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ARTICLE

Health Risks Assessment of Heavy Metal Pollution in the Soil-Crop System from an E-Waste Dismantling Area

Shengting Rao[#], Jia Fang[#] and Keli Zhao[*]

Key Laboratory of Soil Contamination Bioremediation of Zhejiang Province, Zhejiang Agriculture and Forestry University, Hangzhou, 311300, China

[*]Corresponding Author: Keli Zhao. Email: kelizhao@zafu.edu.cn

[#]These authors contributed equally to this work

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ABSTRACT

Soil is an essential resource for agricultural production. In order to investigate the pollution situation of heavy metals in the soil-crop system in the e-waste dismantling area, the crop and soil samples (226 pairs, including leaf vegetables, solanaceous vegetables, root vegetables, and fruits) around the e-waste dismantling area in south-eastern Zhejiang Province were collected. The concentrations of Cd, Cu, Pb, and Cr were determined. The average concentrations of Cd, Cu, Pb, and Cr in soils were 0.94, 107.79, 80.28, and 78.14 mg kg^{-1}, respectively, and their corresponding concentrations in crops were 0.024, 0.7, 0.041, and 0.06 mg kg^{-1}, respectively. The transfer capacity of leaf vegetables was significantly higher than that of non-leaf vegetables, and the accumulation of four heavy metals in crops tended to be Cd > Cu > Cr/Pb. The pollution index's results revealed that the soil pollution degree under different land uses ranked as root vegetables soil > leaf vegetables soil > solanaceous vegetables soil > fruit soil. The carcinogenic and non-carcinogenic risks of heavy metal exposure were ranked as food intake > accidental ingestion > dermal contact > inhalation. The comprehensive non-carcinogenic risk was ranked as Cr > Cd > Pb/Cu. Our results could be used to provide useful information for further crop cultivation layout in the study area, which can guarantee the local residents' health and food safety.

KEYWORDS

E-waste dismantling area; soil-crop system; heavy metal pollution; risk assessment

1 Introduction

As the basis of agricultural production and human survival, the soil plays a vital role in food and ecological security [1]. Up to now, soil has been severely contaminated by heavy metals, which have bioaccumulative and biotoxic features [2–4]. Heavy metals absorbed by the root can enter and accumulate in the plant tissues, affect food security and thus human health through the food chain [5]. Classified as pollutants of great priority by the United States Environmental Protection Agency (USEPA), Cd, Cr, Cu and Pb are the most representative and can seriously endanger the safety of human health [6,7]. For instance, high doses of Pb have the potential to harm blood enzymes and alter the central nervous system, while Cr could influence the normal function of the liver, kidneys and other organs [8–10].

With the tremendous advancement of science and technology in recent years, the lifespan of electronic and electrical products has been shorter, thus forming a large amount of electronic waste. Electronic waste

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(e-waste) refers to discarded electronic products, consisting of all components and consumables that are part of the electronic products when they are disposed of [11]. Notably, nowadays e-waste is becoming an increasingly prominent source of heavy metals during dismantling and incineration [12–15]. According to a recent study, 53.6×10^6 metric tons of e-waste was generated in 2019, but most of it was exported illegally to developing countries [11]. However, China is one of the major recipients of e-waste all over the world, while it has been the highest generator of e-waste in the world (7.2 Mt) since 2017. Therefore, China is now facing a severe challenge of e-waste disposal. Most of the recycling and dismantling workshops were located in Guiyu and Taizhou, where numerous house-hold workshops are engaged in the business of recycling or dismantling [16]. Informal processing and recycling of e-waste such as strong acid leaching and the open burning of dismantled components, has contributed to the release of a large number of heavy metals into the surrounding environment hazardous to human health [17,18]. Studies showed that Chinese workers located in e-waste dismantling areas were more likely to suffer from blood and kidney diseases as well as respiratory, neurological, and immune system disorders [19]. Despite the pollution control policies (PCP) that have been implemented to curb metal contamination since 2012, the concentration of heavy metals like Cd, Cu, Ni, and Zn in soils had no noticeable change, causing persistent ecological and health safety problems [7]. Thus, based on the current situation that the study site was heavily contaminated and difficult to control, it was necessary to investigate the contamination characteristics and evaluate the ecological and health risks.

Most of the related research focused on the pollution characteristics and health risks of rice and soil system surrounding the study area [20–23], but very few studies have examined vegetables and fruit. However, with the change of people's diet structure, people's intake of fruits is also increasing as well as vegetables. Thus, this study will indicate the pollution characteristics and health risks of the soil-crop system (vegetables and fruits) around e-waste dismantling areas. The main objectives of this study were: (1) To identify contamination characteristics and ecological risks of four heavy metals (Cd, Cr, Cu, and Pb) in the soil samples around the study area. (2) To reveal the transfer characteristics of these four heavy metals in different crops. (3) To evaluate the carcinogenic and non-carcinogenic health risks of the metals through different exposure pathways.

2 Materials and Method

2.1 Study Area

The study area is located in Luqiao District, Taizhou City, in the southeastern part of Zhejiang Province, China (121°13' to 121°40'E, 28°20' to 28°38'N, Fig. 1), which has a subtropical marine monsoon climate with an average annual temperature of 17.6°C, ranging from –5.3°C to 36.8°C. The main crops in this area are rice, vegetables, and fruits.

The e-waste recycling industry in the region has highly developed since the 1990s, with numerous home-based e-waste disposal workshops and ubiquitous informal dismantling activities [24,25]. Previous studies reported that there were 30 villages and 384 households that were heavily involved in unauthorized e-waste handling activities, only in the Wenqiao Town of Wenling City [26]. Under the key control measurement of the government, it was listed as one of six priority control areas, meaning that it played an essential role in preventing and remediating polluted soils across China [7].

2.2 Sample Collection

226 soil samples (0–20 cm) and their corresponding crop samples were collected based on a grid of 100 m × 100 m in this study, including 51 leaf vegetables (LV, including chard, amaranth, caper, hollow cabbage, mullein, green vegetables, lettuce, and fava leaves), 93 solanaceous vegetables (SV, including cauliflower, winter squash, red bean, cucumber, cucumber, cowpea, pepper, pumpkin, eggplant, loofah, string bean, tomato, and corn), 6 root vegetables (RV, including green onion and lotus root) and 76 fruits (orange, pear, grape, peach, and watermelon).

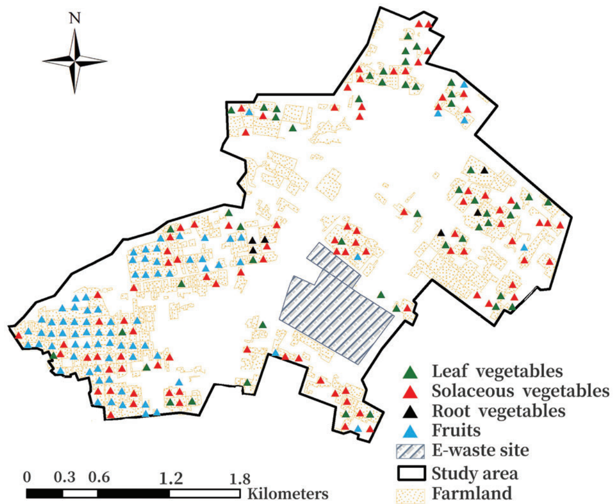

Figure 1: Study area

2.3 Soil and Crop Analysis

The samples of soils were air-dried and processed in an agate-made mortar to pass through 60 meshes sieves for available state and 100 meshes sieves for total-volume, respectively [27]; The samples of vegetables were washed away sediment and other adherents using deionized water and dried until free of water, then crushed, and mixed well for analysis [21,28,29]; The soil-water ratio of 1:2.5 was adopted to determine the soil pH [30]; The soil and vegetable samples were digested with HNO_3–H_2O_2–HF and then determined the content of Cr, Pb, Cr, and Cu through inductively coupled plasma mass spectrometry (ICP-MS, USA) [15]. To ensure accuracy, all samples were repeated and blank samples were added to keep the relative differences within 10% and the spiked recoveries within 95%–110% [31].

2.4 Environmental and Risk Assessment

The single factor pollution index evaluation method was commonly used to evaluate the degree of soil contamination [32] (Formula-1), while the potential Ecological Risk (*RI)* is one of the indexes adopted by many scholars at home and abroad to assess heavy metal pollution (Formulas 2–3). Detailed description related to the formulas can be found in previous studies [32–34].

2.5 Health Risk Assessment

As an effective quantitative strategy to determining the human risks of multiple exposure pathways (hand-to-mouth intake, dermal contact, and inhalation), the health risk assessment model (USEPA, 2009, 2011) divides human risks into carcinogenic and non-carcinogenic risks for separate analysis, calculating ADD (chronic daily intake of heavy metals) under different exposure routes [35] (Formulas 4–8, Table S1). When there are numerous heavy metal pollutants exposed through different pathways, the risks can be added together to calculate the combined carcinogenic risk (CR) and non-carcinogenic health risk (HI). The formula for its calculation and detailed meaning can be found in these researches [36–39].

2.6 Statistics Analysis

In this study, descriptive statistics, one-way ANOVA, and cluster analysis of data were performed by SPSS 21.0 software. One-way analysis of variance for total metal concentrations in soil among different crops with Duncan's multiple comparison was performed (P < 0.05). Microsoft Office Excel 2017 software was used for the calculation of environmental risk evaluation index and health risk evaluation. All graphs were delineated by Origin 9.0 and Arc GIS 10.7 [20].

3 Results and Discussion

3.1 Heavy-Metal Contents in Soil

The average contents of Cd, Cu, Pb, and Cr in soils were 0.94, 107.79, 80.28, and 78.14 mg kg^{-1} (Table 1), respectively. The Cd and Cu contents in the soils were mostly greater than the background values of Zhejiang Province and screening values of soil pollution risk in agricultural land of China, which indicates that the Cd and Cu accumulate heavily in the soils around the e-waste dismantling area. Qing et al. [40] found that the farmland soils closed to an e-waste dismantling plant were mainly contaminated by Cd, followed by Cu, which was in line with our findings. Chen et al. [41] evaluated the soil and road dust samples from Guiyu, indicated that the concentrations of Pb and Cd were 448.73 and 0.71 mg kg^{-1}, which were significantly higher ($P \leq 0.05$) than the reference area. Shi et al. [13] also found that the paddy soils from the e-waste dismantling area were contaminated with Cd and Cu.

Table 1: Descriptive statistics of heavy metals in soil (mg kg^{-1})

Element		Range	Mean	SE	CV/%	BV	Ratio/%	RV	Ratio/%
pH	total	5.24~7.39	6.06	0.05	13.70	—	—	—	—
	leaf vegetables	5.24~7.39	6.06a	0.12	14.09	—	—	—	—
	solanaceous vegetables	5.84~7.26	6.28a	0.07	11.91	—	—	—	—
	root vegetables	5.41~5.90	5.49b	0.07	2.93	—	—	—	—
	fruits	5.35~6.65	5.79ab	0.09	14.58	—	—	—	—
Cd	total	0.11~7.66	0.94	0.07	117	0.13	99	0.30	89
	leaf vegetables	0.18~4.86	1.10a	0.18	121	0.13	100	0.30	78
	solanaceous vegetables	0.12~6.83	0.93a	0.10	113	0.13	98	0.30	90
	root vegetables	0.49~3.51	1.29a	0.59	112	0.13	100	0.30	6
	fruits	0.11~7.66	0.82a	0.10	111	0.13	99	0.30	94
Cu	total	13.20~526	107.79	4.98	72	30.54	99	50	85
	leaf vegetables	29.20~361	99.95ab	8.65	64	30.54	98	50	81
	solanaceous vegetables	29.30~526	118.59ab	8.91	77	30.54	99	50	87
	root vegetables	63.30~447	150.70a	55.91	91	30.54	100	50	6
	fruits	13.20~261	95.39b	6.01	56	30.54	99	50	85
Pb	total	19.70~565	80.28a	3.66	71	30.46	100	90	20
	leaf vegetables	40.10~144	63.17a	2.43	28	30.46	100	90	6
	solanaceous vegetables	33.40~565	81.82a	6.95	87	30.46	100	90	17
	root vegetables	46.80~94.40	72.15a	6.91	23	30.46	100	90	33
	fruits	19.70~489	90.52a	5.88	58	30.46	99	90	34
Cr	total	29.10~213	78.14a	1.41	28	95.91	12	150	2
	leaf vegetables	35.40~96.20	72.76a	1.84	19	95.91	2	150	0
	solanaceous vegetables	34.60~213	80.68a	2.34	30	95.91	15	150	2
	root vegetables	35.20~115	82.15a	11.03	33	95.91	33	150	0
	fruits	29.10~177	78.11a	2.59	29	95.91	13	150	4

Note: CV: coefficient of variation; SE: standard error; BV: background value; SV: risk screening risk value. a The exceeding ratio of heavy metal based on the background values of soils in Zhejiang Province. b. The exceeding ratio of heavy metal based on the risk intervention values for soil contamination of agricultural land with pH < 5.5 of Environmental Quality Standards of Soils in China (2018). c. Different letters within each element of different crops indicate significant differences ($P > 0.05$).

According to Zhao et al. [10], the coefficient of variation (CV) is commonly applied to measure global variability. Yekeen et al. [42] also reported that the variable had a weak variability, if the CV value is <10%, while it stands for an extensive variability if the value was >90%. The data (Table 1) shows that the CV of Cd in the soil is 117%, indicating that the content of Cd in the soils is strongly influenced by human activities. Meanwhile, the CV of Cu, Pb, and Cr were 72%, 71%, and 28%, belonging to moderate variability. Baltas et al. [1] showed the CV of Cr, Cu, and Pb in soils of Sinop Province in Iran was 65.74%, 39.22%, and 33.10%, respectively, reflecting that the heavy metals in this area were mainly influenced by natural factor rather than human activities. The differences between the above results are due to the different levels of anthropogenic activities, implying a higher anthropogenic input of metals in our study area because of the e-waste dismantling activities [43].

3.2 Heavy-Metal Contents in Crops

The average contents (mg kg^{-1}) of Cd, Pb, and Cu of different crops were followed as: leaf vegetables > root vegetables > solanaceous vegetables > fruits (Table 2). The contents of Cd, Pb and Cu in leaf and solanaceous vegetables were significantly higher than in other crops, which was consistent with the results reported by Liu et al. for the vegetables from an e-waste site [32]. Notably, concentrations of Cr in root vegetables were higher than in other crops due to their massive roots and strong active transport capacity. The contents of Cd surpassed the safety limit in most vegetables, while the contents of Pb in portions of the vegetables were exceeded, compared to China's food safety limit standard (except for Cu, which has no standard). These results implied that local residents could be exposed to food safety concerns, which deserve further investigation. The heavy metal contents in different crops (Table 2) are not consistent with the corresponding contents in soil (Table 1). For example, the mean content of Cd in root vegetable soils was 17.3% higher than that in leaf vegetable soils, while the Cd content in root vegetables was 47.6% lower than that in leaf vegetable crops. These differences were correlated with the bioavailability of the metal and the transfer capacity of different crops [44,45].

Table 2: Descriptive statistics of heavy metals in crops/mg kg^{-1}

Element		Range	Mean	Se	CV/%	LV	Exceedances
Cd	total	0.001~0.390	0.024	0.003	200	—	10
	leaf vegetables	0.004~0.390	0.063	0.011	128	0.2	3
	solanaceous vegetables	0.001~0.140	0.016	0.002	156	0.05	7
	root vegetables	0.003~0.091	0.033	0.015	109	0.1	0
	fruits	0.001~0.044	0.007	0.001	129	0.05	0
Cu	total	0.020~2.370	0.700	0.030	67	—	—
	leaf vegetables	0.198~2.360	1.016	0.066	48	—	—
	solanaceous vegetables	0.020~2.370	0.588	0.041	72	—	—
	root vegetables	0.426~4.510	0.961	0.131	33	—	—
	fruits	0.128~1.720	0.613	0.046	66	—	—
Pb	total	0.020~0.230	0.041	0.003	106	—	1
	leaf vegetables	0.020~0.209	0.088	0.008	63	0.3	0
	solanaceous vegetables	0.020~0.230	0.030	0.003	107	0.3	0
	root vegetables	0.020~0.195	0.060	0.025	104	0.1	1
	fruits	0.020~0.044	0.022	0.001	23	0.1	0

(Continued)

Table 2 (continued)

Element		Range	Mean	Se	CV/%	LV	Exceedances
Cr	total	0.010~0.480	0.060	0.006	150	—	0
	leaf vegetables	0.034~0.460	0.155	0.014	67	0.5	0
	solanaceous vegetables	0.010~0.480	0.036	0.006	187	0.5	0
	root vegetables	0.010~0.380	0.169	0.059	86	0.5	0
	fruits	0.010~0.180	0.020	0.003	135	—	—

Note: CV: coefficient of variation; SE: standard error; LV: limited value in food GB 2762-2017.

3.3 Comparison of the Transfer Capacity of Heavy Metals among Crops

The transfer factor (TF) is the ratio of heavy metal content in crops to the corresponding heavy metal content in the soil, which reflects the absorption and transfer capacity of different crops for heavy metals [46]. The data (Table 3) showed the transfer capacity of different crops for the four heavy metals are ranked as follows: Cd > Cu > Pb/Cr, suggesting that the crops had larger transfer capacity for Cd, which was in line with the results of Fan et al. [21]. The TF of different crops for Cd are as follows: leaf vegetables (0.0955) > root vegetables (0.0496) > solanaceous vegetables (0.0252) > fruits (0.0120). In general, leaf vegetables have higher transfer capacity for heavy metals, compared with other crops. Studies indicated that the differences in metal accumulation capacity and soil characteristics may cause heavy metal transfer in different plant tissues. [23,47]. According to Salah et al. [48], transpiration plays an essential role in the transfer of heavy metals inside. Yu et al. [49] reported that heavy metal transport capacity of soil crop systems is synergistically influenced by crop genotypes and environmental factors, among which the soil physico-chemical properties play an essential role.

Table 3: Transfer factor for heavy metal in crops

Mean of transfer factor	Cd	Cu	Pb	Cr
leaf vegetables	0.0955	0.0131	0.0015	0.0022
solanaceous vegetables	0.0252	0.0073	0.0004	0.0004
root vegetables	0.0496	0.0095	0.0001	0.0026
fruit	0.0120	0.0084	0.0003	0.0003

For transfer capacities of Cd, the differences among leaf vegetables, root vegetables, and fruits were significant ($P < 0.05$), but there was no significant difference between root vegetables and fruits ($P > 0.05$). For Cu, leaf vegetables were significantly higher than others. For the Pb, leaf vegetables and root vegetables were significantly different while solanaceous vegetables and fruits were not significantly different. For the Cr, leaf vegetables and root vegetables were significantly higher than solanaceous vegetables and fruits. In general, the transfer capacity of leaf vegetables was significantly higher compared to other crops for different heavy metals, while there was no significant difference between solanaceous vegetables and fruits.

Fig. 3 showed the transfer capacities of different types of crops for heavy metals. Combined with the mean values of TF of different crops for different heavy metals (Fig. 2), solanaceous vegetables and fruits have the lowest transfer capacity for Cd and Cu, root vegetables have medium transfer capacity, and leaf vegetables have the highest transfer capacity. For Pb, leaf vegetables have higher transfer capacity, and solanaceous vegetable fruit and root vegetables have lower transfer capacity. For Cr, the first group consisted of solanaceous vegetables, while the second group of root vegetables and the third group of leaf crops were high transfer crops. Leaf vegetables have a higher transfer capacity, which is likely due to a closer distance from the leaf to its root. Therefore, once the root absorbs the heavy metals, they can fast transport to the leaves.

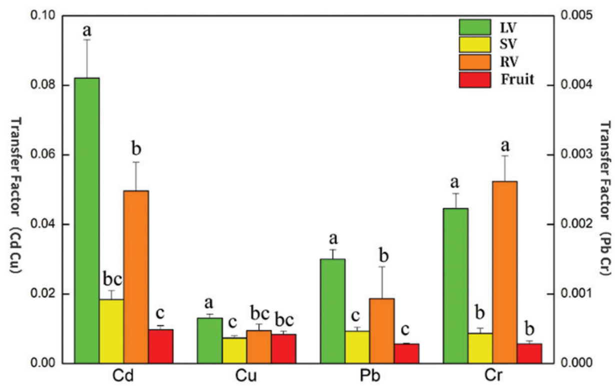

Figure 2: The difference of transfer ability for heavy metals of crops

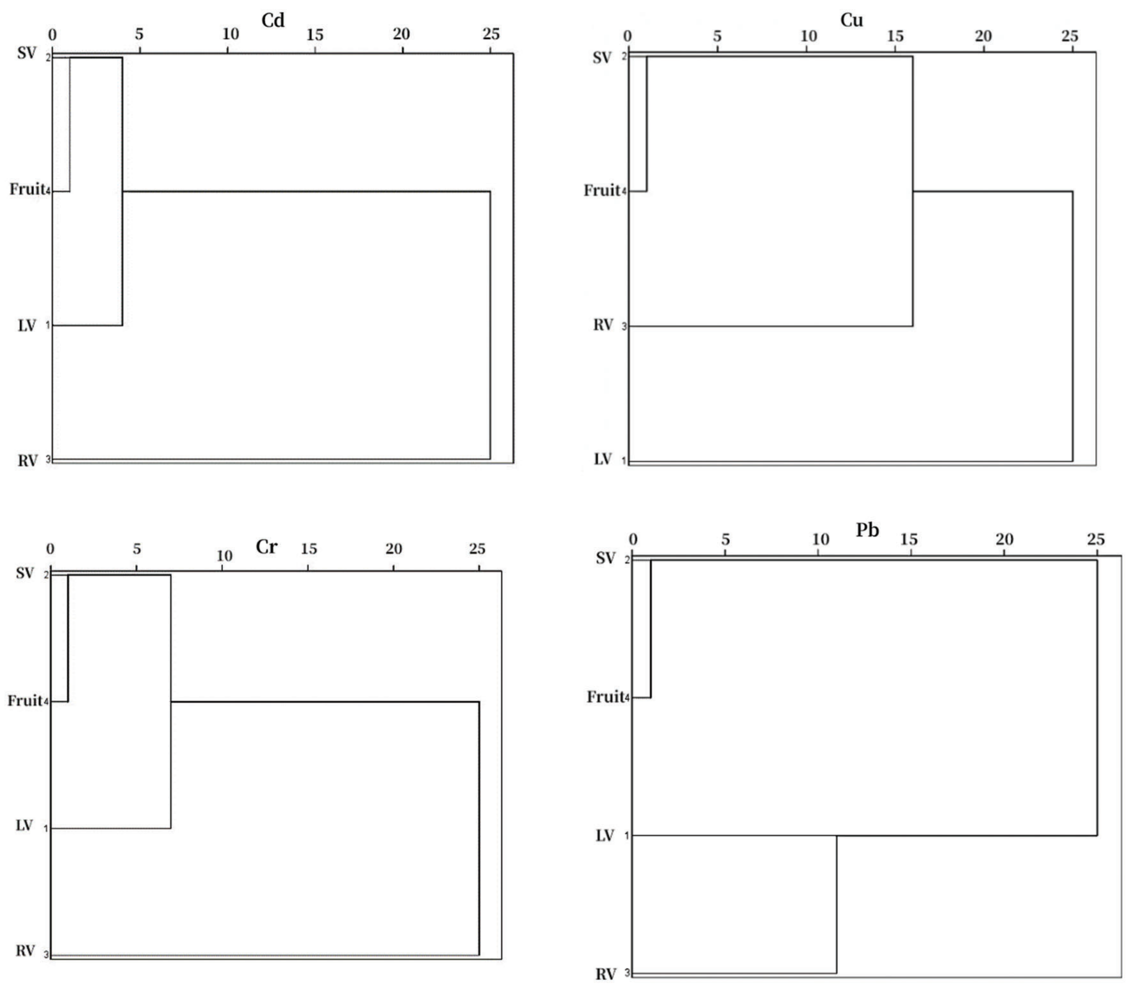

Figure 3: Cluster analysis on transfer ability for heavy metals of different crops

3.4 Environmental Risk Assessment

Based on the background value of soil elements in Zhejiang Province, the single-factor pollution index indicated that the soils in the study area have been contaminated by different heavy metals to varying degrees. As shown in Table 4, Cd is heavily accumulated (7.22). Cu is moderately accumulated (3.53). Pb is lightly accumulated (2.64). Based on the risk screening value of soil elements, the results showed that P_{Cd}, P_{Cu}, $P_{Pb,}$ and P_{Cr} were 3.13, 2.16, 0.89, and 0.52, which indicated that the Cd and Cu caused moderate and light pollution in the study area.

Table 4: Single-factor pollution risk assessment of heavy metals in soils

Mean	Background value				Risk screening value			
	Cd	Cu	Pb	Cr	Cd	Cu	Pb	Cr
total	7.22	3.53	2.64	0.81	3.13	2.16	0.89	0.52
leaf vegetables	8.47	3.27	2.07	0.76	3.67	2.00	0.70	0.49
solanaceous vegetables	7.14	3.88	2.69	0.84	3.10	2.37	0.91	0.54
root vegetables	9.94	4.93	2.37	0.86	4.31	3.01	0.80	0.55
fruit	6.28	3.12	2.97	0.81	2.72	1.91	1.01	0.52

The P_{Cd} of crops was greater than 3.0, which belonged to moderate pollution and above (Fig. 4). The P_{Cu} of crops was greater than 2.0 (total percentage > 70%), which was light pollution and above. The P_{Pb} of crops was greater than 2.0 (total percentage > 50%), which was light pollution and above. The P_{Cr} of crops was less than 1.0 (total percentage > 67%). Therefore, Cd caused the most serious contamination of the soil in the study area, followed by Cu and Pb.

Table 5 showed the mean values of the four heavy metals' ecological risks in the soil of various crops. The E_{Cd} of leaf vegetables (254.14), root vegetables (214.27), solanaceous vegetables (298.23), and fruits (188.25) have high potential ecological risks. In the contrast, the E_{Cu}, E_{Pb} E_{Cr} of crops were less than 30, belonging to slight ecological risks.

3.5 Carcinogenic Health Risk

The carcinogenic risk of several heavy metals in various crops was much higher in youngsters than in adults (Table 6). This finding might be explained by children's unique behaviors, such as frequent pica, finger or hand sucking, and rapid breathing [50]. The carcinogenic risk ranks of the different crops were as follows: root vegetables > leaf vegetables > solanaceous vegetables> fruits. According to Kan et al. [51], CR below 10^{-6} indicates that there are no health risks; CR ranging between 10^{-6} and 10^{-4} is interpreted as acceptable, and CR greater than 10^{-4} is considered unacceptable. The CRs of Cd and Cr for adults and children through accidental ingestion range from 10^{-6} to 10^{-4}, implying the carcinogenic risks from soil Cd and Cr in the study area were acceptable. The carcinogenic health risks produced by the various exposure routes for children and adults were ranked in order: food intake > accidental ingestion > dermal contact > inhalation, which was consistent with Wei's results [52]. The results indicated that children suffer a greater risk of cancer than adults. The main reason for this phenomenon is that children are most likely to ingest metals through their hands and mouths [53]. The combined carcinogenic risk of different types of crops and their soils is from leaf vegetables > rootstocks > solanaceous vegetables > fruits and the combined carcinogenic risk of different heavy metals is ranked as Cd > Cr (Fig. 5). Comparable studies have been carried out in regions where e-waste was being dismantled, and similar tendencies for carcinogenic risk have been discovered [41,54,55].

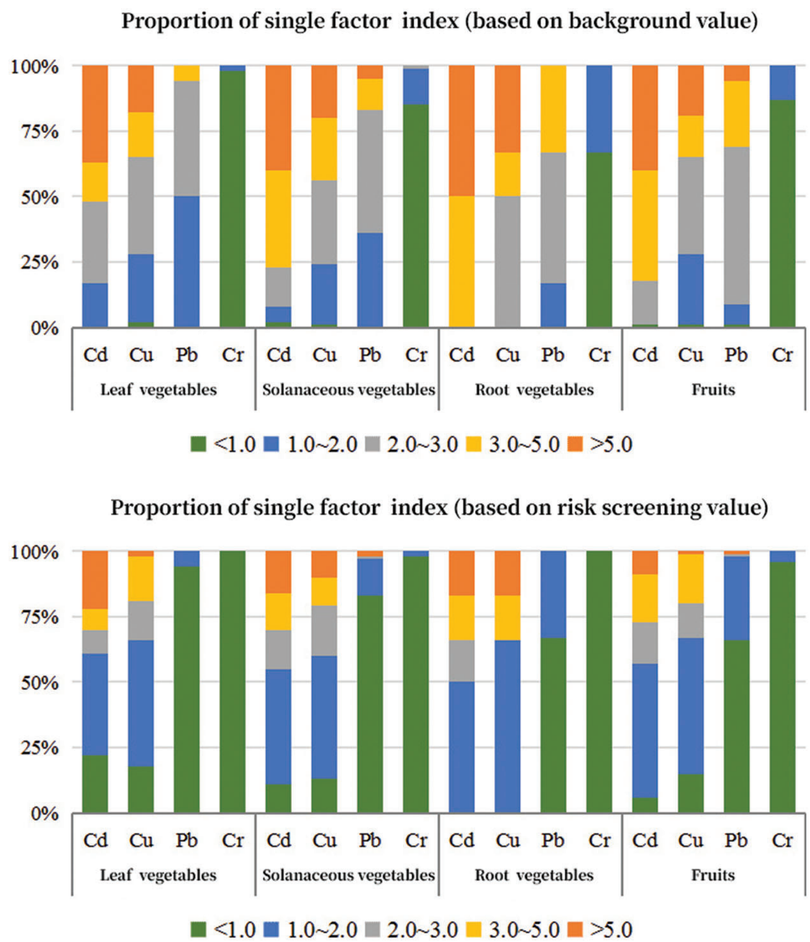

Figure 4: Single-factor pollution index ratio of heavy metals in soils of different crops/%

Table 5: Potential ecological risk index of heavy metals in soil

Vegetable types		E_i			
		Cd	Cu	Pb	Cr
total	range	25.15~1767.69	2.16~86.12	3.24~92.74	0.61~4.44
	mean	216.72	17.65	13.18	0.52
	ecological risk	high	slight	slight	slight
leaf vegetables	range	40.85~1121.54	4.78~59.10	6.58~23.64	0.74~2.01
	mean	254.14	16.36	10.37	1.52
	ecological risk	extremely high	slight	slight	slight
root vegetables	range	27.23~1576.15	4.79~86.17	5.48~92.74	0.72~4.44
	mean	214.27	19.42	13.43	1.68
	ecological risk	high	slight	slight	slight

(Continued)

Table 5 (continued)

Vegetable types		E_i			
		Cd	Cu	Pb	Cr
solanaceous vegetables	range	113.31~1040.77	10.36~73.18	7.68~15.50	0.68~2.40
	mean	298.23	24.67	11.84	1.71
	ecological risk	extremely high	slight	slight	slight
fruit	range	25.15~1767.69	2.16~42.73	3.23~80.27	0.61~3.69
	mean	188.25	15.62	14.86	1.63
	ecological risk	high	slight	slight	slight

Table 6: Carcinogenic health risk index of different heavy metals in the soil of different exposure pathways

Element		Adults				Children			
		LV	SV	RV	Fruit	LV	SV	RV	Fruit
Cd	$ADD_{ing}{}^{a}$	3.94E–06	3.32E–06	4.62E–06	2.92E–06	1.07E–05	9.01E–06	1.25E–05	7.92E–06
	ADD_{inh}	4.34E–10	3.66E–10	5.09E–10	3.21E–10	6.26E–10	5.28E–10	7.34E–10	4.64E–10
	ADD_{derm}	1.40E–08	1.18E–08	1.64E–08	1.04E–08	5.51E–08	4.65E–08	6.47E–08	4.08E–08
	ADD_{crop}	7.62E–04	1.88E–04	3.99E–04	8.09E–05	1.23E–03	3.02E–04	6.43E–04	1.30E–04
Cr	ADD_{ing}	2.13E–05	2.36E–05	2.41E–05	2.29E–05	5.79E–05	6.42E–05	6.54E–05	6.22E–05
	ADD_{inh}	1.91E–07	2.12E–07	2.16E–07	2.05E–07	2.76E–07	3.06E–07	3.11E–07	2.96E–07
	ADD_{derm}	3.03E–06	3.36E–06	3.42E–06	3.25E–06	1.19E–05	1.32E–05	1.35E–05	1.28E–05
	ADD_{crop}	1.53E–04	3.52E–05	1.67E–04	2.01E–05	2.47E–04	5.67E–05	2.69E–04	3.24E–05

Note: ADD_{ing}, ADD_{derm}, ADD_{inh} represent the average daily respective exposures of adults and children to heavy metal through the hand-to-mouth intake, dermal contact, and inhalation.

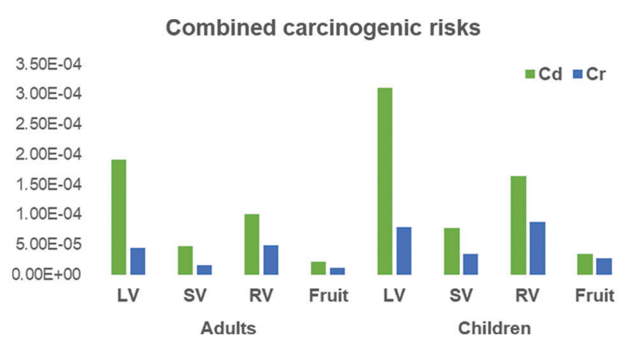

Figure 5: Comprehensive carcinogenic risk of heavy metals in soil-crops

3.6 Non-Carcinogenic Health Risk

For children, their non-carcinogenic risk assessment of heavy metals was both significantly greater than those for adults, implying that the same contaminants were more likely to cause non-carcinogenic hazards for children under the same exposure pathway (Table 7). In addition, the non-carcinogenic risk is related to the exposure pathway, which showed food intake > accidental ingestion > dermal contact > inhalation. Zhang et al. [52] found that in terms of heavy metals exposure to street dusts, the non-carcinogenic health risk for adults was lower than for children. The hazard quotient (HQ) of Cd, Cr in the leaf vegetables and root vegetables for children was higher than 1, found that Cd and Cr were the major elements that posed a health risk to local residents, and they were the key elements that posed a health risk to local residents. Similar results indicated that the HQ total even ranked in the order of Cu > Cd ≈ Pb > Zn [17]. Additionally, the combined non-carcinogenic risk of leaf vegetables and root vegetables was higher than those of solanaceous vegetables (Fig. 6). Also, previous studies had shown that the risks caused by intake of leaf vegetables were much higher than those fruit vegetable intake [53].

Table 7: Non-carcinogenic health risk index of different heavy metals in the soil of different exposure pathways

Element		Adults				Children			
		LV	SV	RV	Fruit	LV	SV	RV	Fruit
Cd	$ADD_{ing}{}^{a}$	1.86E–03	1.57E–03	2.18E–03	1.38E–03	2.10E–02	1.77E–02	2.47E–02	1.56E–02
	ADD_{inh}	1.98E–05	1.67E–05	2.33E–05	1.47E–05	1.19E–04	1.01E–04	1.40E–04	8.83E–05
	ADD_{derm}	2.64E–04	2.23E–04	3.10E–04	1.96E–04	4.34E–03	3.66E–03	5.09E–03	3.21E–03
	ADD_{crop}	3.60E–01	8.86E–02	1.89E–01	3.82E–02	2.41E+00	5.95E–01	1.27E+00	2.56E–01
Cu	ADD_{ing}	4.22E–03	5.01E–03	6.36E–03	4.03E–03	4.77E–02	5.66E–02	7.19E–02	4.55E–02
	ADD_{inh}	4.48E–07	5.31E–07	6.75E–07	4.27E–07	2.69E–06	3.19E–06	4.06E–06	2.57E–06
	ADD_{derm}	1.50E–05	1.78E–05	2.26E–05	1.43E–05	2.46E–04	2.92E–04	3.71E–04	2.35E–04
	ADD_{crop}	1.45E–01	8.36E–02	1.37E–01	8.72E–02	9.70E–01	5.61E–01	9.17E–01	5.85E–01
Pb	ADD_{ing}	3.05E–02	3.95E–02	3.48E–02	4.37E–02	3.45E–01	4.46E–01	3.94E–01	4.94E–01
	ADD_{inh}	3.25E–06	4.21E–06	3.71E–06	4.66E–06	1.95E–05	2.53E–05	2.23E–05	2.80E–05
	ADD_{derm}	7.15E–04	9.26E–04	8.16E–04	1.02E–03	1.17E–02	1.52E–02	1.34E–02	1.68E–02
	ADD_{crop}	1.42E–01	4.91E–02	9.68E–02	3.54E–02	9.56E–01	3.30E–01	6.50E–01	2.37E–01
Cr	ADD_{ing}	4.09E–02	4.54E–02	4.62E–02	4.40E–02	4.63E–01	5.14E–01	5.23E–01	4.97E–01
	ADD_{inh}	5.14E–04	5.69E–04	5.80E–04	5.51E–04	3.09E–03	3.42E–03	3.49E–03	3.32E–03
	ADD_{derm}	5.82E–03	6.45E–03	6.57E–03	6.25E–03	9.56E–02	1.06E–01	1.08E–01	1.03E–01
	ADD_{crop}	2.95E+00	6.76E–01	3.20E+00	3.87E–01	1.98E+00	4.53E–01	2.15E+00	2.60E–01

Note: a: *ADDing, ADDderm, ADDinh* represent the average daily respective exposures of adults and children to heavy metals through the hand-to-mouth intake, dermal contact, and inhalation.

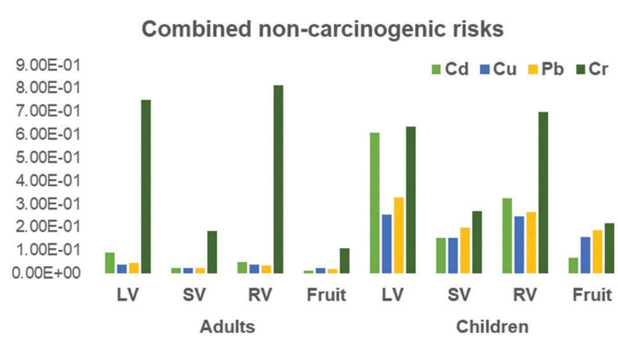

Figure 6: Comprehensive non-carcinogenic risk of heavy metals in soil-crops

4 Conclusion

This research revealed the contamination status of Cd, Pb, Cu, and Cr in the soil-crop system. The study area has been polluted by Cd, Pb, Cu, and Cr as a result of irrational e-waste dismantling activities, especially for Cd. Leaf vegetables suffer more serious heavy metal pollution in the area, which may be due to their high transfer capabilities. The results of the health risk assessment showed that residents in the area faced potential health hazards. Therefore, it is suggested that decrease the intake of these toxic elements and decrease planting high accumulators like leaf vegetables in heavy metal polluted farmland to reduce heavy metal accumulation in crops. Local governments must closely monitor the situation and take steps to address e-waste-related pollution, then ensure that local residents can safely consume the agricultural product.

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Appendix

Table S1: Health risk exposure parameters for heavy metals

	Meaning		Unit	Adults		Children	
IngR	daily intake of soil		mg d^{-1}	100		200	
InhR	daily intake of air		m^3 d^{-1}	14.5		7.5	
IR	daily intake of crops		kg d^{-1}	0.337		0.24	
EF	exposure frequency		d a^{-1}	350		350	
ED	exposure duration		a	25		6	
BW	body weight		kg	56.8		15.9	
AT	exposure time		d	2628(carcinogenic)		2628(carcinogenic)	
				9125(non-carcinogenic)		2190(non-carcinogenic)	
PEF	dust emission factor		m^3 kg^{-1}	1.36 × 109		1.36 × 109	
SA	exposed surface area		cm^2	5074.98		2247.56	
SL	skin adhesion coefficient		mg d cm^{-2}	0.07		0.2	
ABS	skin absorption factor			0.001		0.001	
		exposure pathways		Cd	Cu	Pb	Cr
SF	slope factor	mouth intake	kg d mg^{-1}	6.1	–	–	0.5
		dermal contact		6.1	–	–	20
		inhalation		6.3	–	–	42
RfD	consumption of heavy metals	mouth intake	mg d kg^{-1}	1.0×10^{-3}	4.0×10^{-2}	3.5×10^{-3}	3×10^{-3}
		dermal contact		2.5×10^{-5}	4.0×10^{-2}	5.3×10^{-4}	7.5×10^{-5}
		inhalation		1.0×10^{-5}	4.02×10^{-2}	3.5×10^{-3}	2.55×10^{-5}

Note: a: "-" means that there is no related data in the article.

Formula:

$$P_i = C_i/S_i \tag{1}$$

where P_i represents the single element pollution, C_i is the concentration of heavy metals in soil, S_i is the standard concentration of heavy metals in soil.

$$E_i = T_r^i \times \frac{C_i}{C_n^i} \tag{2}$$

$$RI = \sum E_i \tag{3}$$

where E_i is the risk index (RI) of metal; T_i is the toxic response factor of metal ($T_{Cd} = 30$, $T_{Cu} = T_{Pb} = 5$, $T_{Cr} = 2$); C_i is concentration of metal.

$$ADD_{ing} = \frac{C \times IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (4)$$

$$ADD_{derm} = \frac{C \times SA \times SL \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (5)$$

$$ADD_{inh} = \frac{C \times InhR \times EF \times ED}{PEF \times BW \times AT} \quad (6)$$

where ADD is the chronic daily intake of heavy metals; ADD_{ing}, ADD_{derm}, ADD_{inh} represent the average daily respective exposures of adults and children to heavy metal through the hand-to-mouth intake, dermal contact, and inhalation; C is the mean concentration of heavy metals in vegetables; $IngR$ represents the daily intake of soil; $InhR$ represents the daily intake of air; IR represents the daily intake of crops; EF is the exposure frequency; ED is exposure duration; AT represents the mean exposure time; BW is the mean body weight; RFD was the reference consumption of heavy metals.

$$CR = \sum CR_i = \sum ADD_i \times SF_i \quad (7)$$

$$HI = \sum HQ_i = \sum \frac{ADD_i}{RfD_i} \quad (8)$$

where HI (Hazard Index) is the sum of HQ (hazard quotient) of each heavy metal and represents the total non-carcinogenic risk; CR (carcinogenic risk) is the total carcinogenic risk (USEPA, 2009, 2011).