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Spatial Heterogeneity of Heavy Metals Contamination in Urban Road Dust and Associated Human Health Risks

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Abstract: Rapid urbanization and associated transportation play a crucial role in the distribution of heavy metals in road dust, leading to serious environmental and health concerns. This study explored the concentration and spatial variability of metals, including cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn), in road dust across six urban zones in Guangdong Province (parks, educational, residential, commercial, traffic, and industrial areas). The study also evaluated the bioavailability of these metals to determine their carcinogenic and non-carcinogenic health impacts. The findings revealed significant variations in metal levels, with commercial zones having the highest concentrations of Zn 1316.1 ± 381.6 mg/kg), Cu (426.1 ± 136.7 mg/kg), and Cd (1.29 ± 0.08 mg/kg) due to the deposition of traffic emissions. The bioaccessibility of Pb, Zn, and Cd was found to be higher in the gastric phase, suggesting increased absorption potential when ingested. Children were at a significantly higher non-carcinogenic risk compared to adults, facing more than double the exposure. While the carcinogenic risk from Pb was low but notable, Cd presented minimal risk. These results highlight the need for targeted interventions, including stricter emission regulations and public health strategies, to mitigate the risks of heavy metal exposure in urban areas.

Keywords: heavy metals; road dust; health risks; contamination; exposure risk

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1. Introduction

Air pollution has become one of the major environmental problems hindering the healthy development of cities [1]. With the rapid development of industry and the acceleration of urbanization, a large number of toxic and hazardous substances are discharged into the atmosphere through industrial emissions, fossil fuel combustion, transportation, and other channels, causing air quality to gradually deteriorate [2,3]. Atmospheric dust deposition settles on the ground by gravity under natural circumstances. Particulate matter is not only a harmful substance but also a carrier and reaction bed for other pollutants; it is one of the most complex and harmful pollutants in the atmosphere, with great potential to harm human beings and organisms [4].

In recent years, with the rapid growth of the number of motor vehicles in China, road traffic emissions have become a key factor in urban air pollution. The main source of air pollution from vehicles is the emission of automobile exhaust, followed by the wear and tear of the braking system when the car accelerates and decelerates, and the dust caused by friction between the car tires and the road surface [5]. Road dust pollutants can enter the

nearby soil and water bodies through direct settlement or surface runoff due to rainwater and road cleaning, threatening ecological safety. They can endanger human health through skin contact, respiratory tract entry, and food chain transmission. Therefore, the pollution and hazards caused by the toxic and harmful heavy metals carried in road dust have become an increasingly concerning environmental problem.

Heavy metals in atmospheric dust are loosely bonded to the surface of particles, which has high instability and potential biological availability [6]. Cd, Zn, Pb, Cu, Cr, Hg, and Ni are the main heavy metals in road dust [7]. A large amount of particulate matter accumulates on the surface of plants in the atmosphere, which can clog the pores of plant leaves and act on the plants, together with harmful substances in the particulate matter, to cause physiological damage [8]. Heavy metals entering the soil can change the population of soil microorganisms, inhibit the activity of soil enzymes, and are easily taken up by plants, damaging their metabolic balance [9]. The long-term accumulation of road dust in the human body may cause chronic injuries, especially certain heavy metals, such as Cd and Pb, where even a very small amount can have a serious impact, including carcinogenic, teratogenic, and mutagenic effects [10]. Studies have shown that dust containing Cd can be inhaled through the respiratory tract, causing acute and chronic poisoning. Cd accumulates in the liver and kidneys, damaging the kidney tubes and causing emphysema [11]. In addition, Cd accumulation reduces the body's absorption of calcium and phosphorus, resulting in abnormal metabolism of vitamin D, which, in turn, causes bone lesions, such as Japan's outbreak of "Itai-Itai Disease" [12]. Lead can significantly affect children's intellectual development, including speech ability, memory, and attention. Therefore, it is of great significance to monitor urban environmental health and guide urban environmental pollution control by assessing the pollution of heavy metals in urban roads to evaluate the risk of heavy metals in road dust reduction, especially in high-density population areas.

In recent years, much research has been conducted on the sources and pollution of heavy metals in atmospheric dust [10–13]. However, few studies have been reported on the risk assessment of heavy metals in urban atmospheric dust, and most of the similar studies focus on urban surface dust. For example, [14] conducted research on platinum group metal pollution and its risk assessment on humans and ecosystems in London, Madrid, Rome, Gothenburg, and other cities in Europe from 1997 to 2000. The health hazard index is lower than the threshold, but the continuous increase in the content of metal pollutants in the road and dust still needs attention. Saeedi et al. [15] collected 50 street dust samples in the eastern and southern regions of Tehran to study the contamination of heavy metals and polycyclic aromatic hydrocarbon pollutants and found that all street dust samples were a high risk to ecosystems, particularly the amounts of Cd, Pb, Cu, and Zn that were found. A study in Luanda found that As and Pb in road dust were the main pollutants of concern [16]. Similar studies have been conducted in China, particularly in Beijing [17], Changchun [18,19], Lanzhou [20], Xi'an [21], Nanjing [22], Changsha [19], and Guangzhou [23]. These studies have shown that the average content of heavy metals, such as Pb, Cu, Zn, and Cd, in street dust in some cities has far exceeded the local soil background value of corresponding metal elements. Wei et al. [17] studied the characteristics and potential health risks of heavy metal pollution in the street dust in Beijing traffic, residential, teaching, and tourist areas and found that contents of Cr, Cu, Zn, Cd, and Pb exceeded the soil background value of the corresponding metal elements in Beijing, and the contents of Ni, Cu, Zn, and Pb in the tourist area were the highest. The results of the health risk assessment found that Cr pollution in street dust had a higher risk of non-carcinogenicity in children [17].

Most of the existing research has been performed in cities in northern or western China. There are still few studies on atmospheric dust fall in the Pearl River Delta region, especially heavy metal pollution of urban road dust and its potential ecological and human health

risks. Guangzhou is one of China's largest cities, with a high population density. This study is aimed at the division of different functional areas in Guangzhou (traffic areas, industrial areas, residential areas, commercial areas, park areas, campus areas) to study the pollution characteristics of heavy metals in road dust in different areas and to evaluate the risk of road dust heavy metals to human health. We hypothesize that the diverse origins of road dust in different functional zones will inevitably lead to variations in the bioavailability and human health risks associated with heavy metals in dust. Consequently, by comparing heavy metal pollution levels and risks across different functional zones, it would be possible to better identify pollution sources and facilitate targeted urban management.

2. Materials and Methods

2.1. Division of Functional Areas and Sampling Points

According to different land use properties, the road network in the central urban area of Guangzhou (Haizhu District, Liwan District, Yuexiu District, Tianhe District, Baiyun District, Huangpu District) was divided into 6 functional areas, separately, park area (TourAr), educational area (EdAr), residential area (ResAr), commercial area (CmAr), traffic area (TrfAr), and industrial area (IndAr). A total of 45 representative sampling points were selected. Sampling was done using a multi-point mixing method. Roads were randomly arranged for collection, and road dust samples from impervious street pavements were collected using brushes and plastic dustpans.

Among the 45 sampling sites, there were 5 TourAr sites, 9 EdAr sites, 10 ResAr sites, 4 CmAr sites, 8 TrfAr sites, and 9 IndAr sites. The park areas have been built for more than 50 years; the education areas were selected as undergraduate colleges with a long history. Residential areas are represented by various old residential areas that were built over 10 years ago or large-scale communities. Commercial areas include Tianhe Commercial District (Tiyuxi Road-Tiyubei Road-Gangding Area) and Beijing Road Commercial District (Weihua and Liuhua commercial area). Transportation areas include a large-scale transportation hub while the industrial areas were Huangpu Industrial Area, Chebei Huangpu Industrial Area, Tianhe District, and Baiyun Industrial Area. The distribution of sampling sites is shown in Figure 1.

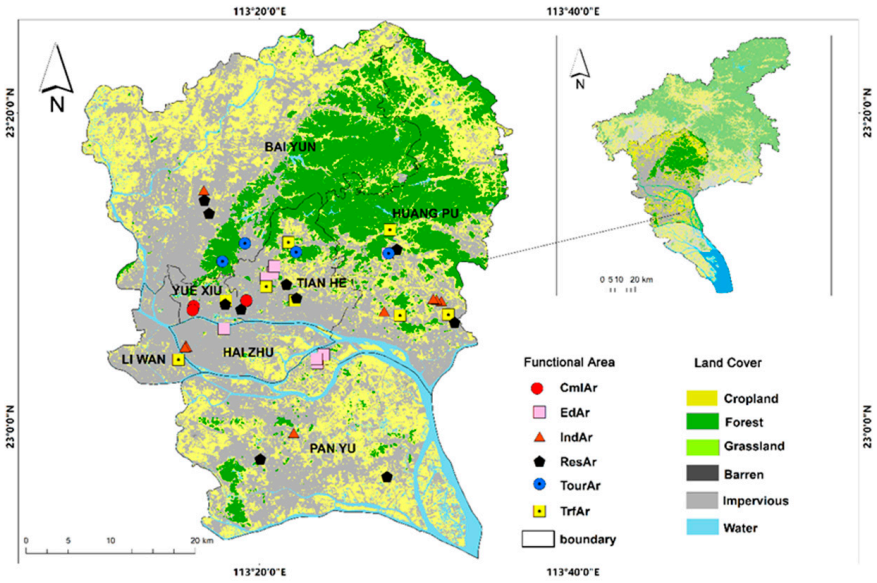

Figure 1. Sampling sites in Guangzhou. The land cover classification originated from the Corine land cover database.

2.2. Sampling Method and Analysis

Road dust samples were air dried, sieved to 0.149 mm, sealed, and preserved. Metals (Pb, Zn, Cu, Cd) were selected as representative traffic pollution indicators due to their (1) high abundance in traffic-related emissions (e.g., brake/tire wear) and (2) inclusion in the USEPA Priority Pollutant List with significant carcinogenic/non-carcinogenic risks. After digesting the sample with the Anton Paar Multiwave PRO microwave digestion system, the Pb, Zn, Cu, and Cd contents in the samples were analyzed in the Zeenit 700P graphite furnace-flame atomic absorption spectrophotometer (Analytik Jena AG, Jena, Germany) [24]. To ensure the accuracy and reliability of the analysis, reagent blanks, duplicate samples, and soil reference materials (the number of Chinese national certified reference material GBW070011, Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences, Langfang, China) were incorporated into the digestion process. During sample concentration analysis, standard concentration reagents were interspersed with the analytical samples to monitor the stability of instrumental analysis. The recovery rates for Pb, Zn, Cu, and Cd in the standard material were 95%, 94%, 92%, and 85%, respectively, all of which met the quality control requirements [25].

In vitro simulation of heavy metal bioavailability in dust was employed using the Physiologically Based Extraction Test (PBET) method, as proposed by [26], to assess the bioaccessibility of heavy metals by simulating the human gastrointestinal tract in two sequential stages: gastric and intestinal. The specific procedure is as follows [27].

In the gastric phase, 0.5 g of dust sample was placed in a 100 mL Sarstedt centrifuge tube and mixed with 50 mL of simulated gastric fluid (containing 1.25 g/L pepsin, 0.5 g/L citric acid, 0.5 g/L malic acid, 420 µL/L DL-lactic acid, 500 µL/L acetic acid, adjusted to pH 1.5 with HCl). The mixture was incubated at 37 °C with shaking for 1 h, followed by centrifugation at 3000 rpm for 10 min. Then, 5 mL of the supernatant was filtered through a 0.45 µm membrane and stored at 4 °C for heavy metal analysis. An additional 5 mL of simulated gastric fluid was added to maintain a 1:100 solid-to-liquid ratio.

In the intestinal stage, 52.5 mg of bile salts and 15 mg of pancreatin were added to the reaction mixture. The pH was then adjusted to 7 using a saturated sodium bicarbonate solution. The mixture was again incubated at 37 °C and 150 rpm for 2 h. Finally, 5 mL of the reaction mixture was collected, filtered through a 0.45 µm membrane, and stored at 4 °C for subsequent heavy metal analysis.

Bioavailability of heavy metals in dust:

$$\mathrm{BA}\ (\%) = \frac{C}{TC} \times 100 \quad (1)$$

where C was the dissolved amount of heavy metals in the stomach or small intestine (mg/kg), and TC represents the total concentration of the heavy metal in the dust (mg/kg).

2.3. Assessment Method

Human health risk assessment.

Using the human health risk assessment model for contaminated sites proposed by the United States Environmental Protection Agency [28–30] and the basic framework, the risk of Guangzhou residents exposed to road dust was evaluated. According to the model, Pb, Zn, Cu, and Cd, all have a chronic non-carcinogenic risk. Meanwhile, Pb compounds (inorganic) are class 2A [31] carcinogenic elements, while Cd and Cd compounds are class I according to classification group orders defined by the International Agency for Research on Cancer [32]. Copper and Zn are not found in the classification group.

The model assumes that residents are exposed to heavy metals in atmospheric dust through three exposure routes: hand–oral ingestion, skin contact, and inhalation. Both non-carcinogenic and carcinogenic risks of these exposure routes were considered. The

carcinogenic risk was calculated for the lifetime exposure, estimated as the incremental probability of an individual developing cancer over a lifetime as a result of total exposure to the potential carcinogen. The exposure formula is calculated as follows [33,34]:

Non-carcinogenic hazard:

$$\mathrm{ADD_{ing}} = \frac{C \times IngR \times EF \times ED}{BW \times AT_{nc}} \times 10^{-6} \quad (2)$$

$$\mathrm{ADD_{inh}} = \frac{C \times IngR \times EF \times ED}{PEF \times BW \times AT_{\mathrm{nc}}} \quad (3)$$

$$\mathrm{ADD_{dermal}} = \frac{C \times SA \times SAF \times ABS \times EF \times ED}{BW \times AT_{nc}} \times 10^{-6} \quad (4)$$

In the formula, $\mathrm{ADD_{ing}}$ is the average daily exposure of road dust by the hand–oral route (mg/(kg·d)), $\mathrm{ADD_{inh}}$ is the average daily exposure of road dust by inhalation (mg/(kg·d)), and $\mathrm{ADD_{dermaL}}$ is the average daily exposure to road dust through the skin contact route (mg/(kg·d)). The meanings and values of other parameters are shown in Table 1. These values were selected based on USEPA guidelines, recent literature, and localized adjustments to ensure they accurately represent exposure scenarios in urban road dust environments.

The non-carcinogenic risk was evaluated by the hazard quotient (HQ) through the ratio of the receptor's exposure dose to the reference dose of heavy metals:

$$\mathrm{HQ} = \mathrm{ADD}/\mathrm{RfD} \quad (5)$$

where RfD is the corresponding reference dose for each heavy metal and exposure pathway below which adverse non-cancer health effects are unlikely to occur. The RfD values of all investigated metals are presented in Table 3 [35,36].

For multiple pollutants and multiple exposure pathways, the non-carcinogenic risk, HI, is:

$$\mathrm{HI} = \sum_{j=0}^{m} \sum_{k=0}^{n} HQ_{jk} \quad (6)$$

where j represents the type of pollutant, and k represents the exposure route. When HQ or HI $\leq$ 1.0, the non-carcinogenic risk is considered low and can be ignored; when HQ or HI > 1.0, it is considered a health risk, which requires attention.

Carcinogenic risk (adult):

$$\mathrm{LADD_{ing}} = \frac{C \times EF}{AT_C} \times \left(\frac{ED_{child} \times IngR_{child}}{BW_{child}} + \frac{ED_{adult} \times IngR_{adult}}{BW_{adult}}\right) \times 10^{-6} \quad (7)$$

$$\mathrm{LADD_{inh}} = \frac{C \times EF}{PEF \times AT_C} \times \left(\frac{InhR_{child} \times ED_{child}}{BW_{child}} + \frac{InhR_{adult} \times ED_{adult}}{\mathrm{BW_{adult}}}\right) \quad (8)$$

$$\mathrm{LADD_{dermal}} = \frac{C \times ABS \times EF}{AT_C} \times \left(\frac{ED_{child} \times SA_{child} \times SAF_{child}}{BW_{child}} + \frac{ED_{adult} \times SA_{adult} \times SAF_{adult}}{BW_{adult}}\right) \times 10^{-6} \quad (9)$$

Table 1. Meaning and value of related parameters of heavy metal daily exposure. "d/a" means day per annum. "a" means years.

Item	Parameter	Implication	Unit	Value of Child	Value of Adult	References
Basic parameter	*C*	Heavy metal concentration	$\mathrm{mg{\cdot}kg^{-1}}$	95% UCL	95% UCL	
	EF	Exposed frequency	$\mathrm{d{\cdot}a^{-1}}$	180	180	[28–30]
Exposed behavior	*ED*	Exposed period	$\mathrm{a^{-1}}$	6	24	[37]
parameters	*BW*	Average weight	kg	15	64	[38]

Table 1. *Cont.*

Item	Parameter	Implication	Unit	Value of Child	Value of Adult	References
	AT	Average exposed time (non-carcinogenesis)	d	365 × ED	365 × ED	[28]
		Average exposed time (carcinogenesis)	d	70 × 365	70 × 365	[28,37]
Hand–oral intake	*IngR*	Hand–oral dust intake	$mg \cdot d^{-1}$	200	100	[28]
Breath intake	*InhR*	Inhalation rate	$m^3 \cdot d^{-1}$	7.63	20	[19]
	PEF	Particulate emission factor	$m^3 \cdot kg^{-1}$	1.36×10^9	1.36×10^9	[39]
Skin contact	*SAF*	skin adherence factor	$mg \cdot cm^{-2}$	0.2	0.07	[36]
	SA	Exposed skin areas	cm^2	2800	5700	[37,39]
	ABS	Skin absorption factor	dimensionless	0.001	0.001	[29]

The carcinogenic risk (CR) is expressed as the product of the receptor's lifetime exposure to harmful substances LADD and the carcinogenic slope factor (CSF):

$$CR_{ing} = LADD_{ing} \times CSFo \quad (10)$$

$$CR_{inh} = LADD_{inh} \times IUR \quad (11)$$

$$CR_{dermal} = LADD_{dernal} \times CSFo/GIABS \quad (12)$$

where CSFo is the oral slope factor $(mg/(kg^{-1} \cdot day^{-1})^{-1})$; GIABS is the gastrointestinal absorption factor; IUR is the inhalation unit risk $(\mu g/m^3)^{-1}$, all of which were found in RAIS [40]. The values are shown in Table 4.

For multiple pollutants and multiple exposure routes, the total carcinogenic risk is:

$$CR_{total} = \sum CR = CR_{ing} + CR_{inh} + CR_{dermal} \quad (13)$$

The U.S. Environmental Protection Agency recommends that the risk of cancer can be ignored when RI < 10^{-6}; when RI is 10^{-6}–10^{-4}, it is an acceptable range of risk control, and harmful cancer risk is considered when RI > 10^{-4}.

2.4. Data Analysis

Descriptive statistics and Pearson correlation analysis were conducted to assess the total concentrations and bioaccessible fractions of heavy metals in road dust. One-way analysis of variance (ANOVA) was employed to compare heavy metal concentrations and bioaccessibility of road dust across different functional areas. The least significant difference (LSD) test was used for post-hoc multiple comparisons. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using SPSS 13.0 for Windows.

3. Results and Discussion

3.1. Heavy Metal Content in Road Dust

The distribution of heavy metal content at 45 sampling sites in Guangzhou is shown in Figure 2. There was significant variation in heavy metal content across dust samples, with Pb ranging from 6.0 to 312.2 mg/kg, Zn from 129.4 to 2297.6 mg/kg, Cu from 23.4 to 1321.7 mg/kg, and Cd from 0.3 to 2.2 mg/kg. Zinc exhibited the highest average concentration among the four heavy metals (Zn > Cu > Pb > Cd). The background value of Pb, Zn, Cu, and Cd heavy metals in soils of Guangdong Province was 36.0 mg/kg, 47.3 mg/kg, 17 mg/kg, and 0.056 mg/kg, respectively [41]; the sample average content exceeded 2.25, 14.2, 11.4, and 14.4 times the background content, and the concentration of sampling sites to the background value reached as high as 95.6%, 100%, 100%, and

97.8%, respectively. The significant variation in heavy metal content across dust samples highlights the heterogeneous distribution of these contaminants in various study areas. This heterogeneity is influenced by a complex interplay of factors, including local pollution sources [42,43], meteorological conditions [44,45], and topographical features [46]. Urban runoff, particularly from highways, is a significant source of lead, copper, cadmium, and zinc. Key contributors include building materials, vehicle brake emissions, tire wear, and atmospheric deposition [47]. Industrial activities and construction sites are also common sources of heavy metal pollutants in road dust [48,49]. In this study, significant correlations ($p < 0.05$) were observed for the pairs Cu and Pb (r = 0.41) and Cu and Zn (r = 0.49), suggesting that these heavy metals may originate from similar sources, migration pathways, and deposition processes in the environment. Copper, Pb, and Zn were found to often share common sources, particularly from industrial emissions and traffic-related activities. Studies have shown that these metals can be traced back to industrial pollution and vehicular emissions, with isotopic analysis providing detailed source identification [50,51]. Atmospheric deposition is a significant pathway for these metals to enter urban environments. Traffic congestion, rather than traffic volume, has a stronger correlation with the deposition of Pb, Cd, Ni, and Cu, while Zn is more correlated with traffic volume [52].

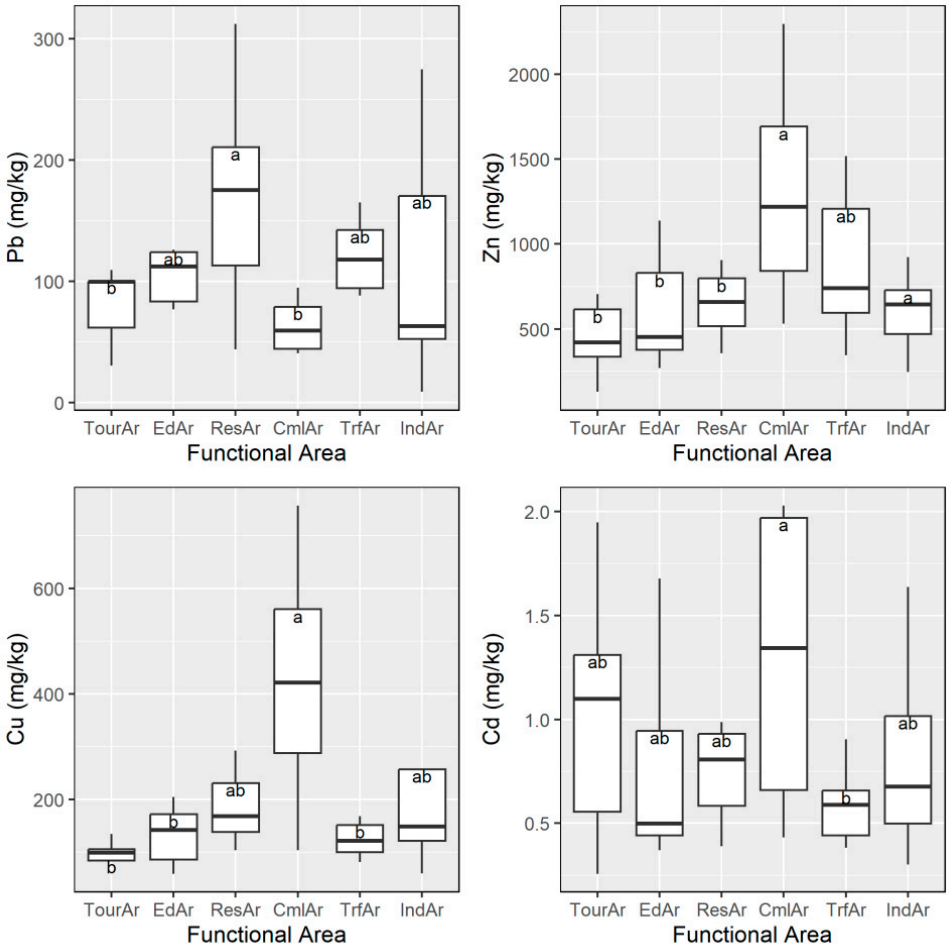

Figure 2. Concentrations of heavy metals in road dust of various functional areas in Guangzhou. Within each heavy metal, the boxes marked with the same letter at the same stage are not significantly different ($p = 0.05$).

Among the different functional zones, samples with the highest Pb contamination were primarily concentrated in residential areas (168 mg/kg), followed by industrial, traffic, and educational zones. This trend may be attributed to the higher traffic volume and

slower vehicle speeds in residential areas, leading to increased emissions of incompletely combusted particulates and more frequent brake wear [53]. Moreover, the dense buildings and narrow roads in residential areas hinder pollutant dispersion and cleaning efforts, resulting in the accumulation of heavy metals in road dust [54]. A potential mitigating strategy could be to carry out soil and air remediation using selected trees [55]. Commercial area samples exhibited significantly higher average concentrations of Zn (1316 mg/kg), Cu (426.1 mg/kg), and Cd (1.29 mg/kg) compared to other zones. This observation is consistent with previous studies conducted in Chengdu [56], Villavicencio [57], and Zahedan [58]. Despite the prohibition of vehicular traffic within commercial areas, their typical location within busy urban transportation hubs has led to the accumulation of heavy metals in dust due to the deposition of vehicle exhaust. The relatively higher Cd content in park areas might be attributed to factors such as soil background values and fertilizers [59]. The variations in heavy metal concentrations within road dust across different urban functional zones are influenced by a multitude of factors. Li (2017) noted that urban areas have diverse land use types with localized and widespread pollution from traffic, households, and industries [56]. Unique activities in each zone emit different heavy metals, causing varying concentrations on streets.

3.2. Bioaccessibility of Heavy Metals in Road Dust

The bioaccessible fraction of heavy metals Pb, Zn, Cu, and Cd in road dust from 45 sampling sites in Guangzhou is presented in Table 2. Significant variations in the bioaccessibility of heavy metals in different dust samples were observed during the gastrointestinal phase. Except for Cu, the bioaccessible fraction of Pb, Zn, and Cd in dust was higher in the gastric phase than in the small intestinal phase. The order of bioaccessibility of the four heavy metals in the gastric phase was Cd > Zn > Pb > Cu, while in the small intestinal phase, it was Cd > Cu > Zn > Pb. The results of the bioaccessible fraction of heavy metals may vary significantly among different studies, influenced by factors such as the source of dust, its chemical composition, and the specific digestion phase. Zheng (2020) [60] observed higher bioaccessibility of Cd, Pb, and Cu in the gastric phase compared to the intestinal phase in street dust samples collected around a zinc smelting plant in northeastern China. In contrast, Kabir et al. [61] reported a higher proportion of bioaccessible Cu, Zn, and Cr in the small intestinal phase of roadside dust from Dhaka city, while only Pb demonstrated higher bioaccessibility in the gastric phase.

When comparing across different functional areas, the intestinal phase Pb absorption ratio of road dust (16.3%) was significantly higher in commercial areas than elsewhere, with the lowest ratio found in educational areas (4.2%). The bioaccessibility of Zn in the gastric phase was significantly higher in educational areas compared to other functional zones (70.9%), but there were no significant differences in bioaccessibility among different zones in the intestinal phase. Conversely, while the absorption ratio of Cu in dust samples from commercial areas was the highest in the gastric phase (30.1%), the highest absorption ratios in the intestinal phase were found in dust samples from park, residential, and industrial areas. Experimental results revealed that Cd in dust from industrial areas was completely absorbed in the gastric phase, whereas the lowest absorption ratio was observed in traffic areas at 78.3%. These discrepancies can be attributed to variations in the sources and chemical speciation of heavy metals in different functional zones, which consequently influence their bioavailability [56]. The findings highlight the need for targeted risk assessments for specific functional zones, as exposure risks may vary depending on the dominant sources of contamination and the bioaccessibility of metals in different phases of digestion.

Table 2. Bioaccessible fraction of each heavy metal in the gastric phase and intestinal phase.

Element		Gastric Phase (%)	Intestinal Phase (%)
Pb	**Area**	**Mean ± SE**	**Mean ± SE**
	TourAr	39.2 ± 4.46 a	8.88 ± 2.95 ab
	EdAr	29.1 ± 5.24 a	4.20 ± 0.70 b
	ResAr	39.2 ± 10.6 a	9.48 ± 1.94 ab
	CmAr	36.4 ± 8.12 a	16.3 ± 2.93 a
	TrfAr	40.4 ± 13.1 a	5.83 ± 2.01 b
	IndAr	44.1 ± 7.11 a	9.79 ± 2.44 ab
	Total	38.1 ± 3.74	8.38 ± 1.12
Zn	TourAr	64.8 ± 1.88 ab	25.9 ± 5.40 a
	EdAr	70.9 ± 5.39 a	17.8 ± 1.58 a
	ResAr	68.0 ± 5.09 ab	25.4 ± 6.30 a
	CmAr	60.9 ± 4.34 ab	21.3 ± 2.57 a
	TrfAr	57.7 ± 4.34 b	20.7 ± 2.53 a
	IndAr	66.5 ± 4.17 ab	21.7 ± 1.88 a
	Total	64.9 ± 1.89	22.0 ± 1.65
Cu	TourAr	20.5 ± 4.14 ab	36.3 ± 3.77 a
	EdAr	22.2 ± 3.95 ab	28.7 ± 3.51 ab
	ResAr	22.9 ± 4.42 ab	31.8 ± 3.52 a
	CmAr	30.1 ± 2.66 a	18.8 ± 2.48 b
	TrfAr	20.5 ± 4.19 ab	31.1 ± 3.92 ab
	IndAr	10.8 ± 3.37 b	32.8 ± 3.81 a
	Total	21.5 ± 1.78	30.6 ± 1.60
Cd	TourAr	92.7 ± 6.38 ab	65.4 ± 8.74 a
	EdAr	88.5 ± 11.7 ab	45.3 ± 2.87 a
	ResAr	98.6 ± 8.54 ab	59.7 ± 7.86 a
	CmAr	97.0 ± 8.05 ab	61.4 ± 13.5 a
	TrfAr	78.3 ± 11.1 b	49.09 ± 8.26 a
	IndAr	109 ± 6.15 a	51.2 ± 7.04 a
	Total	92.4 ± 3.98	54.0 ± 3.13

Within each heavy metal, means with the same lowercase letter across functional areas are not significantly different ($p > 0.05$).

Correlation analysis revealed a strong positive correlation between the dissolved fractions and bioaccessibility of Zn, Cu, and Pb in both the gastric and intestinal phases (Figure 3), while no significant correlation was found for Cd. The results suggest that when the heavy metal content in road dust is at higher levels, the proportion of heavy metals absorbed by the human gastrointestinal tract is relatively low, but this proportion increases as the concentrations rise. Conversely, when the heavy metal content in dust is within a lower concentration range, the absorption rate by the human body tends to reach a relatively high level, potentially even approaching complete absorption. This may be another reason for the differences in absorption rates among different functional zones.

3.3. Non-Carcinogenic Hazard of Heavy Metals in Road Dust

The non-carcinogenic risk assessment results for children and adults exposed to heavy metals in road dust from different functional zones in Guangzhou are presented in Table 3. The results showed that the hazard index (HI) for the four heavy metals in road dust from different functional zones was below the safety threshold of 1.0, suggesting these heavy

metals in road dust do not pose a significant threat to public health. However, it is crucial to acknowledge that long-term exposure or increases in concentration could elevate these risks. The spatial pattern of non-carcinogenic risk mirrors the spatial distribution of heavy metal concentrations. The non-carcinogenic risk of heavy metal exposure through three pathways was ranked as follows: hand-to-mouth ingestion > dermal contact > inhalation. The risk of hand-to-mouth ingestion was approximately 2–3 orders of magnitude higher than that of dermal contact and inhalation. Consistent with previous findings [61–65], children faced a significantly higher risk than adults, with twice the hand-to-mouth ingestion risk and one order of magnitude higher dermal contact risk.

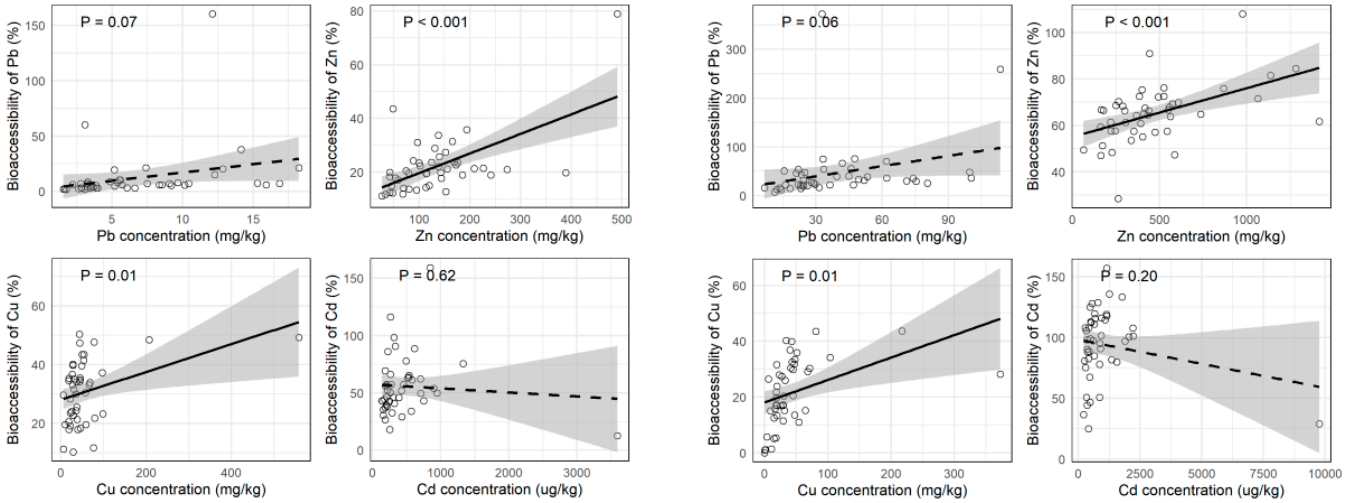

Figure 3. Correlation between the dissolved fractions and bioaccessibility of Zn, Cu, and Pb in both the gastric and intestinal phases. Solid lines indicate statistically significant relationships ($p < 0.05$), while dashed lines represent non-significant trends. The shaded area in gray represents the 95% confidence interval.

This heightened susceptibility can be attributed to their behavioral patterns (e.g., playing in dirt, hand-to-mouth activities), smaller body size, and higher metabolic rates relative to adults [66]. Among the four heavy metals analyzed, the total HI was ranked as follows: Pb > Cu > Zn > Cd. Similar to the study at a traffic training venue in Guangzhou [64], the non-carcinogenic risk caused by Pb was 1–2 orders of magnitude higher than that of Zn, Cu, and Cd and was closest to the non-carcinogenic risk threshold of 1, which should be highly concerning, especially in residential areas with the highest Pb content and high population density, as well as in school areas.

3.4. Carcinogenic Hazard of Heavy Metals in Road Dust

The carcinogenic risk assessment of heavy metals in road dust (Table 4) revealed that the carcinogenic risk of Pb in residential, industrial, and traffic areas varied between 10^{-6} and 10^{-4}, indicating a low but non-negligible carcinogenic risk. The carcinogenic risk (CR) of Cd in dust from all functional zones was significantly below 10^{-6}, indicating a negligible carcinogenic risk. However, it is worth noting that the carcinogenic risk assessment of cadmium has limitations. Currently, there is a lack of research on the slope factor for oral ingestion of Cd in dust, which has hindered the calculation of the carcinogenic risk associated with the oral ingestion of Cd-contaminated dust [67]. Nevertheless, the carcinogenic risk of Cd in dust from parks and commercial areas is still one order of magnitude higher than in other areas, warranting further attention.

Table 3. Non-carcinogenic hazard of heavy metals in road dust.

Elements	RfDing	RfDinh	RfDdermal	Sampling Sites	HQing		HQinh		HQdermal		HI	
					Children	Adult	Children	Adult	Children	Adult	Children	Adult
Pb	3.50×10^{-3}	3.52×10^{-3}	5.25×10^{-4}	TourAr	2.29×10^{-1}	1.14×10^{-1}	6.38×10^{-6}	2.87×10^{-6}	2.44×10^{-3}	6.23×10^{-4}	2.31×10^{-1}	1.15×10^{-1}
				EdAr	2.59×10^{-1}	1.30×10^{-1}	7.24×10^{-6}	3.26×10^{-6}	2.77×10^{-3}	7.07×10^{-4}	2.62×10^{-1}	1.30×10^{-1}
				ResAr	4.11×10^{-1}	2.05×10^{-1}	1.15×10^{-5}	5.15×10^{-6}	4.38×10^{-3}	1.12×10^{-3}	4.15×10^{-1}	2.06×10^{-1}
				CmAr	1.75×10^{-1}	8.77×10^{-2}	4.89×10^{-6}	2.20×10^{-6}	1.87×10^{-3}	4.77×10^{-4}	1.77×10^{-1}	8.81×10^{-2}
				TrfAr	2.71×10^{-1}	1.35×10^{-1}	7.55×10^{-6}	3.40×10^{-6}	2.89×10^{-3}	7.37×10^{-4}	2.74×10^{-1}	1.36×10^{-1}
				IndAr	3.25×10^{-1}	1.62×10^{-1}	9.06×10^{-6}	4.08×10^{-6}	3.47×10^{-3}	8.85×10^{-4}	3.28×10^{-1}	1.63×10^{-1}
Zn	3.00×10^{-1}	3.00×10^{-1}	6.00×10^{-2}	TourAr	1.69×10^{-2}	8.43×10^{-3}	4.73×10^{-7}	2.13×10^{-7}	1.35×10^{-4}	3.44×10^{-5}	1.70×10^{-2}	8.46×10^{-3}
				EdAr	1.69×10^{-2}	8.47×10^{-3}	4.75×10^{-7}	2.14×10^{-7}	1.35×10^{-4}	3.46×10^{-5}	1.71×10^{-2}	8.50×10^{-3}
				ResAr	1.83×10^{-2}	9.15×10^{-3}	5.13×10^{-7}	2.31×10^{-7}	1.46×10^{-4}	3.74×10^{-5}	1.85×10^{-2}	9.19×10^{-3}
				CmAr	4.85×10^{-2}	2.43×10^{-2}	1.36×10^{-6}	6.13×10^{-7}	3.88×10^{-4}	9.91×10^{-5}	4.89×10^{-2}	2.44×10^{-2}
				TrfAr	2.55×10^{-2}	1.28×10^{-2}	7.16×10^{-7}	3.22×10^{-7}	2.04×10^{-4}	5.21×10^{-5}	2.57×10^{-2}	1.28×10^{-2}
				IndAr	1.65×10^{-2}	8.25×10^{-3}	4.63×10^{-7}	2.08×10^{-7}	1.32×10^{-4}	3.37×10^{-5}	1.66×10^{-2}	8.28×10^{-3}
Cu	4.00×10^{-2}	4.02×10^{-2}	1.20×10^{-2}	TourAr	2.31×10^{-2}	1.15×10^{-2}	6.45×10^{-7}	2.90×10^{-7}	1.23×10^{-4}	3.14×10^{-5}	2.32×10^{-2}	1.16×10^{-2}
				EdAr	3.11×10^{-2}	1.56×10^{-2}	8.69×10^{-7}	3.91×10^{-7}	1.66×10^{-4}	4.24×10^{-5}	3.13×10^{-2}	1.56×10^{-2}
				ResAr	4.23×10^{-2}	2.11×10^{-2}	1.18×10^{-6}	5.31×10^{-7}	2.26×10^{-4}	5.76×10^{-5}	4.25×10^{-2}	2.12×10^{-2}
				CmAr	1.23×10^{-1}	6.15×10^{-2}	3.43×10^{-6}	1.54×10^{-6}	6.56×10^{-4}	1.67×10^{-4}	1.24×10^{-1}	6.16×10^{-2}
				TrfAr	3.26×10^{-2}	1.63×10^{-2}	9.10×10^{-7}	4.10×10^{-7}	1.74×10^{-4}	4.44×10^{-5}	3.28×10^{-2}	1.63×10^{-2}
				IndAr	9.32×10^{-2}	4.66×10^{-2}	2.60×10^{-6}	1.17×10^{-6}	4.97×10^{-4}	1.27×10^{-4}	9.37×10^{-2}	4.67×10^{-2}
Cd	1.00×10^{-3}	1.00×10^{-3}	5.00×10^{-5}	TourAr	1.09×10^{-2}	5.47×10^{-3}	3.07×10^{-7}	1.38×10^{-7}	3.50×10^{-4}	8.94×10^{-5}	1.13×10^{-2}	5.56×10^{-3}
				EdAr	8.34×10^{-3}	4.17×10^{-3}	2.34×10^{-7}	1.05×10^{-7}	2.67×10^{-4}	6.81×10^{-5}	8.61×10^{-3}	4.24×10^{-3}
				ResAr	7.63×10^{-3}	3.82×10^{-3}	2.14×10^{-7}	9.64×10^{-8}	2.44×10^{-4}	6.24×10^{-5}	7.88×10^{-3}	3.88×10^{-3}
				CmAr	1.48×10^{-2}	7.41×10^{-3}	4.16×10^{-7}	1.87×10^{-7}	4.74×10^{-4}	1.21×10^{-4}	1.53×10^{-2}	7.53×10^{-3}
				TrfAr	4.70×10^{-3}	2.35×10^{-3}	1.32×10^{-7}	5.94×10^{-8}	1.50×10^{-4}	3.84×10^{-5}	4.85×10^{-3}	2.39×10^{-3}
				IndAr	7.24×10^{-3}	3.62×10^{-3}	2.03×10^{-7}	9.14×10^{-8}	2.32×10^{-4}	5.91×10^{-5}	7.47×10^{-3}	3.68×10^{-3}

Table 4. Carcinogenic risk from heavy metals in road dust.

Elements	95%UCL (mg/kg)	CSFo	IUR $(\mu g/m^3)^{-1}$	GIABS	Sampling Sites	$LADD_{ing}$	$LADD_{inh}$	$LADD_{dermal}$	CRing	CRinh	CR_{dermal}	CR
Pb (Lead and Compounds)	121.7195486	0.0085	0.000012	1	CmAr	1.01×10^{-4}	6.65×10^{-9}	6.09×10^{-7}	8.56×10^{-7}	7.97×10^{-14}	5.17×10^{-9}	8.62×10^{-7}
	138.1002814				EdAr	1.14×10^{-4}	7.54×10^{-9}	6.90×10^{-7}	9.72×10^{-7}	9.05×10^{-14}	5.87×10^{-9}	9.78×10^{-7}
	218.5271501				ResAr	1.81×10^{-4}	1.19×10^{-8}	1.09×10^{-6}	1.54×10^{-6}	1.43×10^{-13}	9.29×10^{-9}	1.55×10^{-6}
	93.31945578				CmAr	7.72×10^{-5}	5.10×10^{-9}	4.67×10^{-7}	6.57×10^{-7}	6.11×10^{-14}	3.97×10^{-9}	6.61×10^{-7}
	144.120245				TrfAr	1.19×10^{-4}	7.87×10^{-9}	7.21×10^{-7}	1.01×10^{-6}	9.44×10^{-14}	6.12×10^{-9}	1.02×10^{-6}
	172.921536				IndAr	1.43×10^{-4}	9.44×10^{-9}	8.64×10^{-7}	1.22×10^{-6}	1.13×10^{-13}	7.35×10^{-9}	1.22×10^{-6}
Cd (Diet)	1.66399128		0.0018	0.025	TourAr	1.38×10^{-6}	9.09×10^{-11}	8.32×10^{-9}	-	1.64×10^{-13}	-	1.64×10^{-13}
	1.2682386				EdAr	1.05×10^{-6}	6.92×10^{-11}	6.34×10^{-9}	-	1.25×10^{-13}	-	1.25×10^{-13}
	1.16069613				ResAr	9.61×10^{-7}	6.34×10^{-11}	5.80×10^{-9}	-	1.14×10^{-13}	-	1.14×10^{-13}
	2.25412418				CmAr	1.87×10^{-6}	1.23×10^{-10}	1.13×10^{-8}	-	2.22×10^{-13}	-	2.22×10^{-13}
	0.71491635				TrfAr	5.92×10^{-7}	3.90×10^{-11}	3.57×10^{-9}	-	7.03×10^{-14}	-	7.03×10^{-14}
	1.1008246				IndAr	9.11×10^{-7}	6.01×10^{-11}	5.50×10^{-9}	-	1.08×10^{-13}	-	1.08×10^{-13}

4. Conclusions

The study demonstrated notable variations in heavy metal concentrations in road dust across different zones, with commercial areas showing particularly high levels of Zn, Cu, and Cd, largely due to vehicular emissions. The bioaccessibility of Pb, Zn, and Cd was greater in the gastric phase compared to the small intestinal phase, indicating a higher potential for these metals to be absorbed when ingested. Children were identified as being at a significantly higher non-carcinogenic risk from exposure to these heavy metals, facing more than double the risk compared to adults. The carcinogenic risk assessment showed a low but non-negligible risk for Pb, while Cd posed minimal risk; however, elevated Cd levels in parks and commercial areas require further investigation. These findings show the importance of implementing protective measures, particularly in areas with heavy traffic, to safeguard vulnerable populations from the risks associated with heavy metal contamination. Strict emission controls in residential areas with high traffic volumes and regular monitoring of heavy metal levels in road dust, particularly Pb, are recommended. Additionally, targeting commercial areas near busy urban transportation hubs for similar emission controls and monitoring Zn, Cu, and Cd concentrations is crucial, given their significantly higher average heavy metal levels attributed to vehicle exhaust deposition. Special attention should be given to minimizing exposure to children by implementing dust management strategies and raising public awareness. Phytoextractors or planting phytostabilizers could have the dual benefit of mitigating soil pollution while contributing to air remediation. Additionally, further research focusing on the carcinogenic risks of Cd, especially in parks and commercial zones, is crucial for policy-making.

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