects of individual metallic components in ambient PM_{2.5} on different subgroups of children. The significance of differences in effect estimates between subgroups (gender and age) was tested using Equation (2). A difference was considered statistically significant if its 95% confidence interval (CI) excluded zero[21]. The specific formula is as follows:

$$(\beta_1 - \beta_2) \pm 1.96 \sqrt{(SE_1)^2 + (SE_2)^2} \quad (2)$$

In the formula:

β_1 and β_2 -Estimates of effects for different subgroups(ER)

SE_1 and SE_2 -Standard errors corresponding to different subgroups

2.5.3 Sensitivity Analysis

To validate the robustness of the single-metal component models, we conducted a sensitivity analysis. By varying the degrees of freedom for the long-term temporal trend (5 to 6 per year), daily mean temperature (3 to 4), and daily mean relative humidity (3 to 4), we examined how changes in the concentrations of individual metallic components in ambient PM_{2.5} affected pediatric respiratory disease outpatient visits.

2.6 Effects of Combined Exposure to Metallic Components in Ambient PM_{2.5} on Pediatric Respiratory Diseases

The quantile g-computation(Qgcomp)model was employed to assess the combined effect of exposure to mixtures of metallic components in ambient PM_{2.5} on pediatric respiratory disease outpatient visits. To focus on metals with robust and significant effects at the level of total respiratory outpatient visits, we incorporated metal elements that showed statistically significant associations ($P < 0.05$) in the single-metal GAM analysis into the Qgcomp mixed-exposure model, using the optimal lag concentration for each metal identified in the total outpatient model. The analysis was conducted at the decile level, estimating the change in pediatric respiratory disease outpatient visits associated with a simultaneous one-decile increase in all metal elements.

All statistical analyses were performed using R software (version 4.4.2). Two-tailed statistical tests were used, and $P<0.05$ was considered statistically significant.

3. Results

3.1 Basic Situation Description

3.1.1 Outpatient Visits for Pediatric Respiratory Diseases and Meteorological Factors

From 2020 to 2023, a total of 841, 934 outpatient visits for pediatric respiratory diseases were recorded in Shijiazhuang City, with a median daily outpatient volume of 550 visits. The majority of visits were by male children (median daily: 319 visits) and children aged 0-6 years (median daily: 437 visits). Among these, acute upper respiratory tract infections accounted for 33.3% of all pediatric respiratory disease outpatient visits, while influenza and pneumonia and acute lower respiratory tract infections accounted for 15.4% and 13.8%, respectively. During the same period, the average daily temperature was 15.8°C, and the average daily relative humidity was 59.0% (Table 1).

Table 1 Descriptive statistics of pediatric respiratory disease outpatient visits and meteorological factors in Shijiazhuang, 2020–2023

Variable	Min	P_{25}	Median	P_{75}	Max
Disease data					
Outpatient volume	38	291	550	831	1587
Gender					
Boys	17	169	319	472	927
Girls	15	119	231	359	677
Age					
0-6 years	21	215	437	684	1083
7-14 years	4	58	93	147	703
Disease type					
AURIs	10	120	187	254	831
FLU&PN	0	25	62	115	562
ALRIs	1	26	71	121	264
meteorological factor					
Daily mean temperature/(°C)	-10.8	6.0	15.8	24.7	35.8
Daily mean relative humidity /(%)	7.0	42.0	59.0	73.0	100.0

Note: AURIs: outpatient visits for acute upper respiratory tract infections; FLU&PN: outpatient visits for influenza and pneumonia; ALRIs: outpatient visits for acute lower respiratory tract infections.

3.1.2 Atmospheric PM_{2.5} and its metallic component concentration data

From 2020 to 2023, the median annual average concentration of PM_{2.5} in Shijiazhuang was 37.0 µg/m³, which exceeds the Grade II annual mean limit (35µg/m³) specified in the Ambient Air Quality Standards (GB3095-2012). During the study

period, Shijiazhuang recorded 252 days with PM_{2.5} concentrations exceeding the standard, corresponding to an exceedance rate of 17.2%. Additionally, the median annual average concentrations of As, Cr, Hg, and Pb were 0.006, 0.005, 0.001, and 0.027 µg/m³, respectively, all within the annual mean limits set by the Ambient Air Quality Standards (GB3095-2012) (As: 0.006 µg/m³; Cr: 0.005 µg/m³; Hg: 0.050 µg/m³; Pb: 0.500 µg/m³) (Table2).

Table 2 Basic Information on Atmospheric PM_{2.5} and Its Metal Components in Shijiazhuang City, 2020–2023

Variable	Median(<i>P</i> ₂₅ – <i>P</i> ₇₅)	IQR
Air pollutant		
PM _{2.5} /(µg/m ³)	37.0(25.0–61.0)	36.0
Metallic components/(µg/m ³)		
As	0.006(0.002–0.011)	0.009
Ba	0.038(0.012–0.097)	0.085
Ca	0.742(0.394–1.982)	1.588
Cr	0.005(0.003–0.008)	0.005
Fe	0.679(0.424–1.170)	0.746
Hg	0.001(0–0.002)	0.002
K	0.637(0.370–0.984)	0.614
Mn	0.039(0.021–0.061)	0.040
Pb	0.027(0.018–0.042)	0.024
Se	0.004(0.002–0.007)	0.005
V	0.001(0–0.003)	0.003
Zn	0.128(0.076–0.202)	0.126

3.2 Effects of Single-Metal Component Exposure on Pediatric Respiratory Disease Outpatient Visits

3.2.1 Effects on Total Pediatric Respiratory Disease Outpatient Visits

The GAM results indicated that As, Ca, Cr,Fe, K, Mn, Pb, and Zn all had significant effects on daily pediatric respiratory disease outpatient visits. Their strongest effects were observed at a moving average lag of 0-7 days (lag0-7), with each IQR increase in concentration associated with respective increases in daily outpatient visits of 5.106% (95% CI: 2.257%-8.035%), 3.473%(95%CI:1.424%-5.563%),2.440%(95%CI:0.252%-4.675%),3.083%(1.194%-5.007%),1.932% (95% CI: 0.789%-3.088%), 4.657% (95% CI: 1.783%-7.612%), ,13.188% (95% CI: 9.157%-17.369%), and 9.685% (95% CI: 5.612%-13.915%). No significant associations were found between Ba, Hg, Se, or V and daily pediatric respiratory disease outpatient visits (Figure1).

3.2.2 Impact on Outpatient Visits for Acute Upper Respiratory Infections in Children

As, Ca, Cr, Fe, K, Mn, Pb, and Zn exhibited significant effects on daily outpatient visits for acute upper respiratory infections in children, with the strongest effects observed at a moving average lag of 0-7 days (lag0-7). For each interquartile range (IQR) increase in concentration, outpatient visits increased by 9.937% (95% CI: 6.424%-13.566%), 5.763% (95% CI: 3.192%-8.397%), 3.421% (95% CI: 0.794%-6.115%), 5.410% (95% CI: 3.040%-7.835%), 2.798% (95% CI: 1.471%-4.142%), 8.439% (95% CI: 4.859%-12.141%), 24.510% (95% CI: 19.309%-29.937%), and 21.327% (95% CI: 15.999%-26.899%), respectively (Figure 2).

3.2.3 Effects on Outpatient Visits for Pediatric Influenza and Pneumonia

Ca, Fe, K, Mn, and Pb exhibited delayed effects on daily outpatient visits for pediatric influenza and pneumonia. Among these, the effects of Fe, Mn, and Pb on daily outpatient visits for pediatric influenza and pneumonia peaked at a lag of 7 days (lag7). For each interquartile range (IQR) increase in concentration, daily outpatient visits increased by 1.979% (95% CI: 0.490%-3.490%), 2.714% (95% CI: 0.562%-4.913%), and 2.476% (95% CI: 0.406%-4.588%), respectively. Ca and K showed the strongest effects at a moving average lag of 0-7 days (lag0-7), with each IQR increase in concentration associated with increases of 3.110% (95% CI: 0.356%-5.940%) and 2.037% (95% CI: 0.836%-3.253%) in daily outpatient visits for pediatric influenza and pneumonia, respectively. No significant effects were observed for As, Cr, or Zn on pediatric influenza and pneumonia outpatient visits (Figure 3).

3.2.4 Effects on Outpatient Visits for Pediatric Acute Lower Respiratory Infections

Ca, Cr, Fe, K, Mn, Pb and Zn were associated with daily outpatient visits for acute lower respiratory infections (ALRIs) in children. The effects of Ca, Cr, Fe, K, Mn, Pb, and Zn on daily pediatric ALRI outpatient visits were strongest at a moving average lag of 0-7 days (lag0-7). For each interquartile range (IQR) increase in concentration, daily ALRI outpatient visits in children increased by 5.081% (95% CI: 2.07%-8.181%), 4.77% (95% CI: 1.437%-8.213%), 3.988% (95% CI: 1.293%-6.755%), 2.464% (95% CI: 0.879%-4.074%), 6.032% (95% CI: 1.785%-10.456%), 12.912% (95% CI: 6.926%-19.233%), and 9.045% (95% CI: 3.031%-15.411%), respectively. No significant association was observed for As (Figure 4).

3.3 Effects of Single-Metal Component Exposure on Outpatient Visits Across Different Subgroups

The optimal lag period for each metallic component in ambient PM_{2.5} affecting pediatric respiratory disease outpatient visits was determined using the single-metal component models. The optimal lag period for As, Ca, Cr, Fe,K, Mn, Pb, and Zn was lag 0-7 days. Stratified analyses were then conducted by gender and age.

Gender-stratified results revealed that Ca, Fe, K, and Zn exerted greater effects on daily respiratory disease outpatient visits in girls than in boys (*P*<0.05). Lead (Pb) showed a significant effect in girls (ER = 14.089%, 95% CI: 9.843%-18.498%), but the intergroup difference was not statistically significant. Age-stratified results indicated that Pb (ER = 16.801%, 95% CI: 11.429%-22.431%) and Zn (ER = 15.799%, 95% CI: 10.194%-21.690%) had significantly stronger effects on children aged 7-14 years than on those aged 0-6 years, with statistically significant intergroup differences (*P*<0.05). Calcium, Fe, and K exhibited more pronounced effects in children aged 0-6 years, and the differences were statistically significant (*P*<0.05). No significant differences were observed for As or Mn across age groups. Additionally, a significant effect of Cr exposure was detected exclusively in the 0-6 age group (Table 3).

Table 3 Gender- and age-stratified analysis of the effects of metallic components in ambient PM_{2.5} on pediatric respiratory disease outpatient visits, Shijiazhuang, 2020–2023

Component	ER%(95%CI)			
	Boys	Girls	0~6 years	7~14 years
As	5.115(2.290~8.017)	5.085(2.112~8.144)	4.944(2.147~7.817)	5.448(1.421~9.636)
Ca*	3.300(1.269~5.370)	3.711(1.571~5.896)	3.967(1.963~6.010)	1.728(-1.243~4.788)
Cr	2.689(0.525~4.900)	2.109(-0.180~4.451)	2.381(0.246~4.561)	2.886(-0.293~6.166)
Fe*	3.043[1.170~4.952]	3.142[1.173 ~ 5.150]	3.536(1.689 ~5.418)	1.739[-1.003~ 4.557]
K*	1.721(0.582~2.873)	2.225(1.039~3.425)	2.219(1.037~3.416)	1.434(0.068~2.819)
Mn	4.856(2.009~7.782)	4.394(1.393~7.483)	4.994(2.174~7.893)	4.042(-0.069~8.322)
Pb*	12.530(8.558~16.646)	14.089(9.843~18.498)	12.102(8.074~16.280)	16.801(11.429~22.431)
Zn*	9.292(5.275~13.462)	10.213(5.934~14.666)	7.780(3.756~11.960)	15.799(10.194~21.690)

* Indicates that the differences between gender or age groups were statistically significant.

3.4 Effects of Combined Exposure to Metallic Components on Pediatric Respiratory Disease Outpatient Visits

The eight metallic components identified in the GAM analysis as influencing the risk of pediatric respiratory disease outpatient visits (As, Ca, Cr, Fe, K, Mn, Pb, and Zn) were incorporated into the Qgcomp model. Without restricting the direction of effects for individual components, combined exposure to these eight metallic components in ambient PM_{2.5} was positively associated with the risk of pediatric respiratory disease outpatient visits. For each decile increase in combined exposure, the odds ratio (OR) for pediatric respiratory disease outpatient visits was 3.059 (95% CI: 2.416-3.444). Weighted results indicated that Pb (0.358) played the dominant role in the positive association, followed by Cr (0.297), As (0.160), and K (0.131).

Subgroup analyses by gender and age revealed that combined exposure to the eight metallic components in ambient PM_{2.5} was positively associated with the risk of respiratory disease outpatient visits among children of different genders and ages. For each one-decile increase in combined exposure, the odds ratios (OR) for respiratory disease outpatient visits were 2.468 (95% CI: 1.826-2.851) for boys, 2.249 (95% CI: 1.605-2.639) for girls, 2.809 (95% CI: 2.194-3.186) for children aged 0–6 years, and 1.541 (95% CI: 0.392-2.062) for children aged 7-14 years. Weighted analysis indicated that among children of different genders, Pb played the dominant role in the positive association (boys: 0.364; girls: 0.350), followed by Cr, As, and K. Among children aged 0-6 years, Cr played the dominant role (0.362), followed by As and Pb. Furthermore, Pb continued to contribute the largest proportion (weight index: 0.518) to the positive association between the mixture of eight metallic components and respiratory disease outpatient visits among children aged 7-14 years (Table 4, Figure 5).

Table 4 Association between combined exposure to eight metallic components in PM_{2.5} and pediatric respiratory disease outpatient visits as assessed by the Qgcomp model

group	$\beta(95\%CI)$	P
Population	3.059(2.416~3.444)	<0.001
Gender		
Boys	2.468(1.826~2.851)	<0.001
Girls	2.249(1.605~2.639)	<0.001
Age		
0~6years	2.809(2.194~3.186)	<0.001
7~14years	1.541(0.392~2.062)	0.004

Note: Covariates including air pollutants and meteorological factors were adjusted for in the model.

3.5 Sensitivity Analysis

To assess the robustness of the single-metal exposure model, we conducted a sensitivity analysis by varying the degrees of freedom for time, temperature, and relative humidity. When the long-term trends of time (Time), daily mean temperature (Temp), and daily mean relative humidity (Rhum) were varied, the estimated effects of exposure to Pb, Zn, Mn, Ca, Fe, and K in atmospheric PM_{2.5} on daily outpatient visits for pediatric respiratory diseases showed no significant changes compared to the base model. However, the estimated effects of arsenic (As) and chromium (Cr) decreased and were no longer statistically significant. Detailed results of the sensitivity analysis are presented in Supplementary Material Table S1.

4. Discussion

This study systematically evaluated the short-term effects of individual and combined exposure to various metallic components in ambient PM_{2.5} on pediatric respiratory disease outpatient visits in Shijiazhuang. The main findings were as follows: (1) Pb and Zn were the individual metallic components with the strongest associations; (2) The health effects of metals exhibited disease-subtype specificity; (3) Girls and children of different age groups showed varying sensitivities to specific metals; (4) Combined exposure to eight metals demonstrated a positive synergistic effect, with Pb and Cr contributing the highest weights. These findings confirm the important role of metallic components in the health hazards of PM_{2.5} and provide a scientific basis for implementing prevention and control strategies tailored to specific metallic components and population differences.

Analysis of the effects of individual metallic component exposure on pediatric respiratory disease outpatient visits revealed that multiple metallic components were significantly associated with the volume of such visits. Among these, Pb and Zn exhibited the most pronounced effects, while As and Mn also showed strong associations. Consistent with our findings, a time-series study in Guangzhou reported that concentrations of As and Cr bound to ambient PM_{2.5} were significantly associated with an increased risk of pediatric outpatient visits for respiratory diseases[22]. Valdés et al. [23] found that particulate matter with high concentrations of Cr, Cu, and S was more strongly associated with mortality from respiratory diseases and chronic obstructive pulmonary disease (COPD). Collectively, these studies confirm that metallic components in ambient PM_{2.5} are closely related to the onset and progression of respiratory diseases.

Subtype analysis revealed that metallic components exert differential effects on various respiratory diseases. Pb showed the strongest association with outpatient visits for acute upper respiratory infections (AURIs) (ER = 24.510%, 95% CI: 19.309%–29.937%), while iron (Fe) and manganese (Mn) also exhibited significant effects on acute lower respiratory infections (ALRIs). These findings suggest that different metals may act on distinct segments of the respiratory tract through varying mechanisms. This observation is consistent with a study conducted in Guangzhou[22], implying that the

specific relationship between pollutant types and disease categories should be considered when formulating prevention and control strategies.

Stratified analysis revealed that the health effects of certain metals vary across different population groups. This study found that girls are more sensitive to exposure to metals such as Ca, Fe, K, and Zn. These differences may be related to intrinsic variations in immune regulation and oxidative stress defense mechanisms. Studies have shown that, at similar exposure levels, girls may exhibit a stronger tendency toward immune activation, and the metabolism of certain metals (e.g., iron) interacts with oxidative stress processes, potentially amplifying their damaging effects on the respiratory mucosa[24]. The effects of Pb and Zn on school-aged children (7-14 years) were significantly greater than those on preschoolers (0-6 years) (Pb: ER = 16.801% vs. 12.102%; Zn: ER = 15.799% vs. 7.780%). This may be due to a substantial increase in outdoor activity time and commuting needs among school-aged children, leading to a significant rise in their respiratory environmental exposure doses[25]. Furthermore, the lungs of children in this age group are still undergoing critical developmental stages, such as alveolarization, making them potentially more sensitive to air pollutants[26]. These findings are consistent with reports from Beijing indicating that school-aged children exhibit a more pronounced response to particulate matter components[27].

Environmental pollutants often coexist in mixtures and act jointly on the human body; their combined effects may not simply be the sum of individual effects but may involve synergistic or antagonistic interactions[28]. In this study, the Qgcomp model was used to analyze the increased risk of pediatric respiratory disease outpatient visits associated with co-exposure to eight metals. The results showed that Pb (weight: 0.358) and Cr (weight: 0.297) contributed the most to the combined effect, suggesting that prioritizing the control of Pb and Cr emissions may yield greater health benefits in the context of complex pollution. This finding aligns with recent research trends on pollutant mixture effects, emphasizing the need to shift from single-pollutant to multi-pollutant synergistic control[29].

Sensitivity analysis indicates that the main findings of this study are generally robust. However, when the number of time-related degrees of freedom was increased, the estimated effects of As and Cr disappeared, which may be related to the model's over-adjustment for short-term trends. Given that As and Cr have lower concentrations in PM_{2.5} and exhibit greater temporal variability, their effects are more susceptible to the influence of model specifications. Nevertheless, major metals such as Pb and Zn remained significant across all sensitivity analyses, further supporting the reliability of their association with outpatient visits for childhood respiratory diseases.

This study has several strengths. First, it focuses on a typical heavily polluted region in northern China, thereby addressing the lack of relevant evidence in this area. Second, it employs both lag models and mixed-exposure models to reveal the health risks associated with metals from different perspectives. Third, it conducts stratified analyses by disease subtype, gender, and age. However, this study also has limitations. The exposure assessment was based on environmental monitoring data from fixed stations and did not account for variations in children's daily activities, which may lead to a misestimation of actual individual exposure levels.

In conclusion, this study confirms that multiple metallic components in ambient PM_{2.5} in Shijiazhuang are significantly associated with the risk of pediatric respiratory disease outpatient visits, with variations observed across disease subtypes and population subgroups. Combined exposure to these metals also exhibited a significant effect, with Pb and Cr contributing the highest weight in the mixture. It is recommended that relevant authorities, while controlling PM_{2.5}, prioritize the regulation of Pb and Cr-Pb primarily originates from industrial emissions and vehicle exhaust, while Cr may stem from industrial activities such as electroplating and metallurgy. Targeted emission reduction measures should be implemented for these key pollution sources. Furthermore, as Pb and Zn are the individual metallic components with the strongest effects, and their impact is particularly pronounced among school-aged children (7-14 years), it is recommended that during heavy pollution alerts, special attention be paid to changes in the concentrations of these two metals, and that personalized health protection advisories be issued for this vulnerable population. Additionally, girls

were more sensitive to metals such as Ca, Fe, and K, indicating that gender differences should be considered in health impact assessments and risk communication. Through these measures, the harm of air pollution to children's health can be minimized to the greatest extent.

5. Conclusions

Multiple metallic components in ambient PM_{2.5} in Shijiazhuang were significantly associated with an increased risk of pediatric respiratory outpatient visits. Pb and Zn showed the strongest single-metal effects. The impacts varied by disease subtype, gender, and age. Girls were more sensitive to Ca, Fe, K, and Zn, while Pb and Zn showed stronger effects in children aged 7-14 years. Combined exposure to eight metals significantly increased the outpatient risk, with Pb and Cr contributing the most. These findings support targeted air pollution control and child health protection strategies.

Declarations

Ethics Approval and Consent to Participate

All participants signed written informed consents prior to the study, and this study was approved by the Ethics Committee of Shijiazhuang Center for Disease Control and Prevention in accordance with the Declaration of Helsinki (Approved on March 6, 2024.).

Consent for publication

Not applicable.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

Funding

This work was supported by the Shijiazhuang Scientific And Technological Projects(2414605403).

Availability of data and materials

The data supporting the findings of this study are available from the corresponding author upon request.

Authors' contributions:

D. X., X.N. and G.M. formulated the research questions and designed the study. D.X. and X.N. wrote the manuscript. C.S. and T.Z. cleaned datasets. G.M., Z.X. and W.L. analyzed data, prepared tables and figures. C.F. and X.M. provided critical study oversight and contributed to the critical revision of the manuscript for important intellectual content. All authors approve the submission and publication of the manuscript.

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Figures

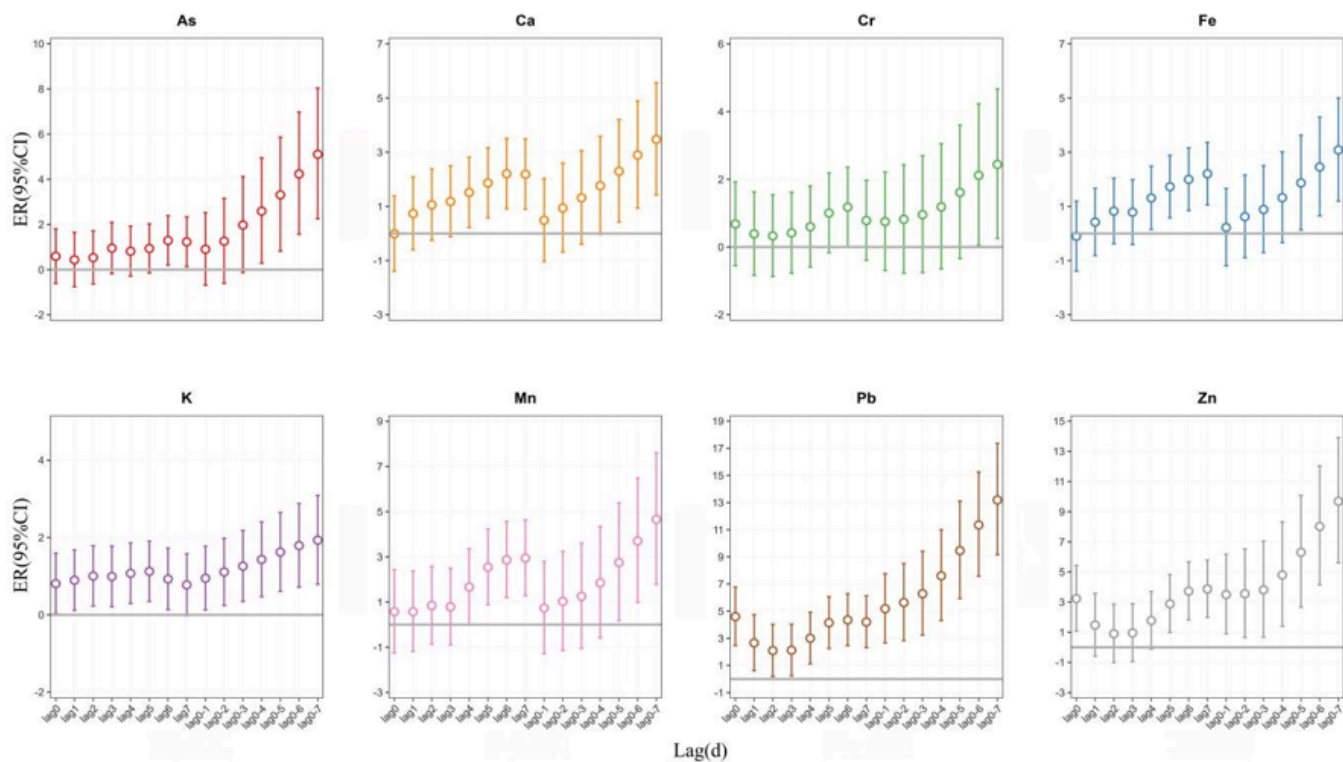


Figure 1

Impact of Metal Components in Atmospheric PM_{2.5} on Total Pediatric Respiratory Disease Outpatient Visits, 2020–2023.

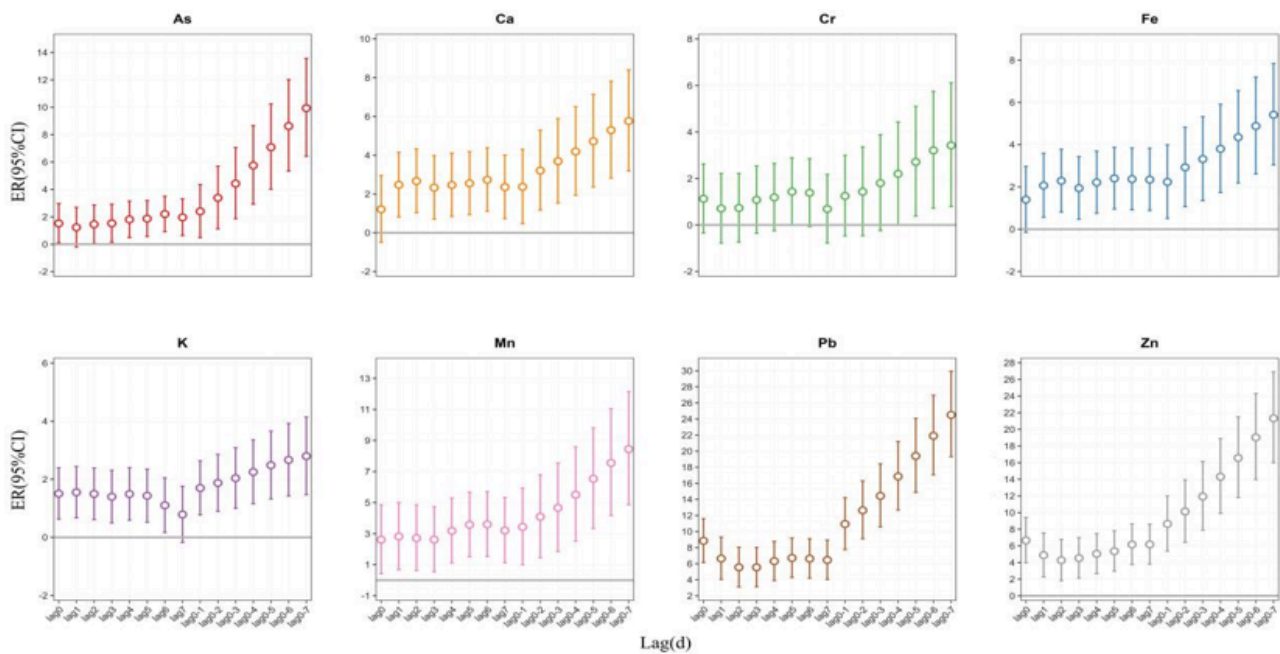


Figure 2

Impact of Metal Components in Atmospheric PM_{2.5} on Outpatient Visits for Acute Upper Respiratory Tract Infections in Children from 2020 to 2023.

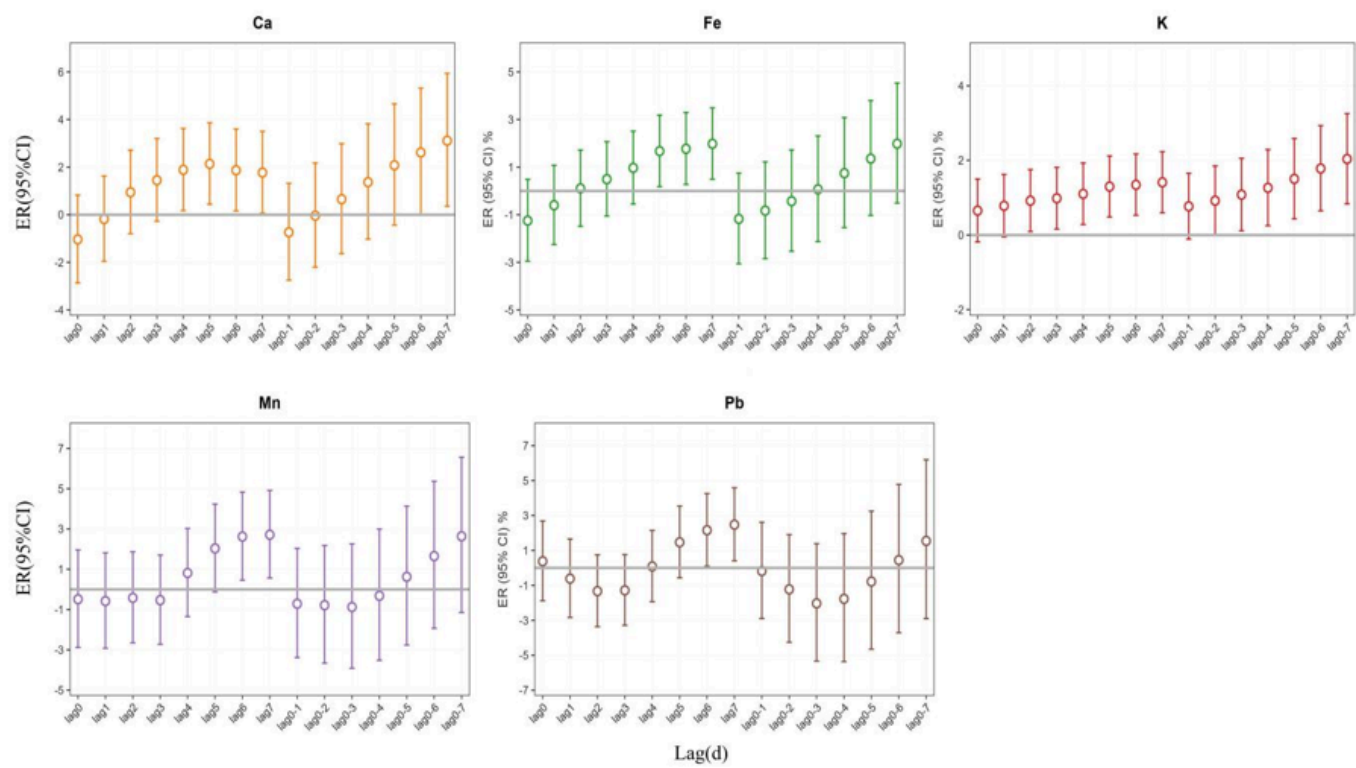


Figure 3

Impact of Metal Components in Atmospheric PM_{2.5} on Outpatient Visits for Influenza and Pneumonia in Children from 2020 to 2023.

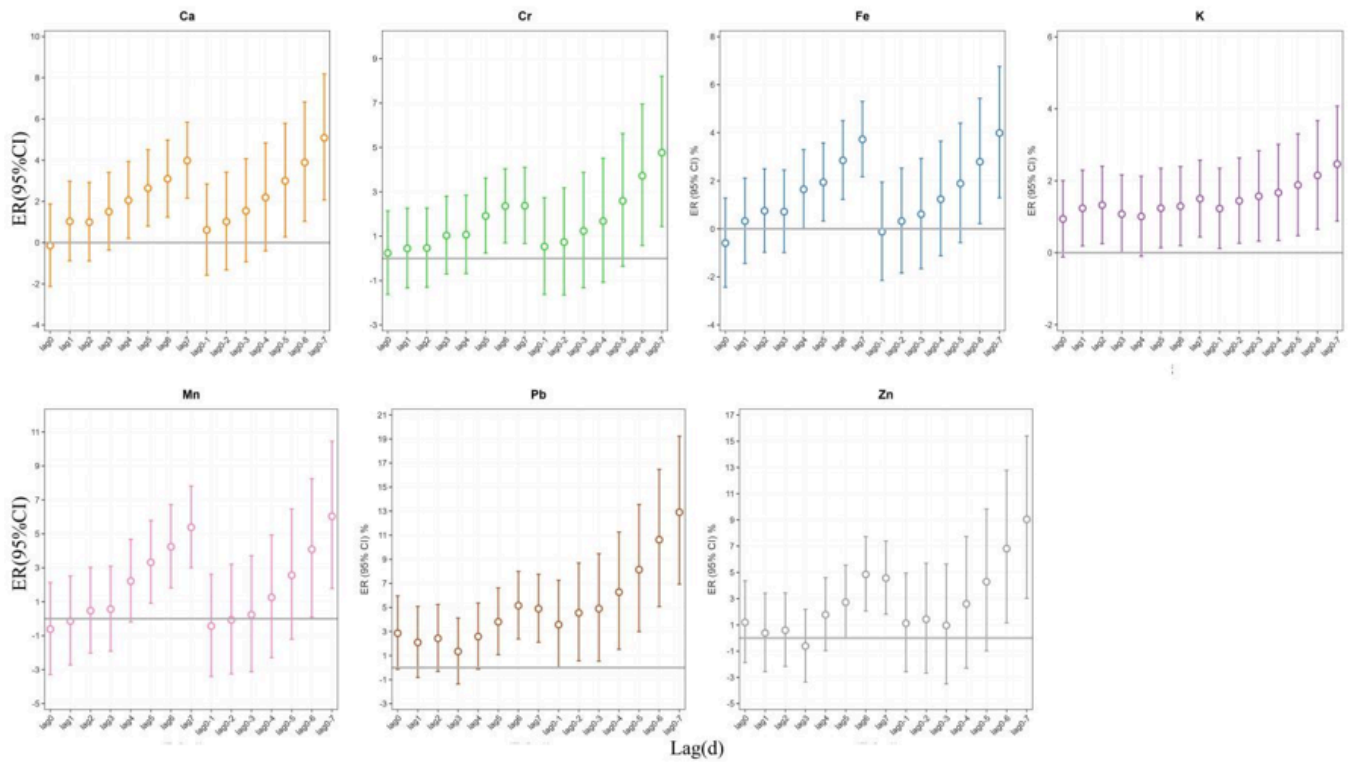


Figure 4

Impact of Metal Components in Atmospheric PM_{2.5} on Pediatric Outpatient Visits for Acute Lower Respiratory Infections, 2020–2023.

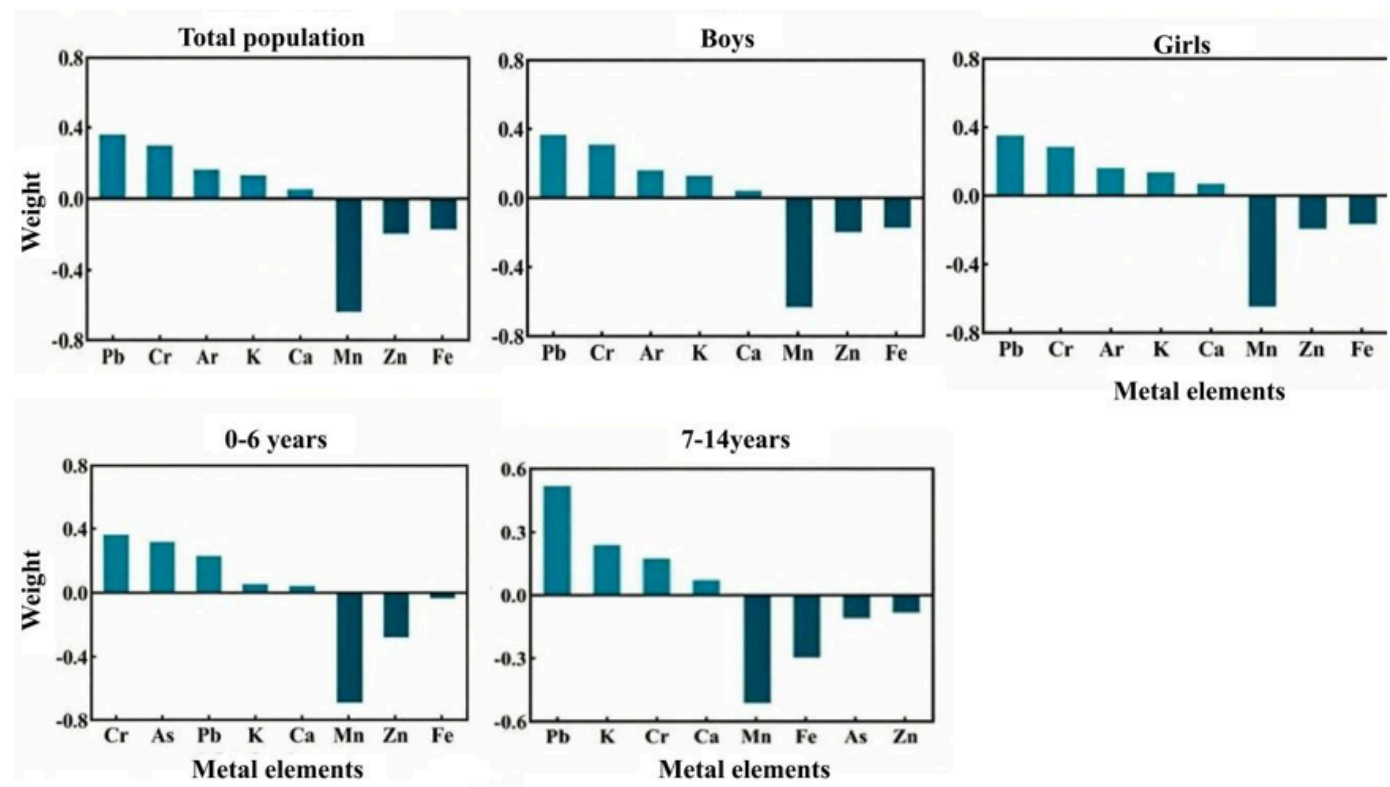


Figure 5

Weight plot of combined exposure to eight metallic components based on the Qgcomp model.

Supplementary Files

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