*Article*

# Metal Exposure and Associated Health Risk to Human Beings by Street Dust in a Heavily Industrialized City of Hunan Province, Central China

**Guangyi Sun [1,2], Zhonggen Li [1,*], Ting Liu [1,2,3], Ji Chen [1,4], Tingting Wu [1,5] and Xinbin Feng [1,*]**

[1]  State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China; sunguangyi@mail.gyig.ac.cn (G.S.); liuting@ihb.ac.cn (T.L.); jigerchen@163.com (J.C.); wutingtingcc@163.com (T.W.)
[2]  University of Chinese Academy of Sciences, Beijing 100190, China
[3]  Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China
[4]  Guizhou Provincial Laboratory for Mountainous Environment, Guizhou Normal University, Guiyang 550001, China
[5]  Key Laboratory of Karst Environment and Geohazard Prevention, Guizhou University, Guiyang 550003, China
*  Correspondence: lizhonggen@vip.skleg.cn (Z.L.); fengxinbin@vip.skleg.cn (X.F.); Tel.: +86-13608517028 (Z.L.); Fax: +86-851-8589-1334 (Z.L.)

**Abstract:** Fifty-five urban street dust samples were collected from Zhuzhou, an industrial city in central China and analyzed for a range of toxic elements. Potential carcinogenic and non-carcinogenic health effects on children and adults due to exposure to street dust were assessed. Concerning the two subgroups, the child cohort is confronted with considerably greater health risks than adults. According to the Hazard Quotient (HQ) method, ingestion of dust particles poses primary risk to children and adults, followed by dermal contact and inhalation for all of the metals investigated except Hg, for which inhalation of its elemental vapor constitute a slightly higher risk than ingestion. For children, Pb, As, Cd, Cr, Hg and Sb exposure were deemed as the highest contributors to non-cancer health risks, while As and Cr represent an enhanced cancer risk for children. For adults, risk indicator values for both cancer and non-cancer effects obtained were within the safety threshold. In a comparison with other locations within and outside mainland China, exposure to arsenic is prominent for the population of Zhuzhou, indicating more attention and preventive actions should been taken.

**Keywords:** street dust; health risk; cancer; arsenic; metals

## 1. Introduction

Street dust, a special type of environmental medium with a complex composition in urban regions, could potentially cause adverse effects on exposed populations. Metal contamination character and source identification are the main concern of most previous literature on street dust [1–6]. On the basis of toxic metal contents solely, it is difficult to produce a quantitative health assessment. Although some metals are considerably enriched in street dust, both cancer and non-cancer risk normally falls below the acceptable level by the corresponding regulatory authorities [7]. Researches both from epidemiological and toxicological studies have showed that metals and metalloids can accumulate in fatty tissues, affecting the functions of organs and disrupting the nervous system or endocrinal system; or interact directly with DNA to cause mutations [8–13]. Nonetheless, in heavy impacted municipalities, there is an urgent need to assess the health risk associated with toxic metal exposure

for the residents' health. Human health risk assessment has proved to be a useful tool to pinpoint the severity of various toxic metals [14–19]. The health risk, a method combining metal pollution and human health, is developed from a qualitative or quantitative estimate of the likelihood that any of the hazards associated with the agent of concern will be realized in exposed people [20].

The objectives of the present study were to estimate health risk for children and adults due to toxic metal exposure to street dust according to Hazard Indexes (HI) and cancer risk assessment in Zhuzhou, a heavily industrialized city in China, and put the result into a broader perspective of similar studies in China and elsewhere.

## 2. Materials and Methods

### 2.1. Study Area

Zhuzhou, the second largest city of Hunan Province in central China, is located in the middle reaches of the Xiang River watershed (Figure 1) and about 50 km south of Changsha, the provincial capital. The city developed rapidly from a town in the 1950s to a large city, with a population of 1.002 million and a built-up area of 105 km$^2$ by the end of 2009. Zhuzhou has a typical north subtropical monsoon climate, with prevailing NNW winds, except during summer (June–August) with SE winds. Its annual average temperature is 17.6 °C with plenty of precipitation, mainly during March to August, with an annual rainfall of 1409 mm. The topography mostly consists of alluvial plains and gentle hills at an elevation of 50–200 m above sea level. Acidic ferro soils of krasnozem type are here predominant as elsewhere in southern China [21].

Zhuzhou is a major base of heavy industries in Hunan Province. Zhuzhou Electrical Railway Engine Corporation, Zhuzhou Hard Alloy Group, China Southern Power Equipment Corporation and Zhuzhou Smelting Group are all backbone enterprises of the city, predominantly established during the era of China's first and second "Five-year Plan" (1953–1962). The city's industrial output is characterized by production foremost in the categories of metallurgy, machinery, chemistry and building materials [21].
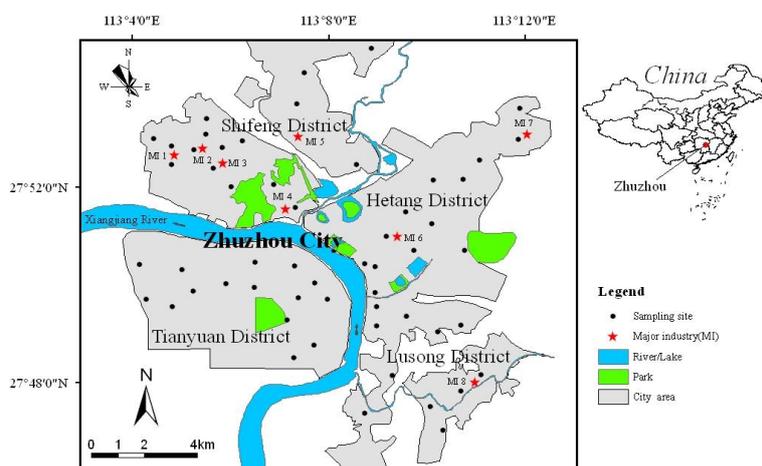


**Figure 1.** Sketch map showing the study area with sampling locations of street dust and the major industries in Zhuzhou city.

### 2.2. Data Sources

The street dust samples were collected in winter of 2010. A total of 55 samples were obtained across the city, as shown in Figure 1. The levels, spatial distributions and possible sources of heavy metals (Ag, As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Zn) in street dust were reported by our previous publication (Li et al. [21]). The data showed that the Zn/Pb smelting activities located in the northwest part of city are the main source of Ag, As, Cd, Cu, Hg Pb, Sb and Zn, while a hard alloy plant in the

central city responsible for the Mo enrichment, nevertheless Co, Cr and Ni are mainly ascribed to the natural sources.

## 2.3. Risk Assessment Method

Human exposure to trace elements in street dust can induce health risks via three main paths: (a) direct ingestion of substrate particles ($D_{ing}$); (b) inhalation of suspended particles through mouth and nose ($D_{inh}$); and (c) dermal absorption of potentially harmful elements in particles adhered to exposed skin ($D_{dermal}$). The dose received through each of the three pathways was calculated using Equations (1)–(3), which were adopted from U.S. Environmental Protection Agency [22,23] and Zheng et al. [15,16]. For Hg, exposure via inhalation of its elemental vapor is viable following Equation (4). For carcinogens, lifetime average daily dose (LADD) is used for assessment of cancer risk. LADD is calculated as a weighted average for each exposure route as given in Equation (5):

$$D_{ing} = C \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{1}$$

$$D_{inh} = C \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT} \tag{2}$$

$$D_{dermal} = C \times \frac{SL \times SA \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{3}$$

$$D_{vapour} = C \times \frac{InhR \times EF \times ED}{VF \times BW \times AT} \tag{4}$$

$$LADD = C \times \frac{CR \times EF \times ED}{PEF \times BW \times AT} \tag{5}$$

The formulae acronyms used in Equations (1)–(5) are explained in Table 1. The reference values used in the analysis were retrieved from U.S. EPA [24], Van den Berg [19], Naturvårdsverket [25] and De Miguel [24]. Site specific biometric factors were assessed from literature recommendations [19,24].

C (exposure-point concentration, mg·kg$^{-1}$) in Equations (1)–(5), combined with the values of exposure factors shown above, are considered to yield an estimate of the "reasonable maximum exposure" [22], which is the upper limit of the 95% confidence interval for mean (UCL, upper confidence limit) [23]. Considering that the concentration of each trace element investigated followed log-normal distribution among samples, 95% UCL was calculated using the statistical software SPSS 15.0 for Windows (SPSS Inc., Chicago, IL, USA).

The potential carcinogenic and non-carcinogenic risks for human being were calculated using Equations (6) and (7) [26].

$$\text{Carcinogenic Risk} = LADD \times SF \tag{6}$$

$$\text{Hazard quotient (HQ)} = D_i/RfD \tag{7}$$

For carcinogens, the carcinogenic risk is multiplied by the corresponding slope factor (SF) to produce a level. The acceptable or tolerable risk for regulatory purposes is in the range of $1 \times 10^{-6}$–$1 \times 10^{-4}$ [19]. RfD is the reference dose (mg·kg$^{-1}$·day$^{-1}$) and $D_i$ is the daily exposure amounts of the selected metal (mg·kg$^{-1}$·day$^{-1}$). Hazard Quotient (HQ) for non-carcinogenic effects was applied to each exposure pathway in the analysis. The approach assumes that simultaneous sub-threshold exposures to toxic metals could result in adverse health effects and the magnitude of the adverse effect will be proportional to the sum of the ratios of the sub-threshold exposures to acceptable exposures [22]. Hazard index (HI) is equal to the sum of HQ. If the value of HI is less than one, it is assumed that there is no significant risk of non-carcinogenic effects. If HI exceeds one, then there is a chance that non-carcinogenic effects occur, with a probability which tends to increase as the value of HI increases [24]. For a comparison, relative toxicity values (RfD and SF) from this study and from the literature are summarized in Table 2.

**Table 1.** Description of parameters and the default values used in does and health risk assessment.

| Symbol | Meanings | Default Value | Data Source, Year [Reference] |
|---|---|---|---|
| C | Value of elements in street dust | 95% UCL | This study |
| *IngR* | Ingestion rate | 200 mg·day$^{-1}$ (child); 100 mg·day$^{-1}$(adult) | U.S. EPA, 2001 [24] |
| *InhR* | Inhalation rate | 7.6 m$^3$·day$^{-1}$ (child); 20 m$^3$·day$^{-1}$ (adult) | Van den Berg, 1995 [27] |
| *EF* | Exposure frequency (site specific) | 180 day·year$^{-1}$ | Ferreira-Baptista and De Miguel, 2005 [14] |
| *ED* | Exposure duration | 6 year (child); 24 year (adult) | U.S. EPA, 1996, 2001 [23,24] |
| *SA* | Skin area exposed | 1150 cm$^2$(child); 2145 cm$^2$(adult) | Wang et al. 2008 [28] |
| *SL* | Skin adherence factor | 0.2 mg·cm$^{-2}$·day$^{-1}$(child); 0.07 mg·cm$^{-2}$·day$^{-1}$(adult) | U.S. EPA, 1996, 2001 [23,24] |
| *ABS* | Dermal absorption factor | 0.03 (for As); 0.001 (for other elements) | U.S. DOE, 2004 [20] |
| *PEF* | Particle emission factor | $1.36 \times 10^9$ m$^3$·kg$^{-1}$ | U.S. EPA, 2001 [24] |
| *VF* | Volatility factor | 32,675.6 m$^3$·kg$^{-1}$ (elemental mercury vapor) | U.S. EPA, 2001 [24] |
| *BW* | Body weight | 15.4 kg (child); 56 kg (adult) | U.S. EPA, 1996, 2001;Wang et al. 2005 [23,24,29] |
| *AT* | Average time | *ED* $\times$ 365 (for non-carcinogens); *ED* $\times$ 365 (for carcinogens) | U.S. EPA, 1989 [22] |
| *CR* | Contact (absorption) rate | Ingestion: [*CR* = *IngR*]; Inhalation: [*CR* = *InhR*]; Dermal: [*CR* = *SA* $\times$ SL $\times$ ABS] | U.S. EPA, 1996, 2001 [23,24] |

**Table 2.** Relative toxicity values used in this study [14–16,23].

| | Ag | As | Cd | Co | Cr | Cu | Hg | Mo | Ni | Pb | Sb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oral RfD | $5.00 \times 10^{-3}$ | $3.00 \times 10^{-4}$ | $1.00 \times 10^{-3}$ | $2.00 \times 10^{-2}$ | $3.00 \times 10^{-3}$ | $4.00 \times 10^{-2}$ | $3.00 \times 10^{-4}$ | $5.00 \times 10^{-3}$ | $2.00 \times 10^{-2}$ | $3.50 \times 10^{-3}$ | $4.00 \times 10^{-4}$ | $3.00 \times 10^{-1}$ |
| D × 10 rmal. RfD | $9.00 \times 10^{-4}$ | $1.23 \times 10^{-4}$ | $1.00 \times 10^{-5}$ | $1.60 \times 10^{-2}$ | $6.00 \times 10^{-5}$ | $1.20 \times 10^{-2}$ | $2.10 \times 10^{-5}$ | $1.90 \times 10^{-3}$ | $5.40 \times 10^{-3}$ | $5.25 \times 10^{-4}$ | $8.00 \times 10^{-6}$ | $6.00 \times 10^{-2}$ |
| Inhal. RfD | $5.00 \times 10^{-3}$ | $3.00 \times 10^{-4}$ | $1.00 \times 10^{-3}$ | $5.71 \times 10^{-6}$ | $2.86 \times 10^{-5}$ | $4.02 \times 10^{-2}$ | $2.90 \times 10^{-4}$ | $4.95 \times 10^{-3}$ | $2.06 \times 10^{-2}$ | $3.52 \times 10^{-3}$ | $4.00 \times 10^{-4}$ | $3.00 \times 10^{-1}$ |
| Vapour RfD | | | | | | | $8.57 \times 10^{-5}$ | | | | | |
| Oral SF | | $1.50 \times 10$ | | | | | | | | | | |
| D × 10 rmal SF | | $3.66 \times 10$ | | | | | | | | | | |
| Inhal. SF | | $1.51 \times 10$ | $6.30 \times 10$ | $9.80 \times 10$ | $4.20 \times 10^1$ | | | | $8.40 \times 10^{-1}$ | | | |

## 3. Results and Discussion

### 3.1. Trace Elements in the Street Dust

Descriptive statistical results of trace element concentrations investigated in Zhuzhou city, as well as their background value in surface soils of Hunan province [30], are summarized in Table 3. In particular, the average concentration of Zn and Pb is enhanced at 2379 mg·kg$^{-1}$ and 956 mg·kg$^{-1}$, respectively. The arithmetic mean concentration for elements followed in the order of Zn > Pb > Cu >Cr > As >Cd > Ni > Sb > Co > Mo > Ag > Hg.

**Table 3.** Trace elements concentrations in street dust collected form Zhuzhou city [21] (N = 55, mg·kg$^{-1}$).

| Element | Median | Mean | SD | Min | Max | 95% UCL | Skewness | Reference Value | EF |
|---|---|---|---|---|---|---|---|---|---|
| Ag | 1.17 | 2.49 | 4.56 | 0.46 | 28.7 | 3.72 | 4.49 | 0.108 | 10.83 |
| As | 41.8 | 87.8 | 182.9 | 15.4 | 1194.1 | 137.2 | 5.05 | 15.7 | 2.7 |
| Cd | 10.3 | 41.4 | 117.3 | 2.2 | 691 | 73.1 | 4.71 | 0.126 | 81.75 |
| Co | 13 | 15 | 11 | 8 | 84 | 18 | 4.85 | 14.6 | 0.86 |
| Cr | 115 | 124.6 | 54.1 | 59.5 | 302 | 139 | 1.78 | 71.4 | 1.61 |
| Cu | 97.6 | 139 | 148.3 | 39.2 | 1020 | 179 | 4.44 | 27.3 | 3.58 |
| Hg | 0.21 | 0.92 | 2.7 | 0.08 | 14.6 | 1.65 | 4.69 | 0.116 | 1.77 |
| Mo | 3.2 | 6.4 | 12.4 | 1.3 | 90.1 | 9.7 | 6.02 | 1.4 | 2.25 |
| Ni | 35 | 40 | 16 | 20 | 105 | 45 | 1.95 | 31.9 | 1.1 |
| Pb | 254 | 956 | 2815 | 96 | 17,578 | 1717 | 5.03 | 29.7 | 8.54 |
| Sb | 9.8 | 15.8 | 21.7 | 3.7 | 115.4 | 21.7 | 3.81 | 1.87 | 5.24 |
| Zn | 1140 | 2379 | 5145 | 317 | 35,400 | 3770 | 5.46 | 94.4 | 12.08 |

SD: Std. Deviation; Min: Minimum; Max: Maximum; Reference value in the soil of Hunan province, (CNEMC, 1990) [30]; EF, enrichment factor = median/reference value.

The concentration distribution in samples for all of the studied elements display a positive skewness (>1) and can be approximated as a log-normal one. Furthermore, enrichment factors (EFs) for all the elements except for Co are greater than unity signifying anthropogenic influences. Among the elements, the magnitude of EF peaking for Cd (81.75) but is also considerably high (>10) for some adjacent elements in the periodical table, namely Zn and Ag.

### 3.2. Non-Carcinogenic Risk of Metals

For non-carcinogenic health effects among children and adults, the calculated overall risk and the corresponding contribution for each exposure pathway are summarized in Table 4. In the case of children, the rank for exposure risk among the three routes was for all elements ingestion > dermal contact > inhalation. Hg is an exception, for which inhalation of Hg vapor is the primary cause of exposure and not by particulate matter [13]. This result also applies to adults. Similar results were obtained by Ferreira-Baptista and DeMiguel [14], and Zheng et al. [21,22].

In general, children exposure non-cancer risks of toxic metals were nearly one order of magnitude higher than the values of adult. So, children are confronted by greater harmful health risks due to the street dust than other population groups. This is similar to other reports [7].

HIs for metals to children and adult decrease in the order of Pb > As > Cd > Sb > Cr > Hg > Zn > Cu > Ni > Mo > Co > Ag and Pb > As > Hg > Cd > Sb > Cr > Zn > Cu > Ni > Mo > Co > Ag, respectively, The above showed that Pb/Zn smelting may be the most important factor raising risk to human health, due to Pb mainly related to Pb/Zn smelting. Except for Pb and As, HIs for other metals due to street dust exposure in this study are lower than the safety limit of unity, indicating less non-cancer risks from these elements for children and adult.

*Int. J. Environ. Res. Public Health* **2017**, *14*, 261

6 of 11

**Table 4.** Daily exposure amounts and hazard quotient of metals in street dust to adult and child through three routes.

| mg·kg⁻¹·day⁻¹ | Ag | As | Cd | Co | Cr | Cu | Hg | Mo | Ni | Pb | Sb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Adult** | | | | | | | | | | | | |
| Ding | $3.28 \times 10^{-6}$ | $1.21 \times 10^{-4}$ | $6.44 \times 10^{-5}$ | $1.59 \times 10^{-5}$ | $1.22 \times 10^{-4}$ | $1.58 \times 10^{-4}$ | $1.45 \times 10^{-6}$ | $8.54 \times 10^{-6}$ | $3.96 \times 10^{-5}$ | $1.51 \times 10^{-3}$ | $1.91 \times 10^{-5}$ | $3.32 \times 10^{-3}$ |
| Dd × 10 rmal | $4.92 \times 10^{-9}$ | $5.44 \times 10^{-6}$ | $9.67 \times 10^{-8}$ | $2.38 \times 10^{-8}$ | $1.84 \times 10^{-7}$ | $2.37 \times 10^{-7}$ | $2.18 \times 10^{-9}$ | $1.28 \times 10^{-8}$ | $5.95 \times 10^{-8}$ | $2.27 \times 10^{-6}$ | $2.87 \times 10^{-8}$ | $4.98 \times 10^{-6}$ |
| Dinh | $4.82 \times 10^{-10}$ | $1.78 \times 10^{-8}$ | $9.47 \times 10^{-9}$ | $2.33 \times 10^{-9}$ | $1.80 \times 10^{-8}$ | $2.32 \times 10^{-8}$ | $2.14 \times 10^{-10}$ | $1.26 \times 10^{-9}$ | $5.83 \times 10^{-9}$ | $2.22 \times 10^{-7}$ | $2.81 \times 10^{-9}$ | $4.88 \times 10^{-7}$ |
| Dvapour | | | | | | | $8.89 \times 10^{-6}$ | | | | | |
| HQing | $6.55 \times 10^{-4}$ | $4.03 \times 10^{-1}$ | $6.44 \times 10^{-2}$ | $7.93 \times 10^{-4}$ | $4.08 \times 10^{-2}$ | $3.94 \times 10^{-3}$ | $4.84 \times 10^{-3}$ | $1.71 \times 10^{-3}$ | $1.98 \times 10^{-3}$ | $4.32 \times 10^{-1}$ | $4.78 \times 10^{-2}$ | $1.11 \times 10^{-2}$ |
| HQd × 10 rmal | $5.47 \times 10^{-6}$ | $4.42 \times 10^{-2}$ | $9.67 \times 10^{-3}$ | $1.49 \times 10^{-6}$ | $3.06 \times 10^{-3}$ | $1.97 \times 10^{-5}$ | $1.04 \times 10^{-4}$ | $6.75 \times 10^{-6}$ | $1.10 \times 10^{-5}$ | $4.32 \times 10^{-3}$ | $3.59 \times 10^{-3}$ | $8.31 \times 10^{-5}$ |
| HQinh | $9.64 \times 10^{-8}$ | $5.92 \times 10^{-5}$ | $9.47 \times 10^{-6}$ | $4.08 \times 10^{-4}$ | $6.29 \times 10^{-4}$ | $5.77 \times 10^{-7}$ | $7.37 \times 10^{-7}$ | $2.54 \times 10^{-7}$ | $2.83 \times 10^{-7}$ | $6.32 \times 10^{-5}$ | $7.03 \times 10^{-6}$ | $1.63 \times 10^{-6}$ |
| HQvaour | | | | | | | $1.04 \times 10^{-1}$ | | | | | |
| HI = ∑HQ | $6.61 \times 10^{-4}$ | $4.47 \times 10^{-1}$ | $7.40 \times 10^{-2}$ | $1.20 \times 10^{-3}$ | $4.45 \times 10^{-2}$ | $3.96 \times 10^{-3}$ | $1.09 \times 10^{-1}$ | $1.72 \times 10^{-3}$ | $1.99 \times 10^{-3}$ | $4.36 \times 10^{-1}$ | $5.14 \times 10^{-2}$ | $1.12 \times 10^{-2}$ |
| **Child** | | | | | | | | | | | | |
| Ding | $2.38 \times 10^{-5}$ | $8.79 \times 10^{-4}$ | $4.68 \times 10^{-4}$ | $1.15 \times 10^{-4}$ | $8.90 \times 10^{-4}$ | $1.15 \times 10^{-3}$ | $1.06 \times 10^{-5}$ | $6.21 \times 10^{-5}$ | $2.88 \times 10^{-4}$ | $1.10 \times 10^{-2}$ | $1.39 \times 10^{-4}$ | $2.41 \times 10^{-2}$ |
| Dd × 10 rmal | $2.74 \times 10^{-8}$ | $3.03 \times 10^{-5}$ | $5.38 \times 10^{-7}$ | $1.33 \times 10^{-7}$ | $1.02 \times 10^{-6}$ | $1.32 \times 10^{-6}$ | $1.22 \times 10^{-8}$ | $7.14 \times 10^{-8}$ | $3.31 \times 10^{-7}$ | $1.26 \times 10^{-5}$ | $1.60 \times 10^{-7}$ | $2.78 \times 10^{-5}$ |
| Dinh | $6.66 \times 10^{-10}$ | $2.46 \times 10^{-8}$ | $1.31 \times 10^{-8}$ | $3.22 \times 10^{-9}$ | $2.49 \times 10^{-8}$ | $3.20 \times 10^{-8}$ | $2.95 \times 10^{-10}$ | $1.74 \times 10^{-9}$ | $8.05 \times 10^{-9}$ | $3.07 \times 10^{-7}$ | $3.88 \times 10^{-9}$ | $6.75 \times 10^{-7}$ |
| Dvapour | | | | | | | $1.23 \times 10^{-5}$ | | | | | |
| HQing | $4.76 \times 10^{-3}$ | $2.93 \times 10$ | $4.68 \times 10^{-1}$ | $5.76 \times 10^{-3}$ | $2.97 \times 10^{-1}$ | $2.87 \times 10^{-2}$ | $3.52 \times 10^{-2}$ | $1.24 \times 10^{-2}$ | $1.44 \times 10^{-2}$ | $3.14 \times 10$ | $3.47 \times 10^{-1}$ | $8.05 \times 10^{-2}$ |
| HQd × 10 rmal | $3.04 \times 10^{-5}$ | $2.46 \times 10^{-1}$ | $5.38 \times 10^{-2}$ | $8.29 \times 10^{-6}$ | $1.71 \times 10^{-2}$ | $1.10 \times 10^{-4}$ | $5.79 \times 10^{-4}$ | $3.76 \times 10^{-5}$ | $6.14 \times 10^{-5}$ | $2.41 \times 10^{-2}$ | $2.00 \times 10^{-2}$ | $4.63 \times 10^{-4}$ |
| HQinh | $1.33 \times 10^{-7}$ | $8.18 \times 10^{-5}$ | $1.31 \times 10^{-5}$ | $5.64 \times 10^{-4}$ | $8.70 \times 10^{-4}$ | $7.97 \times 10^{-7}$ | $1.02 \times 10^{-6}$ | $3.51 \times 10^{-7}$ | $3.91 \times 10^{-7}$ | $8.73 \times 10^{-5}$ | $9.71 \times 10^{-6}$ | $2.25 \times 10^{-6}$ |
| HQvaour | | | | | | | $1.43 \times 10^{-1}$ | | | | | |
| HI = ∑HQ | $4.80 \times 10^{-3}$ | $3.18 \times 10$ | $5.22 \times 10^{-1}$ | $6.34 \times 10^{-3}$ | $3.15 \times 10^{-1}$ | $2.88 \times 10^{-2}$ | $1.79 \times 10^{-1}$ | $1.25 \times 10^{-2}$ | $1.45 \times 10^{-2}$ | $3.17 \times 10$ | $3.67 \times 10^{-1}$ | $8.09 \times 10^{-2}$ |

Concerning the two population groups, they both experience potential health risk by Pb and As exposure from street dust. For children, the Hazard Indexes for Pb and As exceed the safe level (both greater than 3, Table 4). There has a great possibility to pose potential adverse health effects to human beings that non-carcinogenic effects may occur, with a probability which tends to increase as the value of HI increases [15,16,24]. According to De Miguel et al. [31], adverse health effects may occur at HI values >0.1 level in the child cohort. Consequently, Cd, Cr, Hg and Sb, that with HIs greater than 0.1 for the child, exposure to the street dust in Zhuzhou cannot be overlooked, and its ecological and health implications need investigated in detail in the further.

### 3.3. Risks Associated with the Carcinogenic Elements As, Cd, Cr, Co and Ni

The overall carcinogenic risks owing to exposure to As, Cd, Co, Cr and Ni in street dust are shown in Table 5. The carcinogenic risk levels of Cd, Co and Ni exposure for both cohorts are within the same low order of magnitude ($10^{-8} \sim 10^{-9}$), which means that they pose a negligible risk [32,33].

In terms of children, the calculated value for As ($1.04 \times 10^{-6}$) and Cr ($1.07 \times 10^{-6}$) in street dust falls within the range of threshold values ($10^{-4} – 10^{-6}$) which is an internationally accepted precautionary risk criterion [32,33]. In contrast, adult exposure carcinogenic risk for these elements falls below this threshold ($1.29 \times 10^{-7}$ and $6.05 \times 10^{-7}$ for As and Cr, respectively). As in street dust is introduced by the nonferrous smelting activities and Cr is naturally enriched in the local soil of Zhuzhou [21]. As a carcinogen, arsenic can cause lung and skin cancer [34] and Cr can trigger lung cancer and stomach cancer [34] if an excessive buildup of both elements occurs. In view of the above, the risk of lung cancer disease increased by one times for the two subpopulations. Hence, further research should be undertaken to reveal the synergistic influence from Cr and As on human health.

**Table 5.** Daily exposure amounts and Cancer Risk of metals in street dust to adult and child through three routes.

| mg·kg$^{-1}$·day$^{-1}$ | As | Cd | Co | Cr | Ni |
|---|---|---|---|---|---|
| Adult | | | | | |
| LADD-Oral | $8.88 \times 10^{-8}$ | | | | |
| LADD-Dermal | $4.00 \times 10^{-9}$ | | | | |
| LADD-Inhal. | $1.78 \times 10^{-8}$ | $9.47 \times 10^{-9}$ | $2.33 \times 10^{-9}$ | $1.80 \times 10^{-8}$ | $5.83 \times 10^{-9}$ |
| Risk-Oral | $1.33 \times 10^{-7}$ | | | | |
| Risk-Dermal | $1.46 \times 10^{-8}$ | | | | |
| Risk-Inhal | $2.68 \times 10^{-8}$ | $5.96 \times 10^{-8}$ | $2.28 \times 10^{-8}$ | $7.56 \times 10^{-7}$ | $4.90 \times 10^{-9}$ |
| Risk-Total | $1.75 \times 10^{-7}$ | $5.96 \times 10^{-8}$ | $2.28 \times 10^{-8}$ | $7.56 \times 10^{-7}$ | $4.90 \times 10^{-9}$ |
| Child | | | | | |
| LADD-Oral | $6.46 \times 10^{-7}$ | | | | |
| LADD-Dermal | $2.23 \times 10^{-8}$ | | | | |
| LADD-Inhal. | $2.46 \times 10^{-8}$ | $1.31 \times 10^{-8}$ | $3.22 \times 10^{-9}$ | $2.49 \times 10^{-8}$ | $8.05 \times 10^{-9}$ |
| Risk-Oral | $9.69 \times 10^{-7}$ | | | | |
| Risk-Dermal | $8.16 \times 10^{-8}$ | | | | |
| Risk-Inhal | $3.71 \times 10^{-8}$ | $8.24 \times 10^{-8}$ | $3.16 \times 10^{-8}$ | $1.04 \times 10^{-6}$ | $6.76 \times 10^{-9}$ |
| Risk-Total | $1.09 \times 10^{-6}$ | $8.24 \times 10^{-8}$ | $3.16 \times 10^{-8}$ | $1.04 \times 10^{-6}$ | $6.76 \times 10^{-9}$ |

### 3.4. Comparison of HI and Cancer Risk with Other Researches

The HI and cancer risk assessment results in street dust of Zhuzhou were compared with results from other cities around the world, as shown in Tables 6 and 7. For children, there is only one additional study (Huludao, Liaoning Province) that reported risk values of Cd and Hg exceeding 0.1. Huludao city once hosted the Asia's biggest zinc manufacturer. In addition, a study in Dongying city with large petrochemical industries reveal a HI larger than 0.1 for Cr [35], which was likewise found in this study. Similar discovery were obtained in municipal areas of Shanghai by Shi et al. [7] in a study of health risk of potentially metals in road dust.

*Int. J. Environ. Res. Public Health* **2017**, *14*, 261

8 of 11

**Table 6.** Comparisons of hazard quotient for trace metals in urban dust of different cities.

| City | Factor | Ag | As | Cd | Co | Cr | Cu | Hg | Mo | Ni | Pb | Sb | Zn | Literature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Adult** | | | | | | | | | | | | | | |
| Zhuzhou, China | Industrial pollution | $6.61 \times 10^{-4}$ | $4.47 \times 10^{-1}$ | $7.40 \times 10^{-2}$ | $1.20 \times 10^{-3}$ | $4.45 \times 10^{-2}$ | $3.96 \times 10^{-3}$ | $1.09 \times 10^{-1}$ | $1.72 \times 10^{-3}$ | $1.99 \times 10^{-3}$ | $4.36 \times 10^{-1}$ | $5.14 \times 10^{-2}$ | $1.12 \times 10^{-2}$ | This study |
| Huludao, China | Zinc smelting | | | $2.58 \times 10^{-1}$ | | | $5.71 \times 10^{-3}$ | $8.79 \times 10^{-2}$ | | | $1.44 \times 10^{-1}$ | | $1.40 \times 10^{-2}$ | Zheng et al. 2010 [15] |
| Dongying, China | Oil industry | | $6.73 \times 10^{-2}$ | $2.46 \times 10^{-3}$ | $7.46 \times 10^{-4}$ | $2.24 \times 10^{-2}$ | $1.85 \times 10^{-3}$ | | | $1.86 \times 10^{-3}$ | $4.21 \times 10^{-2}$ | | $2.23 \times 10^{-3}$ | Kong et al. 2011 [17] |
| **Child** | | | | | | | | | | | | | | |
| Zhuzhou, China | Industrial pollution | $4.80 \times 10^{-3}$ | $3.18 \times 10$ | $5.22 \times 10^{-1}$ | $6.34 \times 10^{-3}$ | $3.15 \times 10^{-1}$ | $2.88 \times 10^{-2}$ | $1.79 \times 10^{-1}$ | $1.25 \times 10^{-2}$ | $1.45 \times 10^{-2}$ | $3.17 \times 10$ | $3.67 \times 10^{-1}$ | $8.09 \times 10^{-2}$ | This study |
| Huludao, China | Zinc smelting | | $6.16 \times 10^{-1}$ | | | | $4.75 \times 10^{-2}$ | $1.82 \times 10^{-1}$ | | | $1.08 \times 10$ | | $1.11 \times 10^{-1}$ | Zheng et al. 2010 [15] |
| Dongying, China | Oil industry | | $5.86 \times 10^{-1}$ | $2.10 \times 10^{-2}$ | $5.04 \times 10^{-3}$ | $1.96 \times 10^{-1}$ | $1.73 \times 10^{-2}$ | | | | $3.90 \times 10^{-1}$ | | $2.07 \times 10^{-2}$ | Kong et al. 2011 [17] |
| Luanda, Angola | Industrial pollution | $8.42 \times 10^{-4}$ | $1.36 \times 10^{-1}$ | $1.01 \times 10^{-2}$ | $1.11 \times 10^{-3}$ | $6.63 \times 10^{-2}$ | $7.30 \times 10^{-3}$ | $1.61 \times 10^{-2}$ | $2.81 \times 10^{-3}$ | $3.55 \times 10^{-3}$ | $7.23 \times 10^{-1}$ | $6.58 \times 10^{-2}$ | $7.40 \times 10^{-3}$ | Ferreira−Baptista and De Miguel, 2005 [14] |
| Madrid, Spain | Industrial pollution | $1.67 \times 10^{-4}$ | $1.09 \times 10^{-1}$ | $1.09 \times 10^{-3}$ | | $2.72 \times 10^{-2}$ | $1.41 \times 10^{-3}$ | $1.71 \times 10^{-2}$ | $6.00 \times 10^{-4}$ | $9.61 \times 10^{-4}$ | $3.11 \times 10^{-2}$ | $1.06 \times 10^{-2}$ | $7.10 \times 10^{-4}$ | De Miguel et al. 2007 [31] |

**Table 7.** Comparisons of cancer risk for child in urban dust of different cities.

| City | Factor | As | Cd | Co | Cr | Ni | Literature |
|---|---|---|---|---|---|---|---|
| Zhuzhou, China | Industrial pollution | $1.04 \times 10^{-6}$ | $8.46 \times 10^{-8}$ | $3.24 \times 10^{-8}$ | $1.07 \times 10^{-6}$ | $6.94 \times 10^{-9}$ | This study |
| Huludao, China | Zinc smelting | | | | | $2.36 \times 10^{-8}$ | Zheng et al. 2010 [15] |
| Dongying, China | Oil industry | $7.21 \times 10^{-7}$ | $8.06 \times 10^{-10}$ | $4.35 \times 10^{-8}$ | | $2.94 \times 10^{-8}$ | Kong et al. 2011 [17] |
| Luanda, Angola | Industrial pollution | $7.69 \times 10^{-6}$ | $3.89 \times 10^{-10}$ | $1.53 \times 10^{-9}$ | $5.70 \times 10^{-8}$ | $4.61 \times 10^{-10}$ | Ferreira-Baptista and De Miguel, 2005 [14] |
| Madrid, Spain | Industrial pollution | $4.19 \times 10^{-6}$ | $2.62 \times 10^{-11}$ | | $1.73 \times 10^{-8}$ | $1.37 \times 10^{-9}$ | De Miguel et al. 2007 [31] |

Furthermore, hazard indexes of As and Pb for children exposure with value higher $10^{-1}$ appeared in several studies (see Table 6), so, these two elements could trigger neurological and developmental disorders [14]. As the same time, arsenic was the only element that associated with carcinogenic risk exceeding $10^{-6}$ in the reviewed studies. As and Pb appear to have a widespread impact on children health in polluted cities all over the world.

Since arsenic is outstanding both for cancer and non-cancer risk for many researches. Here we take arsenic as an example, compared the results obtained by this study and other researches. The HI and cancer risk of As for children are calculated according to the date from other literatures [33,36–39]. The HI means of these cities are less than 0.1 (Figure 2) and the cancer risk means are in $10^{-7}$ to $10^{-8}$ level (Figure 2). The maximum of HI in Wuhu (China) and Singapore are $9.29 \times 10^{-1}$, $9.66 \times 10^{-1}$, respectively, which are very close to one. While the data indicated that the HI and cancer risk of As in Zhuzhou are much serious than other cities (HI > 3, and cancer risk > $10^{-6}$), indicating a more worrying polluted status.
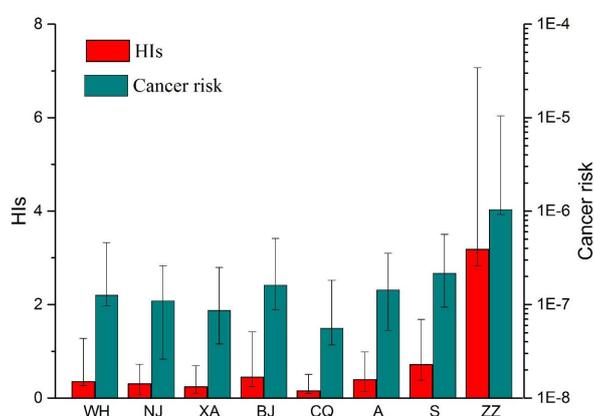


**Figure 2.** A comparison of HIs and cancer risk of arsenic to children in street dust of Wuhu (WH), Nanjing (NJ), Xi'an (XA), Baoji (BJ), Chongqing (CQ), Avilés (A), Singapore (S) and this study (ZZ).

Meanwhile, for adults, HIs for Ag, As, Cd, Co, Cr, Hg, Sb and Zn in these cities (Zhuzhou, Huludao and Dongying are lower than 1, suggesting that there is little adverse health risk due to street dust. From the aforementioned statements, it could be concluded that As and Pb contamination has become a serious environmental problem in a category of cities and further research should be undertaken to explore the particular influence of As on children health.

## 4. Conclusions

This study elucidates that children's health is specifically at risk when exposed to street dust enriched in toxic metals and metalloids such as Pb and As, as the case study in Zhuzhou city of Hunan Province, China, showed. Hazard quotient calculations indicate that ingestion of dust particles pose the highest risk to children and adults in Zhuzhou, followed by dermal contact and subsequently inhalation for all the metals included except Hg, for which inhalation of its vapor presents a slightly higher risk than ingestion. For adults, risk values of both carcinogenic and non-carcinogenic health effects in this study were in the receivable range. For children, Pb, As, Cd, Cr, Hg and Sb are regarded as the most possible contributor to non-carcinogenic health risks, while As and Cr increase the risk for causing cancer. Compared the HI and cancer risk of arsenic for children in this study to others, we found arsenic was regarded as the most possible element to cancer and non-cancer risks for children in those cities (Huludao, Dongying, Luanda, Madrid). Hence, further study should pay more attention to the effects of As in dust on children's health.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1.  Banerjee, A.D.K. Heavy metal levels and solid phase speciation in street dusts of Delhi, India. *Environ. Pollut.* **2003**, *123*, 95–105. [CrossRef]

2.  Zhang, X.M.; Luo, K.L.; Sun, X.Z.; Tan, J.A.; Lu, Y.L. Mercury in the topsoil and dust of Beijing City. *Sci. Total Environ.* **2006**, *368*, 713–722.

3.  Manno, M.; Varrica, D.; Dongarra, G. Metal distribution in road dust samples collected in an urban area close to a petrochemical plant at Gela, Sicily. *Atmos. Environ.* **2006**, *40*, 5929–5941. [CrossRef]

4.  Zhang, M.K.; Wang, H. Concentrations and chemical forms of potentially toxic metals in road-deposited sediments from different zones of Hangzhou, China. *J. Environ. Sci.* **2009**, *21*, 625–631. [CrossRef]

5.  Lu, X.W.; Wang, L.J.; Lei, K.; Huang, J.; Zhai, Y.X. Contamination assessment of copper, lead, zinc, manganese and nickel in street dust of Baoji, NW China. *J. Hazard. Mater.* **2009**, *161*, 1058–1062. [CrossRef] [PubMed]

6.  Bi, X.Y.; Li, Z.G.; Zhuang, X.C.; Han, Z.X.; Yang, W.L. High levels of antimony in dust from e-waste recycling in southeastern China. *Sci. Total Environ.* **2011**, *409*, 5126–5128. [CrossRef] [PubMed]

7.  Shi, G.T.; Chen, Z.L.; Bi, C.J.; Wang, L.; Teng, J.Y.; Li, Y.S.; Xu, S.Y. A comparative study of health risk of potentially toxic metals in urban and suburban road dust in the most populated city of China. *Atmos. Environ.* **2011**, *45*, 764–771. [CrossRef]

8.  Shi, G.T.; Chen, Z.L.; Xu, S.Y.; Zhang, J.; Wang, L.; Bi, C.J.; Teng, J.Y. Potentially toxic metal contamination of urban soils and roadside dust in Shanghai, China. *Environ. Pollut.* **2008**, *156*, 251–260. [CrossRef] [PubMed]

9.  Rico, D.; Martin-González, A.; Diaz, S.; De Lucas, P.; Gutiérrez, J.C. Heavy metals generate reactive oxygen species in terrestrial and aquatic ciliated protozoa. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* **2009**, *149*, 90–96. [CrossRef] [PubMed]

10. Godt, J.; Scheidig, F.; Grosse-Siestrup, C.; Esche, V.; Brandenburg, P.; Reich, A.; Groneberg, D.A. The toxicity of cadmium. *J. Occup. Med. Toxicol.* **2006**, *22*, 1–6.

11. Haefliger, P.; Mathieu-Nofl, M.; Lociciro, S.; Ndiaye, C.; Coly, M.; Diouf, A.; Faye, A.L.; Sow, A.; Tempowski, J.; Pronczuk, J.; et al. Mass lead intoxication from informal used lead-acid battery recycling in Dakar, Senegal. *Environ. Health Perspect.* **2009**, *117*, 1535–1540. [CrossRef] [PubMed]

12. Smith, A.H.; Marshall, G.; Yuan, Y.; Catterina, F.; Jane, L.; Ondine, V.E.; Craig, S.; Michael, N.B.; Steve, S. Increased mortality from lung cancer and bronchiectasis in young adults after exposure to arsenic in utero and in early childhood. *Environ. Health Perspect.* **2006**, *114*, 1293–1296. [CrossRef] [PubMed]

13. Sun, G.Y.; Li, Z.G.; Bi, X.Y.; Chen, Y.P.; Lu, S.F.; Yuan, X. Distribution, sources and health risk assessment of mercury in kindergarten dust. *Atmos. Environ.* **2013**, *73*, 169–176. [CrossRef]

14. Ferreira-Baptista, L.; De Miguel, E. Gechemistry and risk assessment of street dust in Luanda, Angola: A tropical urban environment. *Atmos. Environ.* **2005**, *38*, 4501–4512. [CrossRef]

15. Zheng, N.; Liu, J.S.; Wang, Q.C.; Liang, Z.Z. Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China. *Sci. Total Environ.* **2010**, *408*, 726–733. [CrossRef] [PubMed]

16. Zheng, N.; Liu, J.S.; Wang, Q.C.; Liang, Z.Z. Heavy metals exposure of children from stairway and sidewalk dust in the smelting district, northeast of China. *Atmos. Environ.* **2010**, *44*, 3239–3245. [CrossRef]

17. Kong, S.F.; Lu, B.; Bai, Z.P.; Zhao, X.Y.; Chen, L.; Han, B.; Li, Z.Y.; Ji, Y.Q.; Xu, Y.H.; Liu, Y.; et al. Potential threat of heavy metals in re-suspended dusts on building surfaces in oilfield city. *Atmos. Environ.* **2011**, *45*, 4192–4204. [CrossRef]

18. Wang, W.; Huang, M.J.; Kang, Y.; Wang, H.S.; Leung, A.O.W.; Cheung, K.C.; Wong, M.H. Polycyclic aromatic hydrocarbons (PAHs) in urban surface dust of Guangzhou, China: Status sources and human health risk assessment. *Sci. Total Environ.* **2011**, *409*, 4519–4527. [CrossRef] [PubMed]

19. Faiz, Y.; Siddioue, N.; Tufail, M. Pollution level and health risk assessment of road dust from an expressway. *J. Environ. Sci. Health* **2012**, *47*, 818–829. [CrossRef] [PubMed]

20. U.S. DOE (United States Department of Energy). Available online: http://science.energy.gov/~/media/budget/pdf/sc-budget-request-to-congress/fy-2004/Cong_Budget_2004_BER.pdf (accessed on 10 December 2016).

21. Li, Z.G.; Feng, X.B.; Li, G.H.; Bi, X.Y.; Zhu, J.M.; Qiu, H.B.; Dai, Z.H.; Liu, J.L.; Li, Q.H.; Sun, G.Y. Distribution, sources and pollution status of 17 trace metal/metalloids in the street dust of a heavily industrialized city of central China. *Environ. Pollut.* **2013**, *182*, 408–416. [CrossRef] [PubMed]

22. U.S. EPA (United States Environmental Protection Agency). *Human Health Evaluation Manual. EPA/540/1-89/002. Risk Assessment Guidance for Superfund*; Office of Soild Waste and Emergency Response: Washington, DC, USA, 1989.

23. U.S. EPA (United States Environmental Protection Agency). *Soil Screening Guidance: Technical Background Document*; EPA/540/R-95/128; Office of Soild Waste and Emergency Response: Washington, DC, USA, 1996.

24. U.S. EPA (United States Environmental Protection Agency). *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites*; OSWER 9355.4-24; Office of Solid Waste and Emergency Response: Washington, DC, USA, 2001.

25. Naturvårdsverket, S. *Development of Generic Guideline Values. Model and Data Used for Generic Guideline Values for Contaminated Soils in Sweden*; Report 4639; Swedish Environmental Protection Agency: Stockholm, Sweden, 1996.

26. U.S. EPA (United States Environmental Protection Agency). *Guidance for Evaluating the Oral Bioavailability of Metals in Soils for Use in Human Health Risk Assessment*; OSWER 9285.7-80; EPA: Washington, DC, USA, 2007.

27. Van den Berg, R. *Human Exposure to Soil Contamination: A Qualitative and Quantitative Analysis towards Proposals for Human Toxicological Intervention Values*; RIVM Report No. 725201011; National Institute of Public Health and Environmental Protection (RIVM): Bilthoven, The Netherlands, 1995.

28. Wang, Z.; Liu, S.; Chen, X.; Lin, C. Estimates of the exposed dermal surface area of Chinese in view of human health risk assessment. *J. Saf. Environ.* **2008**, *4*, 152–156. (In Chinese)

29. Wang, X.L.; Sato, T.; Xing, B.S.; Tao, S. Health risks of heavy metals to the general public in Tianjin, China via consumption of vegetables and fish. *Sci. Total Environ.* **2005**, *350*, 28–37. [CrossRef] [PubMed]

30. CNEMC (China National Environmental Monitoring Centre). *The Background Values of Chinese Soils*; Environmental Science Press: Beijing, China, 1990. (In Chinese)

31. De Miguel, E.; Iribarren, I.; Chacón, E.; Ordoñez, A.; Charlesworth, S. Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). *Chemosphere* **2007**, *66*, 505–513. [CrossRef] [PubMed]

32. Meza-Figueroa, D.; De la O-Villanueva, M.; De la Parra, M.L. Heavy metal distribution in dust from elementary schools in Hermosillo, Sonora, Mexico. *Atmos. Environ.* **2007**, *41*, 276–288. [CrossRef]

33. Hu, X.; Zhang, Y.; Luo, J.; Wang, T.J.; Lian, H.; Ding, Z. Bioaccessibility and health risk of arsenic, mercury and other metals in urban street dusts from a mega-city, Nanjing, China. *Environ. Pollut.* **2011**, *159*, 1215–1221. [CrossRef] [PubMed]

34. U.S. EPA (United States Environmental Protection Agency). Integrated Risk Information System (IRIS), 2005. Available online: http://www.epa.gov/iris/subst/0278.htm#carc (accessed on 10 December 2016).

35. Kong, S.F.; Lu, B.; Ji, Y.Q.; Zhao, X.Y.; Bai, Z.P.; Xu, Y.H.; Liu, Y.; Jiang, H. Risk assessment of heavy metals in road and soil dusts within $PM_{2.5}$, $PM_{10}$ and $PM_{100}$ fractions in Dongying city, Shangdong Province, China. *J. Environ. Monit.* **2012**, *14*, 791–803. [CrossRef] [PubMed]

36. Batjargal, T.; Otgonjargal, E.; Baek, K.; Yang, J.S. Assessment of metals contamination of soils in Ulaanbaatar, Mongolia. *J. Hazard. Mater.* **2010**, *184*, 872–876. [CrossRef] [PubMed]

37. Joshi, U.M.; Vijayaraghavan, K.; Balasubramanian, R. Elemental composition of urban street dusts and their dissolution characteristics in various aqueous media. *Chemosphere* **2009**, *77*, 526–533. [CrossRef] [PubMed]

38. Wang, X.L. Pollution Analyse of Street Dust in Core District of Chongqing. Master Dissertation, Southwest University, Chongqing, China, 2008; p. 20. (In Chinese)

39. Fang, F.M.; Zhang, Z.M.; Chen, W.J.; Yang, D. Spatial and particle size distribution of mercury and arsenic on surface dust in spring in the Wuhu urban district. *Acta Sci. Circumst.* **2009**, *29*, 1871–1877. (In Chinese)