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Heavy metal contamination in soils and vegetables near an e-waste processing site, south China

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ABSTRACT

Environmental pollution due to uncontrolled e-waste recycling activities has been reported in a number of locations of China. In the present study, metal pollution to the surrounding environment from a primitive e-waste processing facility was investigated. Soils at sites where e-waste is burned in the open air, those of surrounding paddy fields and vegetable gardens, as well as common vegetable samples were collected and analyzed for heavy metals. The results showed that the soils of former incineration sites had the highest concentrations of Cd, Cu, Pb, and Zn with mean values of 17.1, 11,140, 4500, and 3690 mg kg^{-1}, respectively. The soils of nearby paddy fields and vegetable gardens also had relatively high concentrations of Cd and Cu. In the edible tissues of vegetables, the concentrations of Cd and Pb in most samples exceeded the maximum level permitted for food in China. Sequential leaching tests revealed that the Cu, Pb, and Zn were predominantly associated with the residual fraction, followed by the carbonate/specifically adsorbed phases with the exception of Cd, which was mainly in the extractable form in paddy fields and vegetable soils. The data showed that uncontrolled e-waste processing operations caused serious pollution to local soils and vegetables. The cleaning up of former incineration sites should be a priority in any future remediation program.

1. Introduction

Driven by profits, the recycling of e-waste using primitive processes is being carried out extremely actively in a few locations in south China. It is becoming an important new source of environmental pollution in these regions [1–3]. The operations commonly used in processing e-waste in order to extract precious metals, such as strong acid leaching and the open burning of dismantled components, has led to the release of large quantities of toxic metals and organic pollutants into the surrounding environment. The air, surface water, ground water, soil, and river sediment of e-waste processing sites have been severely contaminated by heavy metals, such as Cd, Cu, and Pb, as well as organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated diphenyls ethers (PBDEs) [3–8]. The laborers dismantling discarded electronic items and local residents may be seriously affected through direct inhalation and dermal contact with these contaminants. Strikingly high concentrations of 100 $\mu g\,l^{-1}$ lead [9,10], and 3100 $ng\,g^{-1}$ lipid BDE-209 [1] have been found in the blood of workers engaged in this work, and in that of the children living nearby. As well, a very high occurrence of various diseases has been reported in primitive e-waste processing areas [11]. An increasing amount of attention is being paid to this emerging environmental issue in China and other developing countries [12–16].

E-waste processing sites are usually located in fields adjacent to land used for agricultural purposes. Heavy metals released from salvaging useful materials and from the uncontrolled open burning of electronic waste could penetrate the soils where vegetables and crops are grown by contaminating irrigation water and through direct deposition by air. Plants can take up these metals from soil by their roots, transport them upwards to their shoots, and finally accumulate them inside their tissues, although there are large variations among different plant species in terms of metal accumulation ability [17,18]. In addition, direct foliar uptake of heavy metals from the atmosphere can also occur during plant growth [19]. Oral ingestion of contaminated food has been proved to be an important pathway for the transfer of heavy metals from the environment to human bodies. Investigations on the accumulation of heavy metals from rice, and organic pollutants from vegetables grown around uncontrolled e-waste recycling sites have revealed high levels of Pb, Cd, polybrominated biphenyls (PBBs), PBDEs, and PCBs in these local food samples [20,21]. In this context, the risks associated with the consumption of contaminated

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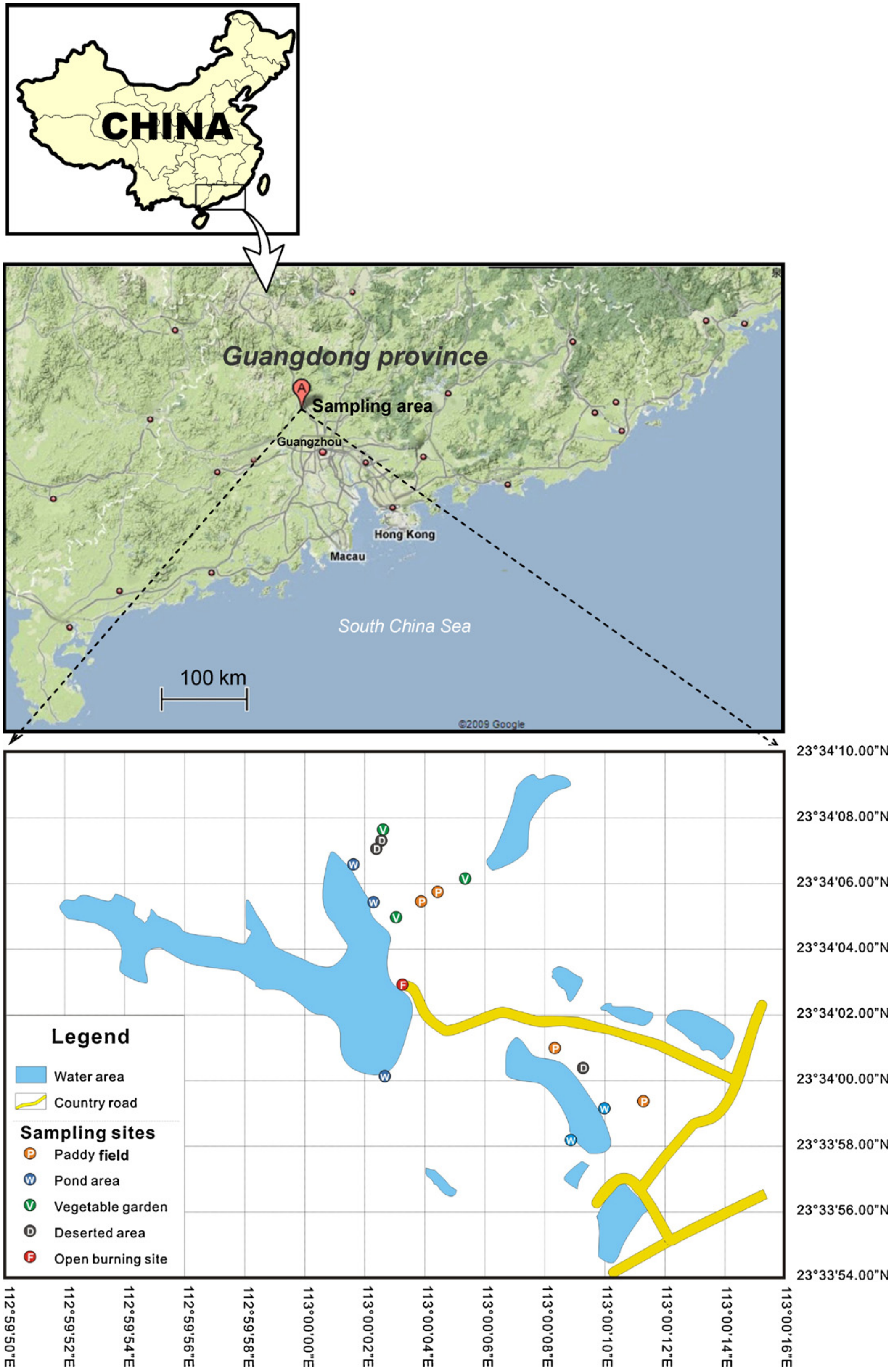

Fig. 1. Map of the sampling location. P, paddy field; W, pond area; V, vegetable garden; D, deserted area; and F, open burning sites.

food grown in e-waste processing regions may be a potential health concern.

The present study was carried out in a small town of Longtang in northern Guangdong province with 100 thousand residents, and the local economy is mainly dependent on the manufacturing industry, agriculture and metal recycling from obsolete electronic products. This site was one of the e-waste processing villages in south China, where e-waste recycling can be traced back to the

1990s. In the past several years, there were intensive recycling activities of e-waste, with about 1000 workshops, and more than 50,000 laborers engaging in the business of dismantling e-waste, and about one million tons of e-waste were processed annually in the surrounding area [15,22]. Although at present all the uncontrolled workshops are being banned by the local governments, there are still some operations on-going in some places of the region. Most uncontrolled e-waste processing sites are located in or close to agricultural land. Vegetables and rice are planted in these fields, and the potential contamination of these local food items may pose a significant threat to local residents. In the present study, soil samples were collected from former e-waste incineration sites and surrounding vegetable gardens, paddy fields, and a reservoir area, together with the vegetable samples. The objective of the present research was to investigate the effect of uncontrolled e-waste recycling activities on the surrounding environment and food products, especially the important metal contaminants. The results can be useful for selecting appropriate clean-up measures for the deteriorated environment, and the protection of the local community from potential health hazards.

2. Materials and methods

2.1. Study area

The study area is situated in Guangdong province of south China. It has a typical subtropical monsoon climate with an annual temperature of 22.6 °C, and annual rainfall of about 1700 mm. The active uncontrolled processing of e-waste has left open incineration sites scattered among agricultural fields, and electronic debris dumped beside the river. Amid the e-waste recycling activities, agricultural operations, such as the planting of rice and vegetables, and raising of fish, were still taking place in the affected area. As shown in Fig. 1, all of the sampling locations in the present study can be classified into five different groups: an e-waste open incineration site, a vegetable garden, a paddy field, an area of deserted soil, and a pond area.

2.2. Soil and vegetable sampling

The sampling was conducted in the September of 2007. Fifty-six samples of top soil (0–15 cm) from the e-waste incineration site and surrounding vegetable garden, paddy field, deserted soil, and pond area were collected using a stainless steel spade. Thirty-six vegetables from garden fields and their corresponding soils were also obtained. All of the samples were put in polythene zip-bags and transported to the laboratory on the day of sampling. Each individual plant sample was separated into shoot and root subsamples. The fresh plant samples were washed with tap water, rinsed with DIW, and the fresh weight was recorded. Soil and plant samples were freeze-dried, and the dry weight of plant samples was measured. After drying, the stones were removed, and the soil was passed through a 2-mm sieve. Then sub-samples of the plant and soil were ground with an agate mortar, and used for a further metal analysis.

2.3. Sample analysis

The total concentrations of metals were determined by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES, Perkin Elmer Optima 3300DV) after strong acid digestion (1:4 concentrated HNO_3 and $HClO_4$ (v/v)) of about 200 mg of ground plant and soil samples. Cadmium was analyzed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, Perkin Elmer Elan 6100 DRC^{Plus}) due to the low concentration in the samples. In the analysis of metals, certified standard reference materials (SRM 1515 for plants and SRM 2709 for soils) of the National Institute of Standards and Technology (NIST), USA, were used in the digestion and analysis as part of the QA/QC protocol. Reagent blank and analytical duplicates, comprised of 10% of the total samples, respectively, were also used where appropriate to test the accuracy and precision of the analysis. The recovery rates were around 90 ± 8% for all of the metals in the soil (NIST SRM 2709) and plant reference materials (NIST SRM 1515).

Soil samples from the e-waste incineration site, vegetable garden, paddy field, and pond area were analyzed for the chemical partitioning of Cd, Cr, Cu, Ni, Pb, and Zn using a modified Tessier sequential chemical extraction process to evaluate the mobility and potential bio-availability of these metals [23,24]. The analytical procedure used in this study followed that described by Wong et al. [25,26]. The extraction procedure used in this study divided trace metals into five operationally defined chemical fractions: (1) the exchangeable fraction: readily soluble and exchangeable; (2) the carbonate bound and specifically adsorbed fraction: carbonate-bound, specifically adsorbed, and weak organic and inorganic complexes; (3) the Fe–Mn oxide fraction: bound to iron and manganese oxides (Fe–Mn oxide); (4) the organic/sulphide fraction: bound to stable organic and/or sulphide (organic) complexes; and (5) the residual fraction: held in primary and secondary minerals within their crystal structure. Quality controls similar to that of the strong acid digestion method were carried out in the sequential extraction experiment. The overall recovery rates of Cd, Cr, Cu, Ni, Pb, and Zn (the sum of the five fractions compared with the total metal concentrations) were 80%, 110%, 92%, 90%, 112%, and 89%, respectively.

2.4. Data analysis

2.4.1. Transfer factor from soil to the edible parts of a vegetable

The transfer factor (TF) of metals from soil to the edible parts of a vegetable was defined as the ratio of the metal concentration (mg kg^{-1} FW) in the plant's tissues to the total metal concentration in soil (mg kg^{-1} DW).

2.4.2. Estimated daily intake of heavy metals from vegetables

The estimated daily exposure to metals (EDEM) through vegetables was dependent on metal concentrations in vegetables, daily vegetable consumption, as well as body weight, which was calculated with the following formula:

$$\text{EDEM} = \frac{\text{daily intake of metals (DIM)}}{\text{body weight}}$$

$$\text{DIM} = \text{daily vegetable consumption} \times \text{mean vegetable metal concentration}$$

where the average daily intake of metals in 345 g of vegetables per day for adult residents was used [27,28], and the body weight of an adult resident was set to 60 kg in the present study.

2.4.3. Calculation of health risk

In this study, the health risk associated with the consumption of vegetables was defined as the ratio of the estimated daily intake of metals to the reference dose oral (RfDo) for each metal [29,30], as in the following equation:

$$\text{Risk index} = \frac{\text{EDEM}}{\text{RfDo}}$$

where RfDo represents safe levels of exposure by oral intake for a lifetime [29]. If the risk index was less than 1, no obvious risk is involved. If the risk index was equal to or higher than 1, there is a potential health risk, and related interventions and protective measurements should be taken. In the present study, metals concerned were Cd, Cu, Pb, and Zn, and only the chronic risk RfDo was considered in the risk assessments.

2.4.4. Statistical analysis

The data were statistically analyzed using the statistical package, SPSS 10.0 (SPSS, USA). A variance analysis ($p < 0.05$) of total metal concentrations among different sampling sites was performed using a one-way ANOVA test (Tukey HSD). Two-sample *t*-tests were employed to examine the statistical significance of the differences in the mean concentrations of trace metals among different vegetable samples. The correlation analysis was conducted by a Pearson correlation, and the level of significance was set at $p < 0.05$ (two-tailed).

3. Results and discussion

3.1. Soil contamination

The concentrations of trace metals in different soil samples are presented in Table 1. The former e-waste incineration sites had the highest concentrations of metals, with the average being 17.1 mg kg^{-1} of Cd, 11,140 mg kg^{-1} of Cu, 4500 mg kg^{-1} of Pb, and 3690 mg kg^{-1} of Zn. These greatly exceeded the action values of the Dutch standard [32], and highlighted the significant impact of e-waste processing activities on these spots. The Pearson correlations of these metals in different sampling sites confirmed the contamination of Cd, Cu, Pb, and Zn in these soils (see Table 2). Although Cr and Ni did not show significantly high concentrations, they were still 1.36 and 4.17 times greater than the background values in the soils of Guangdong province (Table 1). The concentrations of heavy metals were comparable to the values reported by Wong et al. [12] in the soils of e-waste incineration sites in Guiyu Town, southeast Guangdong province. The extremely high concentrations of metals are probably due to the burning of circuit boards or other metal chips in the recycling process. The next highest concentrations of metals were found in the pond area. In the e-waste recycling sites, e-waste combustion locations are usually close to ponds and streams because these provide a convenient supply of water for metal extraction processes. High concentrations of metals could be leached out from the sites and contaminate the pond water and sediment. In addition, it is very common for electrical debris to be dumped beside ponds, and metals in these scraps could enter with rainwater into aquatic systems.

The contamination of paddy fields and vegetable gardens is a major concern because rice and vegetables are still being grown in the soils close to e-waste recycling facilities. The pH of soil plays a great role in the speciation and bio-availability of heavy metals thus, the maximum allowable concentrations in soil vary with soil pH. In the present study, the pH of most soils ranged between 5.5 and 7.0, with only several samples from the pond area having a pH of less than 4.5. Hence, the soils should be evaluated according to Grade II of the Environmental Quality Standard for Soils of China [31]. In comparison with the maximum permissible concentrations of metals for agricultural soils, these soils were primarily contaminated by Cd and Cu, with the mean values being more than three times that of the Chinese Standard for Agricultural Soils [31], and the concentrations also exceeding the Target Value of the Dutch Standard [32]. The concentrations of Cu in these soils were significantly higher than those in the agricultural soils of the Pearl River Delta [25]. The Cu levels were very close to the concentrations reported at the uncontrolled e-waste recycling sites of Guiyu, where the concentrations of Cu ranged from 29.9 to 240 mg kg^{-1} in rice fields [12]. Lead and Zn in these soils also greatly exceeded the background values of soils in Guangdong province, however, they were still in the range for agricultural use. No contamination

Table 1
The concentrations (mg kg^{-1} DW) of metals at different sampling sites.

	Cd	Cr	Cu	Ni	Pb	Zn
Vegetable garden ($n = 16$)	0.26–1.17 (0.9 ± 0.8)[a]	9.66–19 (12.3 ± 5.1)	210–450 (324 ± 172)	7.04–10.3 (8.83 ± 2.9)	73.3–134 (95.6 ± 19.5)	92.4–142 (122 ± 55.7)
Paddy field ($n = 11$)	0.04–1.43 (1.0 ± 0.4)	10.5–24.1 (17.3 ± 8.1)	40.1–260 (155 ± 94)	10.8–66 (34.5 ± 26.6)	48.1–97 (61.8 ± 24)	62.1–252 (166 ± 76.7)
Incineration site ($n = 11$)	3.05–46.8 (17.1 ± 12.5)	23.6–122 (68.9 ± 53)	1500–21,400 (11,140 ± 9000)	12.2–132 (60.1 ± 59)	629–7720 (4500 ± 3370)	682–8970 (3690 ± 2680)
Deserted soil ($n = 8$)	0.08–0.39 (0.25 ± 0.19)	3.84–11.1 (6.41 ± 4.04)	49.9–95.4 (72.4 ± 52.8)	4.58–19.7 (10 ± 8.4)	47.2–60.2 (52.2 ± 24)	44.5–72.3 (62.6 ± 25.7)
Pond area ($n = 10$)	0.57–18.3 (5.45 ± 7.43)	14–105 (38.9 ± 38.4)	142–12,900 (3550 ± 5480)	18.9–44.9 (32.2 ± 20.7)	37.9–7760 (1880 ± 3340)	123–3800 (1160 ± 1580)
Background value[b]	0.06	50.5	17	14.4	36	47.3
Chinese standard for agricultural soil[c]	≤0.3	≤250	≤50	≤40	≤250	≤200

[a] The value in brackets indicates mean value ± S.D.

[b] Metal background value in the soil of Guangdong province.

[c] National Environmental Protection Agency of China, 1995 (GB15618-1995) [31].

Table 2
The correlation coefficients of metals in soils.

	Al	Ca	Cd	Cu	Fe	Mg	Mn	Pb	Ti	Zn
Al	1									
Ca	0.047	1								
Cd	0.332	0.613[b]	1							
Cu	0.089	0.583[b]	0.931[b]	1						
Fe	0.577[b]	0.128	0.385	0.372	1					
Mg	0.683[b]	0.375	0.447[a]	0.334	0.728[b]	1				
Mn	−0.377	0.116	−0.047	−0.006	−0.563	−0.431	1			
Pb	0.083	0.557[b]	0.917[b]	0.997[b]	0.376	0.320	0.004	1		
Ti	0.259	−0.087	−0.161	−0.150	0.323	0.605[b]	−0.382	−0.147	1	
Zn	0.247	0.570[b]	0.965[b]	0.978[b]	0.429[a]	0.393	−0.068	0.977[b]	−0.145	1

[a] Correlation is significant at the 0.05 level (2-tailed).
[b] Correlation is significant at the 0.01 level (2-tailed).

of Cr was found in any of the paddy and vegetable gardens. With regard to agricultural soils, the major input of heavy metals is the application of agrochemicals and other soil amendments [25]. In the present study, e-waste recycling activities were the dominant source of metal pollution in the vicinity. High levels of Cu and other metals in the affected agricultural soils were consistent with the patterns observed at former e-waste open incineration sites, suggesting that metals released from the processing of e-waste may enter the surrounding paddy fields and vegetable gardens through air deposition and water irrigation.

3.2. Chemical partitioning in soils

The mobility and toxicity of metals are mainly dependent on metal speciation in the environmental medium. The chemical speciation of heavy metals in soil samples was analyzed using a

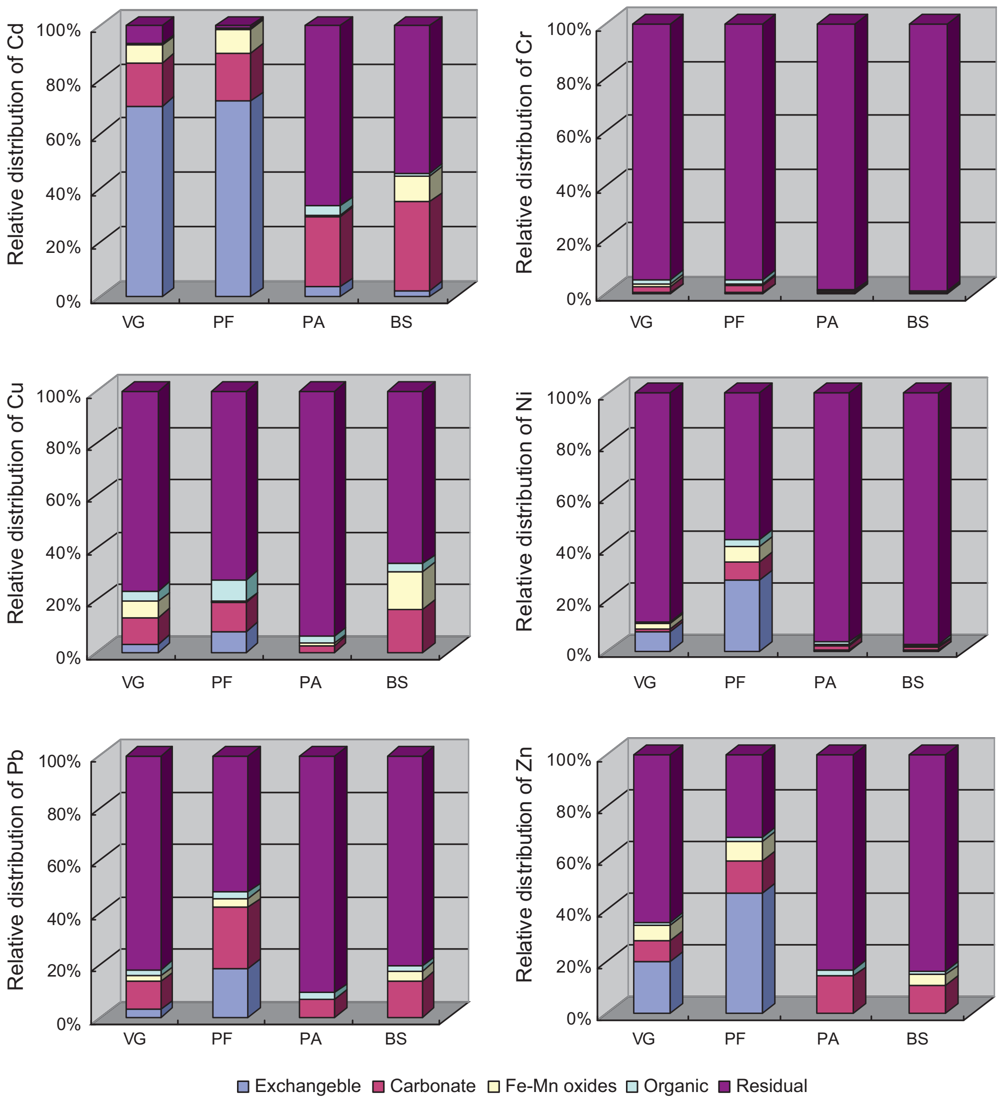

Fig. 2. Chemical fractionation of Cd, Cr, Cu, Ni, Pb, and Zn in the selected soils of the vegetable garden, paddy field, pond area, and e-waste incineration site. VG, vegetable garden; PF, paddy field; PA, pond area; and BS, burning site.

modified sequential chemical extraction procedure to provide further information on metal distribution with different operationally defined geochemical phases (Fig. 2). In general, the results indicated that in the selected soil samples, Cu, Cr, and Pb were predominantly associated with the residual fraction, followed by the carbonate/specifically adsorbed phases. The two fractions accounted for more than 76%, 98%, and 75% of the total concentrations in soils. A higher percentage of the exchangeable phase was found in the soils of the vegetable garden and paddy field than in those of the incineration site and pond area (Fig. 2). As shown in the previous section, the level of Cu (1500–21,400 mg kg^{-1}) in the incineration site was extremely high. Although the extractable phase accounted for a low percentage, the concentration of Cu in this phase was still very high and could pose a significant risk of contaminating the surrounding soil and groundwater. As for Ni and Zn, in the soils of incineration site and pond area, they were mainly bound to the residual fraction, followed by the carbonate/specifically adsorbed phases. However, in the paddy field and vegetable soils, the two metals in the exchangeable fraction exceeded those in the carbonate/specifically adsorbed phases. Higher concentrations of metals in the exchangeable phase would indicate high solubility and bioavailability, meaning that the metals can be more readily taken up by plants grown in soil.

In comparison with other metals, Cd displayed a distinct character in the paddy field and vegetable soils, where the extractable form accounted for more than 70% of the total concentrations. The second dominant form of Cd in the paddy field and vegetable soils was the carbonate/specifically adsorbed phase, accounting for more than 10% of the total amount of Cd. By contrast, in the incineration site and pond area, Cd was mainly associated with the residual fraction, which reached 66% and 94% of the total Cd content, followed by the carbonate/specifically adsorbed phase with 16% and 3% of the total in soils. In the study area, a great deal of water was required to irrigate the soil because of the planting of rice and vegetables. Under some circumstances, this water was directly taken from the metal-contaminated streams and ponds. In this way, some readily soluble elements, such as Cd, would enter the soil with the irrigation water. Cd from this source could account for a large percentage of the total Cd in the soil, which could also be a major factor for the high levels of exchangeable Cd in the nearby paddy field and vegetable soils. More importantly, the high level of exchangeable Cd in vegetable garden soils may facilitate the high uptake of Cd by plants, accumulating in the edible parts.

3.3. Plant contamination

Plant samples collected in the present study included vegetables, rice, and wild plants in the field. The concentrations of heavy metals (mg kg^{-1} DW) in the plant samples are given in Table 3. The concentrations of metals varied greatly among plant species and sampling locations. On average, the highest concentrations of Cu, Pb, and Zn in shoots were found in the wild plant samples, at 94.3, 54.8, and 143 mg kg^{-1}, respectively. The highest concentration of Cd in shoots (2.62 mg kg^{-1}), however, appeared in the vegetable samples. As shown in Table 1, the former e-waste incineration site had the highest amounts of metals in soils. This could provide a partial explanation of why the highest average concentrations of metals observed in the wild plant samples were found there. Another major factor contributing to high metal accumulation in the shoots of these plant samples could probably be ascribed to atmospheric deposition. When e-waste was burned, heavy smoke containing various kinds of heavy metals, metalloids, and organic pollutants would have been discharged into the air, and the plants growing on the sites could well have been the first recipients of these substances. The foliar uptake of atmospheric Pb has been proved to be the dominant pathway for Pb entering

Table 3
The concentrations (mg kg^{-1} DW) of metals in the shoots of vegetables, rice, and wild plants.

		Cd	Cu	Pb	Zn
Vegetables	*Pisum sativum* L.	0.4 ± 0.2	11.5 ± 1.3	2.62 ± 0.3	109 ± 15
	Chrysanthemum coronarium L.	3.26 ± 0.4	28.5 ± 3.1	5.14 ± 0.6	227 ± 17
	Brassica rapa L. (Pekinensis group)	2.62 ± 0.15	44.3 ± 3.5	3.54 ± 0.5	243 ± 25
	Lactuca sativa L. var.romana Gars	3.11 ± 0.2	18.9 ± 2.1	4.34 ± 0.5	174 ± 15
	Raphanus sativus L.	0.54 ± 0.4	6.54 ± 0.7	1.21 ± 0.4	79.9 ± 9.8
	Colocasia esculenta (L.) Schott	3.61 ± 0.26	31.8 ± 0.5	14.4 ± 1.2	113 ± 10
	Allium ascalonicum L.	3.66 ± 0.31	12.2 ± 1.5	3.93 ± 0.1	98.3 ± 8.7
	Brassica oleracea L. var. capitata L	2.74 ± 0.3	15.8 ± 2.5	8.82 ± 1.5	89.4 ± 9.5
	Lactuca sativa L.	4.22 ± 0.51	23.2 ± 2.5	8.59 ± 0.9	172 ± 18
	Daucus carota L.	2.05 ± 0.1	11 ± 1.8	5.3 ± 1.5	41 ± 3.6
Rice	*Oryza sativa* L.	0.43 ± 0.21	42.3 ± 5.6	13.6 ± 2.8	94 ± 12.3
Wild plants	*Neyraudia arundinacea* (L.) Henr.	0.21 ± 0.1	93 ± 6.5	55 ± 6.5	97.6 ± 10
	Bidens pilosa L.	4.29 ± 0.3	71.4 ± 10.2	43.7 ± 5.6	168 ± 18
	Echinochloa crusgalli (L.) Beauv.	0.27 ± 0.1	119 ± 8.9	65.6 ± 4.9	164 ± 20

The value shown is mean ± S.D.

Table 4
The concentrations (mg kg^{-1} FW) of metals in the edible parts of different vegetables.

Vegetables	Edible tissue	Cd	Cu	Pb	Zn
Pisum sativum L.	Shoots	0.04 ± 0.01a	1.04 ± 0.2b	0.24 ± 0.02a	9.79 ± 0.1b
Chrysanthemum coronarium L.	Shoots	0.29 ± 0.1c	2.57 ± 0.4c	0.46 ± 0.05a	20.4 ± 3.2d
Brassica rapa L. (Pekinensis group)	Shoots	0.24 ± 0.03bc	3.99 ± 0.05d	0.32 ± 0.04a	21.9 ± 2d
Lactuca sativa L.var.romana Gars	Shoots	0.28 ± 0.04b	1.71 ± 0.2c	0.39 ± 0.06a	15.7 ± 2.5c
Raphanus sativus L.	Roots	0.05 ± 0.01a	0.59 ± 0.6a	0.11 ± 0.02a	7.20 ± 1ab
Colocasia esculenta (L.)Schott	Tubers	0.32 ± 0.04c	2.87 ± 0.5c	1.30 ± 0.4c	10.1 ± 1.5bc
Allium ascalonicum L.	Shoots	0.33 ± 0.05c	1.10 ± 0.3b	0.35 ± 0.5a	8.85 ± 0.9b
Brassica oleracea L. var. capitata L	Shoots	0.25 ± 0.03bc	1.42 ± 0.4b	0.79 ± 0.1b	8.06 ± 0.5b
Lactuca sativa L.	Shoots	0.38 ± 0.08c	2.09 ± 0.3c	0.77 ± 0.2b	15.5 ± 4.5c
Daucus carota L.	Roots	0.18 ± 0.04a	0.99 ± 0.2ab	0.48 ± 0.3a	3.69 ± 0.65a
Maximum allowable level in food[A]		0.05	10	0.2	20

The value shown is mean ± S.D. The different small letters stand for statistical significance at $p < 0.05$ with the *t*-test.

[A] Tolerance limit of contaminants in food: Cd, GB 15201-94 [33]; Cu, GB 15199-94 [34]; Pb, GB 14935-94 [35]; Zn, GB 13106-91 [36].

Table 5
Transfer factors of metal from soil to the edible vegetable.

Vegetables	Edible tissue	Cd	Cu	Pb	Zn
Pisum sativum L.	Shoots	0.038 ± 0.002a	0.003 ± 0.000a	0.003 ± 0.000a	0.081 ± 0.005a
Chrysanthemum coronarium L.	Shoots	0.275 ± 0.030b	0.008 ± 0.000a	0.005 ± 0.000a	0.170 ± 0.020c
Brassica rapa L. (Pekinensis group)	Shoots	0.258 ± 0.035b	0.014 ± 0.001b	0.004 ± 0.000a	0.195 ± 0.006c
Lactuca sativa L.var.romana Gars	Shoots	0.239 ± 0.041b	0.004 ± 0.001a	0.003 ± 0.000a	0.112 ± 0.010b
Raphanus sativus L.	Roots	0.043 ± 0.005a	0.002 ± 0.000a	0.001 ± 0.000a	0.057 ± 0.006a
Colocasia esculenta (L.)Schott	Tubers	0.309 ± 0.041b	0.020 ± 0.003c	0.021 ± 0.002c	0.073 ± 0.005a
Allium ascalonicum L.	Shoots	1.258 ± 0.072c	0.005 ± 0.000a	0.005 ± 0.001a	0.096 ± 0.008ab
Brassica oleracea L. var. capitata L	Shoots	0.943 ± 0.008c	0.007 ± 0.000a	0.011 ± 0.002b	0.087 ± 0.005a
Lactuca sativa L.	Shoots	0.365 ± 0.250b	0.007 ± 0.000a	0.009 ± 0.000b	0.127 ± 0.023b
Daucus carota L.	Roots	0.105 ± 0.061ab	0.005 ± 0.000a	0.007 ± 0.000a	0.040 ± 0.005a

The value shown is mean ± S.D.

Table 6
Estimated mean and range daily intake for a 60 kg body weight adult.

Metals	DIM (mg/d FW)	RfDo[a] (mg kg^{-1} d^{-1})	Estimated exposure (mg kg^{-1} d^{-1})	Risk index
Cd	0.08	5.00E−04	1.36E−03	2.71E+00
Cu	0.63	4.00E−02	1.06E−02	2.64E−01
Pb	0.18	0.0035[b]	3.00E−03	8.57E−01
Zn	4.19	3.00E−01	6.98E−02	2.33E−01

[a] US-EPA (2002) [29].
[b] JECFA (1993) [41].

the leaf and grain tissues of maize grown in nearby zinc smelting factories [19].

3.4. Vegetable contamination and the implications for human health

The accumulation of metals in the edible parts of vegetables could have a direct impact on the health of nearby inhabitants, because vegetables produced from gardens are mostly consumed locally. Therefore, the concentration of metal contaminants in vegetables could be a concern to local residents. The concentrations of Cd and Pb in most vegetables exceeded the food safety limit in China, with the average levels of Cd and Pb being 4.7 and 2.6 times that of the maximum permissible level, respectively (see Table 4). No Cu contamination was detected in any vegetables. With regard to Zn, only a few individual samples were slightly higher than the maximum allowable level. Of all of the vegetables that were tested, the concentrations of heavy metals in the edible part of leafy vegetables were significantly higher than in the edible portion of roots/tuberous vegetables ($p < 0.05$), which was in agreement with previous reports [37,38]. Leafy vegetables usually grow quickly and have high transpiration rates. This favors the uptake of metals by roots, and the resulting translocation of metals from roots to above-ground tissues. In addition, their broad leaves make these plants more susceptible to physical contamination by dust from soil and the splashing of rainwater.

The transfer factor (TF) of metals can be used to evaluate the potential capability of plants to transfer metals from soil to edible tissues. Metals with high TF are more easily transferred from soil to the edible parts of plants than ones with low TF. As seen from Table 5, large variations in TFs were observed among different vegetables and metals. The TF values for Cd varied from 0.038 to 1.258, with a mean of 0.383, which was the highest among the selected four metals, and was more than 50 times the TFs of Cu and Pb. Cd is a readily mobile metal. Due to the high concentration of exchangeable Cd in vegetable soils, the Cd in the edible parts of vegetables probably came from the root uptake from soils. The TF of Zn ranged from 0.04 to 0.195, with an average of 0.104. The Cu and Pb had similar TF values, far lower than those of Cd and Zn. Although the total concentration of Cu was high in soil, the extractable fraction was low, which greatly limited the uptake by plant roots. As mentioned previously, a major pathway for Pb to enter the above-ground tissues of plants is through atmospheric deposition. Therefore, the factual TF of Pb should be lower than the calculated value. Among the TFs, root plants, such as *Raphanus sativus* L. and *Daucus carota* L., showed lower TF values than the leafy vegetables, together with lower concentrations of metals in the edible tissues. Therefore, it may be suitable to grow metal-excluding species of root plants in the surrounding area, which would reduce the potential health risks associated with the consumption of local food.

An index of the risk for residents of ingesting these metals by consuming vegetables grown around the sampling area was calculated on the basis of the oral reference dose being 0.5 μg kg^{-1} d^{-1} for Cd, 40 μg kg^{-1} d^{-1} for Cu, 3.5 μg kg^{-1} d^{-1} for Pb, and 300 μg kg^{-1} d^{-1} for Zn [29,39]. The risk index was in the descending order of Cd < Pb < Cu < Zn. The risk index for Cd was higher than 1, while the risk indexes for Cu, Pb, and Zn were less than 1 (see Table 6). The result indicates that those living around the e-waste processing area were probably exposed to some potential health risks through the intake of Cd via consuming locally grown vegetables. For Cu, Pb, and Zn, there was no significant risk from the intake of vegetables. When determining the risk index, it was assumed that the intake is equal to the absorbed dose [40], which may magnify the effect of the ingested contaminants to some extent because part of the heavy metals that were ingested may be egested [41]. From this point of view, it was reasonable that no obvious adverse health effects from exposure to the heavy metals could be observed on those living around the e-waste processing area.

By comparing the results with other studies (shown in Table 7), the health risk for adults from consuming vegetables in the e-waste processing region was comparable to, or even higher than, those associated with the consumption of vegetables from gardens impacted by wastewater irrigation, mining, or smelting activities [38,42–49]. In addition, the accumulation of metals in rice was not quantified in the current research. Rice is a staple food in south China, and the rice produced in the sampling area is also consumed by local residents. According to the study of Fu et al. [20] on rice pollution in another e-waste processing area, Cd and Pb were the two major contaminants in rice grains. The concentrations of Pb in the rice grains exceeded the Chinese standard for food safety, and the geometric mean of the Pb concentration was 3.5 times higher than the maximum allowable concentration [20]. The concentrations of Pb in the paddy soils in our study were even higher than the values reported by Fu et al. [20]. Therefore, it may be speculated

Table 7

Comparison with other reports of metal concentrations (mg kg^{-1} FW) in vegetables.

District (Country)	Sampling site description		Cd	Cu	Pb	Zn	References
Huludao (China)	Near a Zn plant (20)[a]	Range (mean)	0.011–4.58 (0.996)	0.405–2.13 (0.992)	0.067–5.45 (1.6)	2.93–66.9 (16.7)	38
		DIM (μg d^{-1})	301	293	574	5260	
		Risk index	5.134	0.133	2.299	0.295	
Varanasi (India)	Urban area (270)	Range (mean)	1.1–4.5 (2.08)	20.5–71.2 (36.4)	0.9–2.2 (1.42)	45.3–141 (79.5)	42
		Risk index	2.96[b]				
Gyöngyösoroszi	Near an abandoned Zn/Pb mine	Range (mean)	0.005–0.13 (0.056)		0.079–1.06 (0.44)	1.41–60.5 (23.4)	44
		Risk index	0.033		0.087	0.049	
Mortagne du Nord (France)	Near a former Zn smelter	Range (mean)	0.01–0.46 (0.111)		0.02–0.35 (0.075)		44
Nanning (China)	Near a Pb/Sb smelter (32)	GM[c]	0.24	0.76	3.78	11.2	45
		GDIM[d] (μg d^{-1})	220	350	2830	5810	
		Risk index	7.42	0.146	1.35	0.323	
Kayseri (Turkey)	Vegetable garden (132)	Range[e]	0.24–0.97	22.2–76.5	3–10.7	3.56–259	46
		DIM (μg d^{-1})	63.7	637	228	14890	
Zlatna (Romania)	Near a Cu smelter	Range (mean)	0.2–0.97 (0.04)	0.3–0.8 (0.5)	0.19–9.1 (0.55)	1.8–12.95 (4.75)	47
Harare (Zimbabwe)	Wastewater irrigated garden	Mean	0.15	0.2	0.35	9.1	48
		DIM (μg d^{-1})	20–40	40–50	50–90	600–3300	
Dabaoshan (China)	Near a mine	Range (mean)	0.001–0.71 (0.19)	0.28–3.61 (1.179)	0.01–0.39 (0.17)	2.34–48.1 (9.7)	49
		Risk index	<1	<0.2	<0.25	<0.2	
		DIM (μg d^{-1})	49	327	45	2590	
Present study	Near an e-waste incineration site (40)	Range (mean)	0.04–0.38 (0.236)	0.59–3.99 (1.84)	0.11–1.3 (0.521)	3.69–21.9 (12.1)	
		DIM (μg d^{-1})	80	630	180	4190	
		Risk index	2.71	0.264	0.857	0.233	

[a] The value in brackets represents the number of samples.

[b] The total amount of heavy metals (sum of the four metals) pollution risk index.

[c] Geometric mean.

[d] Geometric daily intake of metals.

[e] The unit of the metals shown is mg kg^{-1} DW.

that the rice grains produced around the studied e-waste recycling sites could be a significant source of Pb to local residents. The exposure to two or more pollutants from consuming rice may result in additive and/or interactive effects [50]. If the whole intake of metals through dietary means (vegetables and rice) is taken into account, the potential health risks involved in the consumption of local food should not be ignored.

4. Conclusion

The intensive uncontrolled processing of e-waste in the past has resulted in the release of large amounts of heavy metals in the local environment, and caused high concentrations of metals to be present in the surrounding soils and water. Vegetables grown in the nearby sites were also contaminated by the relevant heavy metals, especially Cd and Pb, which could be a potential health concern to local residents. The former e-waste incineration site may now act as a source of pollution for the surrounding area, due to the extremely high concentrations of heavy metals in the affected soils. A long-term risk assessment needs to be carried out on the leachability and migration potential of these toxic chemicals at the contaminated sites.

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