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Functional-area distribution and non-carcinogenic health risk of heavy metals in street dust from Shanghai, China

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Abstract
Street dust is an important carrier of heavy metals in urban environments and may pose potential health risks to local residents. In this study, the concentrations of Pb, Zn, Cu, Cr, Ni, and Mn in street dust from five functional areas of Shanghai, including industrial, traffic, residential, agricultural, and clean areas, were investigated to characterize their distribution patterns and evaluate non-carcinogenic health risks. The results showed that the concentrations of most heavy metals generally followed the order of industrial area > traffic area > residential area > agricultural area > clean area, indicating a strong influence of anthropogenic activities on metal accumulation. Among the studied metals, Pb, Zn, and Cu exhibited the most pronounced functional-area differences. Significant positive correlations were observed among all six metals, with correlation coefficients ranging from 0.55 to 0.76, suggesting that they were affected by overlapping urban input processes. Health risk assessment based on ingestion, inhalation, and dermal contact showed that ingestion was the dominant exposure pathway for both children and adults, whereas inhalation contributed little to the overall risk. Children exhibited consistently higher hazard quotient and hazard index values than adults, indicating greater susceptibility to dust-borne metal exposure. Mn was identified as the major contributor to non-carcinogenic risk, while Pb and Cr also showed relatively notable contributions. Overall, heavy metals in Shanghai street dust exhibited clear functional-area differentiation and posed greater potential health risks to children than to adults. These findings provide useful evidence for the management of urban street dust pollution and the protection of sensitive populations.

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I. Introduction

Urban street dust is an important environmental medium that receives and stores particulate pollutants derived from both natural and anthropogenic processes(Cao et al., 2025). Due to its fine particle size, strong adsorption capacity, and long residence time on road surfaces, street dust can accumulate considerable amounts of heavy metals and act as a secondary source of urban contamination through resuspension, surface runoff, and direct human contact. In densely populated cities, heavy metals in street dust have attracted increasing attention because they can enter the human body through ingestion, inhalation, and dermal contact, thereby posing potential health risks, especially to sensitive populations such as children(Aguilera et al., 2022).

Previous studies have shown that the accumulation of heavy metals in street dust is closely related to urban land use and human activity intensity(Jiang et al., 2017). Industrial production, traffic emissions, mechanical wear, building materials, and atmospheric deposition are all important contributors to the metal burden of urban surface dust. As a result, heavy metal concentrations often vary substantially among different functional areas within a city(Isinkaralar et al., 2024). However, many existing studies have mainly focused on the overall contamination level of entire cities, while relatively fewer investigations have examined how street dust heavy metals differ among urban functional zones within a single megacity. In addition, although health risk assessment has been widely applied in street dust studies, the combined interpretation of functional-area differences, inter-metal relationships, and population-specific exposure risk remains insufficient in many case(Jaffar et al., 2017)s.

Shanghai is one of the largest and most economically developed cities in China, with highly diverse urban functions, including industrial districts, traffic-intensive corridors, residential communities, peri-urban agricultural land, and low-disturbance background areas(Wang et al., 2019). These contrasting functional settings provide a suitable basis for evaluating how human activities influence the accumulation of heavy metals in street dust. Therefore, this study investigated the concentrations of Pb, Zn, Cu, Cr, Ni, and Mn in street dust collected from five functional areas of Shanghai. The objectives were to: (1) characterize the distribution patterns of heavy metals across different functional areas; (2) examine the correlations among these metals and their possible common source implication; and (3) assess the non-carcinogenic health risks to children and adults through ingestion, inhalation, and dermal contact. The results are expected to provide useful evidence for understanding urban dust pollution and for supporting health-oriented management of street environments in megacities.

II. Materials and Methods

2.1. Study area and sample collection

Shanghai is a typical megacity in eastern China, characterized by intensive industrial activity, dense traffic networks, large residential districts, and peri-urban agricultural land. Such diverse land-use types provide suitable conditions for investigating the variation of heavy metals in street dust under different urban functional settings.

Street dust samples used in this study were collected from five functional areas of Shanghai, including industrial areas (IA), traffic areas (TA), residential areas (RA), agricultural areas (AG), and clean areas (CA). A total of 60 samples were included, comprising 15 samples from IA, 15 from TA, 15 from RA, 10 from AG, and 5 from CA. The clean area was used as a low-disturbance reference group for comparison with the other functional zones.

After collection, all samples were transported to the laboratory, air-dried at room temperature, and manually cleared of visible debris such as plant residues and small stones. The dried samples were then homogenized and sieved through a [please insert actual mesh size]-mesh sieve prior to chemical analysis.

2.2 Heavy metal concentrations

Approximately 0.2 g of each dust sample was accurately weighed into a PTFE digestion vessel and digested with a mixed acid solution consisting of 5 mL HNO_3, 5 mL HF, 5 mL HCl, and 3 mL $HClO_4$. The digestion was conducted at 180 °C for 3 h using a graphite block digestion system. After digestion, the solution was evaporated to approximately 0.1 mL using residual heat, then allowed to cool to room temperature. The residue was quantitatively transferred into a 50 mL centrifuge tube, rinsed repeatedly with 5% HNO_3, and diluted to a final volume of 50 mL with 5% HNO_3.

The resulting solutions were filtered through 0.45 μm membrane filters and analyzed for Cu, Cr, Fe, Zn, Mn, Pb, Al, and Ni using inductively coupled plasma optical emission spectrometry (ICP-OES). All laboratory glassware and vessels were pre-cleaned by acid soaking and thoroughly rinsed with deionized water prior to use. Procedural blanks and the certified reference material GSS-6 (GBW07406) were included in each digestion batch for quality control. Instrument calibration was verified using standard solutions, with blank and standard checks performed every 10 samples to ensure analytical accuracy within ±5%.

2.3 Health Risk Assessment

The non-carcinogenic health risks of heavy metals in street dust were evaluated for both children and adults based on the United States Environmental Protection Agency (USEPA) model. Three exposure pathways were considered, including ingestion, inhalation, and dermal contact. Average daily doses for each pathway were calculated using standard exposure parameters, and the non-carcinogenic risk of each metal was expressed as the hazard index (HI):

$$HI = \sum HQ_i = \sum \frac{ADD_{ing} + ADD_{inh} + ADD_{der}}{RfD_i}$$

where ADD is the average daily dose of a given exposure pathway and RfD is the corresponding reference dose. An HQ or HI value lower than 1 indicates an acceptable non-carcinogenic risk, whereas a value greater than 1 suggests a potential health concern. In this study, the assessment focused on comparing pathway-specific risk contributions and age-related differences between children and adults.

III. Results and discussion

3.1 Heavy metal concentrations in street dust across different functional areas

The concentrations of Pb, Zn, Cu, Cr, Ni, and Mn in Shanghai street dust showed clear differences among functional areas (Table. 1). Overall, the median concentrations of most metals followed a consistent pattern of IA > TA > RA>AG > CA (Fig. 1). This pattern indicates that heavy metal accumulation in street dust was strongly influenced by urban functional zoning and the intensity of human activities.

Table 1 Content of heavy metal elements in street dust samples from Shanghai

Element content	SHANGHAI				
	Range	Mean	Median	STDEV	Background
Pb (mg/kg)	20.12-177.32	86.99	82.27	37.44	24.99
Zn (mg/kg)	93.12-772.10	352.71	340.63	156.95	81.30
Cu (mg/kg)	19.54-189.11	102.68	97.67	39.03	27.20

Cr (mg/kg)	49.93-293.91	165.57	176.36	64.80	70.20
Ni (mg/kg)	28.71-137.21	74.53	68.47	26.01	29.90
Mn (mg/kg)	422.12-998.31	717.63	749.13	170.11	547.99

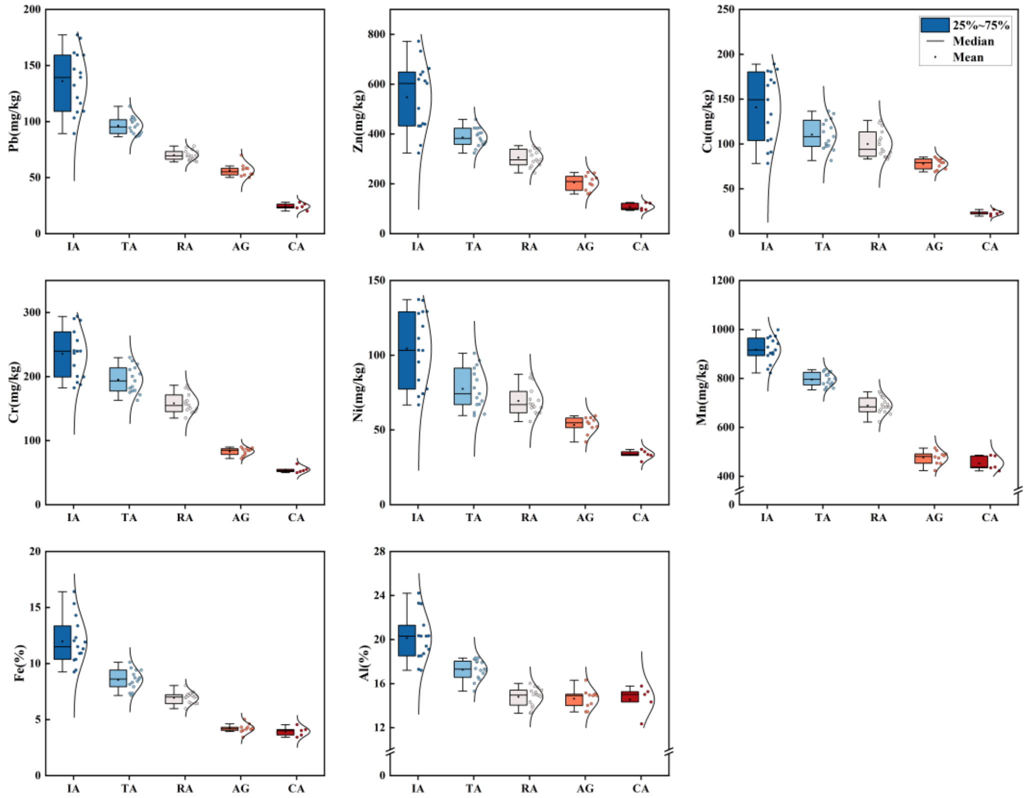

Fig. 1 Concentrations of heavy metals in street dust across different functional areas of Shanghai.

Among the six metals, Pb, Zn, and Cu showed the most pronounced differences across functional areas. Their concentrations were highest in IA and remained relatively elevated in TA, while much lower levels were observed in AG and CA. This trend suggests that these elements were more sensitive to anthropogenic inputs and were closely associated with industrial production, traffic emissions, vehicle-related wear, and road dust resuspension(Sun et al., 2025). In particular, the wide interquartile ranges and extended whiskers in IA indicate not only high metal loads but also strong local heterogeneity, implying more complex and spatially uneven inputs in industrial environments(Zhong et al., 2020).Cr and Ni also exhibited a decreasing trend from IA to CA, although the gradients were slightly weaker than those of Pb, Zn, and Cu. Their relatively high levels in both IA and TA suggest that these metals may be influenced by mixed urban sources rather than by a single dominant activity. Compared with these elements, Mn showed a similar overall decline from IA to CA, but the difference between AG and CA was relatively small. This feature implies that, besides anthropogenic inputs, Mn may also be affected by natural background contributions to a greater extent than the other metals(Sun et al., 2025). The boxplots further show that industrial and traffic areas were characterized by higher mean values and broader concentration ranges, whereas agricultural and clean areas displayed lower concentrations and narrower distributions. Residential areas generally occupied an intermediate position, indicating moderate metal accumulation under mixed influences from daily urban activities and nearby traffic(Rout et al., 2015).

In summary, the heavy metals in Shanghai street dust exhibited distinct functional-area differentiation, with industrial and traffic zones representing the main accumulation areas. The stronger enrichment of Pb, Zn, and Cu suggests that these metals were more responsive to urban anthropogenic disturbance, while Mn showed a comparatively more complex pattern. These results provide a basis for subsequent discussion of inter-metal relationships and health risk characteristics.

3.2 Correlation among heavy metals and source implication

The Spearman correlation matrix showed that all six heavy metals were significantly and positively correlated with each other (Fig. 2), with correlation coefficients ranging from 0.55 to 0.76. This result suggests that the accumulation of Pb, Zn, Cu, Cr, Ni, and Mn in Shanghai street dust was not independent, but instead reflected a considerable degree of co-variation. Several metal pairs exhibited relatively strong correlations. The highest coefficients were observed for Zn–Mn (0.76) and Cu–Cr (0.76), followed by Zn–Cu (0.73), Pb–Ni (0.72), Cu–Ni (0.72), Cu–Mn (0.71), Pb–Zn (0.70), and Cr–Mn (0.70). Moderate but still significant relationships were found for Cr–Ni (0.55), Pb–Cr (0.59), Zn–Ni (0.60), Pb–Cu (0.61), and Ni–Mn (0.62). The generally high and consistent positive correlations indicate that these metals were likely affected by overlapping urban input processes.

When combined with the functional-area pattern described above, the correlation results further imply that industrial activities, traffic-related emissions, mechanical wear, and road dust resuspension may have jointly controlled the metal composition of street dust(Sabouhi et al., 2020). The strong correlations among Pb, Zn, and Cu are particularly consistent with their pronounced enrichment in industrial and traffic areas, suggesting a close association with anthropogenic disturbance. Likewise, the positive relationships involving Cr and Ni indicate that these elements may also participate in mixed urban-source inputs rather than reflecting isolated sources(Soleimani et al., 2018). Although Mn showed significant correlations with the other metals, its relatively smaller difference between AG and CA suggests that natural background contributions should not be excluded.

It should be noted that correlation analysis only reflects the degree of association among variables and cannot by itself identify exact sources. Therefore, the results are better interpreted as evidence of common source influence or similar environmental behavior, rather than as direct proof of specific emission sources. Overall, the strong inter-metal correlations support the view that heavy metals in Shanghai street dust were controlled by combined anthropogenic processes under different urban functional settings.

* p<=0.05 ** p<=0.01

Fig. 2 Spearman correlation matrix of heavy metals in Shanghai street dust.

3.3 Non-carcinogenic health risk of heavy metals in street dust

The non-carcinogenic health risk results showed clear differences among exposure pathways and exposed populations (Fig. 3). For both children and adults, ingestion was the dominant exposure route for most metals, while inhalation contributed very little to the overall risk. Dermal contact also contributed to the total hazard, but its effect was generally much lower than that of ingestion. This pattern indicates that direct intake of dust particles is the main pathway controlling human exposure to heavy metals in Shanghai street dust(Živančev et al., 2019).

A clear age-related difference was observed, with children showing consistently higher HQ and HI values than adults for all six metals. This result is consistent with the greater vulnerability of children to dust-borne pollutants due to their lower body weight, more frequent hand-to-mouth behavior, and higher dust intake relative to body mass. Therefore, children should be considered the more sensitive receptor group in the health risk assessment of urban street dust(Mahato et al., 2023). Among the studied metals, Mn showed the highest risk contribution for both age groups and was the main contributor to the total HI. For children, the HI value of Mn exceeded the safety threshold of 1, indicating a potential non-carcinogenic health concern. In contrast, the HI values of the other metals remained below 1, although Pb and Cr still made relatively important contributions compared with Zn, Cu, and Ni. For adults, all individual HI values were below 1, suggesting that the non-carcinogenic risk remained within an acceptable range(Isinkaralar et al., 2024).

Overall, the total HI was markedly higher in children than in adults, indicating that the potential health burden of heavy metals in street dust was mainly concentrated in the child population(Huang et al., 2022). The risk pattern further suggests that Mn should be regarded as the priority metal of concern, while Pb and Cr also deserve continued attention(Hajduga et al., 2019). These findings highlight the need to strengthen dust control and exposure reduction measures, particularly in urban areas with frequent child activity{Men, 2021 #158}.

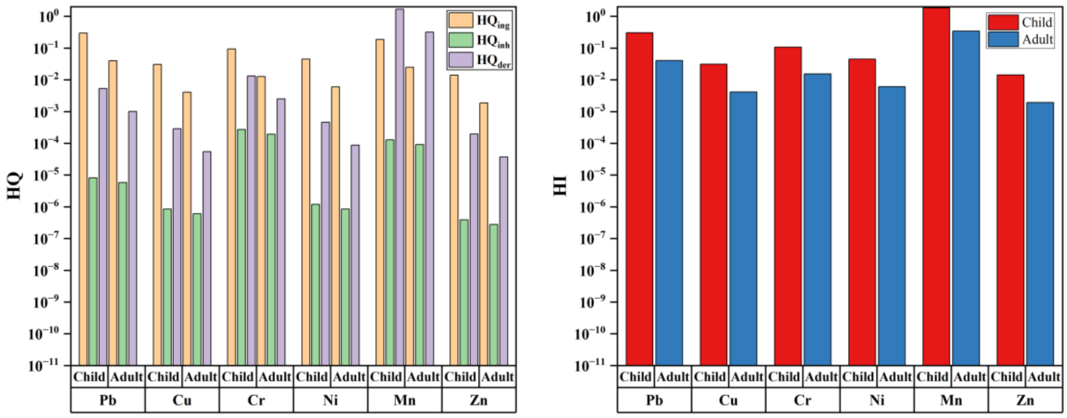

Fig. 3 Hazard quotients (HQs) of different exposure pathways and hazard indices (HIs) of heavy metals in Shanghai street dust for children and adults.

IV. Conclusions

This study investigated the distribution characteristics and non-carcinogenic health risks of heavy metals in street dust from different functional areas of Shanghai. The main conclusions are as follows.

(1) The concentrations of Pb, Zn, Cu, Cr, Ni, and Mn showed clear functional-area differences, generally following the order of IA > TA > RA > AG > CA. Industrial and traffic areas were the main accumulation zones, indicating that heavy metal levels in street dust were strongly affected by anthropogenic activities.

(2) Significant positive correlations were observed among all six metals, with Spearman correlation coefficients ranging from 0.55 to 0.76. This result suggests that the heavy metals were influenced by common or overlapping urban input processes, mainly related to industrial activities, traffic disturbance, and road dust resuspension.

(3) Ingestion was the dominant exposure pathway for both children and adults, whereas inhalation made only a minor contribution to the total risk. Children showed consistently higher HQ and HI values than adults, indicating greater susceptibility to heavy metal exposure from street dust. Among the studied metals, Mn was the major contributor to non-carcinogenic risk and should be considered the priority metal for future monitoring and control.

Overall, heavy metals in Shanghai street dust exhibited clear functional-area differentiation and posed a greater potential health risk to children than to adults. These findings provide useful evidence for pollution control and health-oriented management of urban street dust.

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