



## Ecological and Human Health Risk Assessment of Heavy Metals by Consuming the Aquatic Plant Species Near an Electronic Waste Open Dumpsite in Thailand

Thitima Parkpoom<sup>1</sup>, Somsak Intamat<sup>2</sup>, Uraiwan Phoonaploy<sup>1</sup>, Lamyai Neeratanaphan<sup>1,\*</sup>

<sup>1</sup> Division of Environmental Science, Faculty of Science, Khon Kaen University, Khon Kaen, Thailand

<sup>2</sup> Thatphanom Crown Prince Hospital, Nakornphanom, Thailand

\* Corresponding author: [hlamya@kku.ac.th](mailto:hlamya@kku.ac.th)

### Article History

Submitted: 6 February 2022/ Revision received: 3 June 2022/ Accepted: 19 June 2022/ Published online: 27 June 2022

### Abstract

Heavy metals from electronic waste (e-waste) accumulate in the environment and can affect human health. The purpose of this study was to determine As, Cd, Cr and Pb concentrations in water, sediment and three species of edible aquatic plants (*Ottelia alismoides*, *Ipomoea aquatic* and *Marsilea crenata*) near an e-waste open dumpsite. Samples were collected from six sampling points surrounding an e-waste open dumpsite and heavy metal concentrations were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES). Bioaccumulation factors (BAFs), estimated daily intake (EDI), hazard quotient (HQ), hazard index (HI) and carcinogenic risk (CR) were evaluated in the plants. The Pb concentration in the water samples exceeded the quality standard. The order of the heavy metal concentrations in the sediment was Pb>Cr>As>Cd, and these concentrations were within the limits of the quality standard. The order of the heavy metal concentrations in *O. alismoides*, *I. aquatic* and *M. crenata* was Cr>Pb>As>Cd, Pb>Cr>As>Cd and Pb>Cr>As>Cd, respectively. The concentrations of As, Cd, Cr and Pb in *O. alismoides* and As, Cr and Pb in *I. aquatic* and *M. crenata* exceeded the quality standard of food consumption. Most of the BAF values of the heavy metals in *O. alismoides* were more than one, but in *I. aquatic* and *M. crenata*, they were less than one. The order of the EDI values in *O. alismoides*, *I. aquatic* and *M. crenata* was Cr>Pb>As>Cd, Pb>Cr>As>Cd and Cr>As>Pb>Cd, respectively. The HQ values were greater than one for As, Cd and Pb in *O. alismoides*; Pb in *I. aquatic*; and As and Pb in *M. crenata*. The HQ and CR values show that the consumption of edible plants from an e-waste open dumpsite is a human health risk.

**Keywords:** Electronic waste; Heavy metals; Aquatic plant; Risk assessment; Bioaccumulation factors

### Introduction

The development of economics and improvements in the quality of human life have led

to the use of electrical and electronic devices. The waste generated by this disused equipment is named electronic waste (e-waste). E-waste has

created rapidly increasing pollution problems as the manufacture and application of electrical and electronic instruments have increased substantially [1]. The Thailand Pollution Control Department (PCD) reported that from 2015–2016, the amount of e-waste increased from 384,232 to 394,107 tons [2–3]. The generation of e-waste has led to the development of informal disposal areas [4]. The Khok Sa Ard subdistrict in the Khong Chai district in Kalasin province in Northeastern Thailand contains an e-waste open dumpsite with the greatest e-waste stocks in Thailand, accepting more than 72,000 tons of e-waste per year. The people in this area work as e-waste separators [5]. The valuable parts of e-waste are improperly exposed and separated by residents. The precious materials, such as copper, are stripped from the devices, and the remainder is transported and burned in the community dumpsite. Consequently, heavy metals found in e-waste, such as As, Cd, Cr, Pb, Mn, Ni and Zn, can contaminate the surrounding area as seen in the Agbogbloshie district in the Republic of Ghana [6]. Indeed, 12 out of 124 children in the Khok Sa Ard subdistrict had blood Pb levels over the suggested threshold ( $15 \text{ mg dL}^{-1}$ ) [7]. In addition, a previous study reported that the concentrations of Pb, Ni and Mn were 79,520, 75 and  $1,519 \text{ mg kg}^{-1}$ , respectively, exceeding the soil quality standards [8]. Neeratanaphan et al. [9] detected high heavy metal concentrations in water, soil, aquatic organisms, and plants surrounding an e-waste open dumpsite in the Khok Sa Ard Subdistrict of Khong Chai District. Moreover, the Pb concentration in the samples exceeded the water quality standard [10].

E-waste open dumpsites release hazardous elements from improperly disposed electronic devices, which affects the surrounding environment [11]. Pb, As, Cd and Cr are found in e-waste. Specifically, As is found in electrical circuits, mobile phones and computers. Cd leaks from printing presses, resistors (semiconductors), batteries and cathode-ray tubes. Cr is found in

computers, cathode ray tube (CRT) monitors and circuit boards. Pb is found in paint, oil, rubber, batteries, lead glass and CRT-containing devices. Nonessential elements, such as Pb, are greatly poisonous in small concentrations and can harm the function of many organs in organisms [12].

Heavy metal exposure can adversely affect human health, with both short- and long-term effects, such as genotoxic, mutagenic, central nervous system, cardiovascular, respiratory, gastrointestinal, urinary, hepatic and reproductive effects [13–15]. Exposure of plants to excess heavy metals can cause a variety of adverse effects. Cd reduces seed germination; decreases plant nutrient content; and reduces shoot and root length [16]. Cd also produces alterations in the functionality of membranes by inducing lipid peroxidation [17], disturbs chloroplast metabolism by inhibiting chlorophyll biosynthesis and reduces the activity of enzymes involved in  $\text{CO}_2$  fixation [18]. Cr induced oxidative stress and lipid peroxidation in plants causing severe damage to cell membranes. Oxidative stress induced by Cr also initiates the degradation of photosynthetic pigments causing a decline in growth. High Cr concentrations can disturb the chloroplast ultra-structure thereby disturbing the photosynthetic process [19]. Pb exerts adverse effect on the morphology, growth and photosynthetic processes of plants [20]. High Pb concentrations also induce oxidative stress by increasing the production of ROS (reactive oxygen species) in plants [21]. As reduces seed germination, decreases seedling height, and reduces leaf area and dry matter production [22]. Moreover, heavy metals can induce DNA abnormalities, such as changes in DNA bands and DNA structure, which cause genetic variation in plants [23–24]. Neeratanaphan et al. [25] presented the DNA of *Pistia stratiotes* in terms of genetic values and genomic template stability and found that its structure changed dramatically due to genetic degradation. Thanee et al. [26] found DNA abnormalities in plant species belonging

to acanthus (*Chromolaena odorata* L.), in cattails (*Typha angustifolia* L.) and in mission grass (*Penisetum polystachyon* L.) in an e-waste open dumpsite. Therefore, these heavy metals are transferred from e-waste open dumpsites to various parts of the environment, including plants and animals. These toxic substances are maintained in the food chain and are transferred at high concentrations through the trophic levels [27].

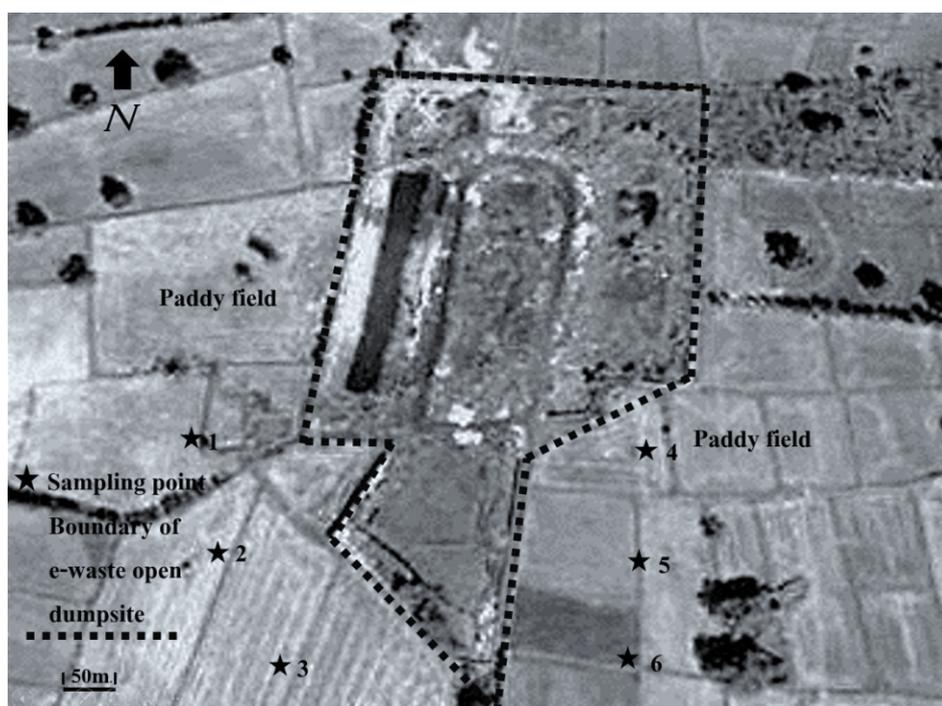
Plants can uptake large amounts of metals from water and soil through active and passive absorption [28]. Heavy metal contamination in the air can be absorbed by leaves, stems and other parts of the plant, depending on the characteristics of the stems or leaves. Heavy metals are transported to all parts of plants, including roots, stems, and leaves, and accumulate in tissues [29]. The e-waste open dumpsite analyzed in this study hosts local edible plants. These species, *Ottelia alismoides* (submerged plant), *Ipomoea aquatic* and *Marsilea crenata* (floating plants) have different characteristics, habitats and phenologies. Plant phenology is an important factor in the accumulation of heavy metals in various

plant tissues [30]. Therefore, the aims of this study were to investigate the heavy metal concentrations accumulated in three local edible plant species (*O. alismoides*, *I. aquatic* and *M. crenata*) surrounding an e-waste open dumpsite. The bioaccumulation factor (BAF) and potential health risks, including the estimated daily intake (EDI), hazard quotient (HQ), hazard index (HI) and carcinogenic risk (CR) were determined.

## Materials and methods

### 1) Study site

Figure 1 shows an e-waste open dumpsite and the location of sampling points in the area surrounding the dumpsite in the Khok Sa Ard Subdistrict, Khong Chai District, in Kalasin Province of Northeastern Thailand. The geographic coordinates of the e-waste area are latitude 16°18'55.81"N and longitude 103°25'30.66E. The distance from the study site to the e-waste open dumpsite was approximately 50 m. The surrounding land near the e-waste open dumpsite was used for paddy fields.



**Figure 1** E-waste open dumpsite and the location of sampling points.

## 2) Sample collection

Six water and sediment samples were collected from flooded paddy fields near the e-waste open dumpsite. The sediment samples were air-dried, pulverized with a porcelain mortar, air-dried again, then crushed and filtered through a 2-mm sieve [31–32]. Three samples of the edible aquatic plants (*O. alismoides*, *I. aquatic* and *M. crenata*) were randomly collected from the e-waste open dumpsite. The aquatic plant samples were collected from sediment, and the stems and leaves were cut into very small fragments, mixed and oven-dried at 80°C. Then, the dry plant fragments were pulverized with a porcelain mortar and pestle [33].

## 3) Preparation of samples and heavy metals analysis

The 20 mL water samples and 1.25 mL of 65% HNO<sub>3</sub> were mixed in a beaker and digested on a hot plate at 105°C for 2 h. Each digested sample was then adjusted to 25 mL with deionized water and filtered with a glass microfiber filter [34]. The dried sediment samples (1.0 g) were digested with HNO<sub>3</sub> (5 mL), HCl (15 mL) and H<sub>2</sub>O<sub>2</sub> (10 mL) and boiled in a digestion block for 2 h. The final solution was filtered by a glass microfiber filter [35]. The plant samples (0.5 g) were digested with HNO<sub>3</sub> (5 mL) and H<sub>2</sub>O<sub>2</sub> (3 mL) and heated on a hot plate at 120°C until the solutions evaporated to near dryness. The solutions were then adjusted with deionized water to 25 mL and passed through a membrane filter. All the solution samples were analyzed for As, Cd, Cr and Pb concentrations by inductively coupled plasma optical emission spectrometry (ICP-OES; model Optima 8300; USA). The limits of detection (LODs) for As, Cd, Cr and Pb were 1, 0.1, 0.2 and 1 µg L<sup>-1</sup>, respectively. The wavelengths of As, Cd, Cr and Pb detection were 188.979, 226.502, 267.719 and 220.353 nm, respectively [36].

## 4) Quality standard control

The precision and accuracy of the analyses were evaluated by comparing replicate sample

assays to standard reference materials for heavy metals. The SRM (1643f) was obtained from the National Institution of Standard and Technology, USA. The results were found not to deviate by more than 2% of the certified levels [34]. The heavy metal recovery values in the range of 85–115% were accepted [37].

## 5) Statistical analysis

A Kruskal-Wallis test was applied to assess the concentrations of heavy metals in the three edible plant species. The statistical analysis was performed by SPSS software version 22.0 at a 95% confidence level.

## 6) Bioaccumulation factor (BAF)

The BAF demonstrates the potential of aquatic plants to collect specific heavy metals related to their concentration in sediment. The BAF is calculated as follows Eq. 1 [10].

$$\text{BAF} = \frac{(\text{Heavy metal}) \text{ aquatic plants}}{(\text{Heavy metal}) \text{ sediment}} \quad (\text{Eq. 1})$$

## 7) Human health risk assessments

### 7.1) Estimated daily intake (EDI)

The estimated daily intake indicates the transfer of heavy metals from aquatic plants to humans and is illustrated by 3 factors: heavy metal concentration of aquatic plants (C), the quantity of aquatic plants consumed daily (D) and average body weight (BW). The EDI is calculated as follows Eq. 2.

$$\text{EDI} = \frac{C \times D}{(\text{BW})} \quad (\text{Eq. 2})$$

The daily average plant consumption was 0.176 kg person<sup>-1</sup> d<sup>-1</sup>. The average BW of people in the region is 62.45 kg person<sup>-1</sup> [38].

### 7.2) Hazard quotient (HQ) and hazard index (HI)

The HQ show noncarcinogenic impacts related to consuming polluted plants. The HQ refers to the ratio of the daily intake of metal in food to the

oral reference dose (RfD). An  $HQ > 1$  for any metal in the diet suggests that consumers face health risks. The HQ is calculated as follows Eq. 3.

$$HQ = \frac{EDI}{RfD} \quad (\text{Eq. 3})$$

The RfDs for As, Cd, Cr and Pb were  $3 \times 10^{-4}$ ,  $1 \times 10^{-3}$ , 1.5 and  $3.6 \times 10^{-3}$   $\text{mg kg}^{-1} \text{d}^{-1}$ , respectively [10]. The hazard index (HI) is calculated by using the individual HQ values for a mixture of elements. HI is equal to the sum of the HQ [39].

### 7.3) Carcinogenic risk (CR)

Carcinogenic risk is expressed as the probability that an individual will develop cancer over a lifetime of exposure to contaminants. The CR is calculated as follows Eq. 4 and Eq. 5.

$$CR = \frac{EDI}{CSfo} \quad (\text{Eq. 4})$$

$$CRt = \sum CR \quad (\text{Eq. 5})$$

CSfo is the oral carcinogenic slope factor and had values of 1.5,  $3.8 \times 10^{-1}$ , 0.5 and  $8.5 \times 10^{-3}$   $\text{mg kg}^{-1} \text{d}^{-1}$  for As, Cd, Cr and Pb, respectively. If numerous carcinogenic elements are present, the cancer risks from all carcinogens (CRt) are summarized (assuming additive results). Risks in the range of  $1 \times 10^{-6}$ - $1 \times 10^{-4}$  are acceptable [40–41].

## Results and discussion

### 1) As, Cd, Cr and Pb concentrations in water and sediment samples

Table 1 show the concentrations of As, Cd, Cr and Pb in the water and sediment samples. The Pb concentration exceeded the water quality standard [42]. In the sediment, the concentrations of heavy metals were greater than those in water and were ordered as follows:  $Pb > Cr > As > Cd$ . However, the concentrations of As, Cd, Cr and Pb were within the soil quality standard [43].

Heavy metals are usually insoluble in water and adsorb to sediment. Sediments have heavy metal concentrations greater than those in water because sediment experiences fewer disturbances,

leading to the long-term settlement of sediment-bound contaminants [44]. The concentration of heavy metals in the sediment affects the concentration of heavy metals in the plant species growing in the sediment. The order of the heavy metal concentration in the sediment was  $Pb > Cr > As > Cd$ ; and these concentrations were within the quality standard [43]. The concentration of Pb was the highest because the nearby e-waste open dumpsite in the Khok Sa Ard subdistrict, Khong Chai District had contained numerous computers and televisions. Pb is the major element in the composition of computers and televisions [45–46]. Rain run-off is a possible mechanism for heavy metal pollution in water [47]. A prior study also indicated high Pb concentrations in soil within ( $577.68 \pm 1.60 \text{ mg kg}^{-1}$ ) and near ( $6.81 \pm 0.10 \text{ mg kg}^{-1}$ ) an e-waste storage area [9]. Regional Environment Office 10 of Thailand [48] found concentrations of As, Cd, Cr and Pb in soil of 2,636, 44, 12 and  $9.6 \text{ mg kg}^{-1}$ , respectively. Various factors such as cultivation season, soil depth, distance from the e-waste open dumpsite, and climate on the day of sampling can have an impact on the concentration of heavy metals [47–49].

### 2) As, Cd, Cr and Pb concentrations in three edible aquatic plant species

Table 2 shows the As, Cd, Cr and Pb concentrations in the three edible aquatic plant species included in this study. The order of the heavy metal concentrations in *O. alismoides*, *I. aquatic* and *M. crenata* were  $Cr > Pb > As > Cd$ ,  $Pb > Cr > As > Cd$  and  $Pb > Cr > As > Cd$ , respectively. The concentrations of As, Cd, Cr and Pb in *O. alismoides* and As, Cr and Pb in *I. aquatic* and *M. crenata* exceeded food consumption standard values. The statistical analysis indicated that As, Cd, Cr and Pb concentrations were significantly different between *O. alismoides* and the other two edible aquatic plants ( $p < 0.05$ ). However, the Cd and Cr concentrations in *I. aquatic* and *M. crenata* were not statistically different.

**Table 1** The concentration of As, Cd, Cr and Pb in water (mg L<sup>-1</sup>) and sediment (mg kg<sup>-1</sup>) samples from an e-waste open dumpsite.

Study area (N=6)	As			Cd			Cr			Pb		
	Certified value	Measured value	Recovery (%)									
Water	0.011	0.01±0.01	91	-	ND	-	-	ND	-	0.61	0.06±0.01	98
Standard*		0.01			0.05			0.05			0.05	
Sediment	2.88	2.58±0.15	90	2.61	2.41±0.15	92	12.27	11.97±1.75	98	68.12	66.16±8.45	97
Standard**		≥6.0			≤67			≤17.5			≤400	

**Note:** \*Surface water quality standard of Thailand [42], \*\*Soil quality standards for habitat and agriculture [43]

**Table 2** The concentration of As, Cd, Cr and Pb in samples of three edible aquatic plant species from an e-waste open dumpsite (mg kg<sup>-1</sup>, dry weight).

Plant species (N=6)	AS			Cd			Cr			Pb		
	Certified value	Measured value	Recovery (%)									
<i>O. alismoides</i>	6.73	5.93±0.26 <sup>a</sup>	88	3.81	3.55±0.08 <sup>a</sup>	93	7.79	6.42±0.59 <sup>a</sup>	97	7.09	6.42±0.59 <sup>a</sup>	91
<i>I. aquatic</i>	0.67	0.61±0.15 <sup>b</sup>	91	0.07	0.08±0.07 <sup>b</sup>	114	1.65	2.24±0.85 <sup>b</sup>	96	2.64	2.24±0.85 <sup>b</sup>	89
<i>M. crenata</i>	0.42	0.38±0.13 <sup>c</sup>	90	0.13	0.14±0.08 <sup>b</sup>	108	1.12	1.55±0.26 <sup>c</sup>	97	1.82	1.55±0.26 <sup>c</sup>	85
Food quality standard		0.1*			0.2*			1**			0.3**	

**Note:** Different letters in the same column indicate significant differences compared to standards ( $p < 0.05$ ).

\*Joint FAO/WHO food standards program [50],

\*\*FAO: Food and Agriculture Organization of the United Nations [51]

In e-waste open dumpsite soils, the excessive amounts of heavy metals are taken up by edible plants and vegetables, which poses a serious health risk to humans. Heavy metals are absorbed by plant roots and translocated to the above ground portions of the plants (shoots) and accumulate in plant tissues [52]. In general, the concentration of heavy metals in the three analyzed species of edible aquatic plants exceeded the quality standards; only the Cd concentrations in *I. aquatic* and *M. crenata* were within quality standards. In this study, stem and leaf parts were used to determine the heavy metal concentrations. The highest As, Cd, Cr and Pb concentrations were found in *O. alismoides* plants, which grow completely submerged with fibrous roots and small stems. In contrast, *I. aquatic* and *M. crenata* are floating plants that have long stems and root freely from nodes to form large clusters. Submerged plants are rooted to the bottom and their leaves grow entirely underwater. Thus, submerged plants interact with heavy metals from both water and sediment [53]. Edible aquatic plant species have various physiological, genetic, and morphological differences. For example, the mechanisms associated with the uptake and translocation of ions by aquatic plants affects the potential absorption of heavy metals by each plant species [54]. The results of the current study demonstrate that habitat type i.e., the habitats of floating and submerged plants according to the study of Fritioff and Greger [55], is associated with heavy metal concentration and that *O. alismoides* has the highest potential to accumulate heavy metals. In conclusion, if local people consume these edible aquatic plants regularly, they will be risk of heavy metal exposure.

### 3) BAFs of heavy metals in edible aquatic plant species

Table 3 shows the BAFs of As, Cd, Cr and Pb in the three edible aquatic plant species based on their absorption from sediment. In *O. alismoides*, the order of the BAFs was as

follows: As>Cd>Cr>Pb. The BAFs of As and Cd in *O. alismoides* exceeded one, indicating high potential accumulation. In *I. aquatic* and *M. crenata*, the order of the BAFs was As>Cr>Pb>Cd and As>Cr>Cd>Pb, respectively.

The BAFs of As, Cd, Cr and Pb in the three edible aquatic plant species were used to determine the degree of risk and steady-state conditions of accumulated chemicals in the plants. The abiotic factors affecting the values of the BAF are salinity and alkalinity, the oxidation-reduction potential, and the potential of hydrogen ions [56]. BAFs demonstrate the potential of the aquatic plant species for phytoextraction and phytostabilization of heavy metals [57]. The BAFs of As and Cd in *O. alismoides* exceeded one, suggesting high potential absorption. The BAFs of the heavy metals in *I. aquatic* and *M. crenata* were less than one, indicating low potential for absorbing any of the heavy metals. The potential for absorbing toxic substances varied by edible aquatic plant species. Depending on the plants characteristics, microorganism-plant interactions, translocation, tolerance mechanisms and metal and soil characteristics [58], plant species can absorb and hyperaccumulate metal contaminants in root and shoot tissue [59]. *O. alismoides* has shorter stems and larger leaves than *I. aquatic* and *M. crenata*, while *I. aquatic* and *M. crenata* have long stems. Heavy metals are translocated from the roots to the shoots. The phytotransformation process is the breakdown of metal contaminants taken up by plants through metabolic processes within the plant [60–61]. The consumption of these edible aquatic plant species located near the e-waste open dumpsite could affect human health [32].

### 4) Potential human health risks from heavy metals via edible aquatic plant consumption

Table 4 shows the potential human health risks associated with the intake of As, Cd, Cr and Pb from edible aquatic plant species, which were determined by assessing the EDI, HQ, HI and CR values of the population. The EDI values

for heavy metals in *O. alismoides*, *I. aquatic* and *M. crenata* followed the order of Cr>Pb>As>Cd, Pb>Cr>As>Cd and Pb>Cr>As>Cd, respectively. The EDI values indicate the effects of these aquatic plants on the health of the people that consume the plants. The HQ values for As, Cd and Pb in *O. alismoides*, Pb in *I. aquatic* and As and Pb in *M. crenata* indicated a health risk to humans. The HI values for *O. alismoides*, *I. aquatic* and *M. crenata* were greater than one, which is considered a health risk to humans. [39]. The CR values associated with As and Cr were greater than  $1 \times 10^{-4}$  in all three edible aquatic plants. These CR values suggest that the consumption of aquatic plants from areas surrounding the e-waste dumpsite could cause cancer.

The daily intake of heavy metals consumed in edible aquatic plants from this e-waste environment can have an important impact on the health of humans. The EDI, HQ, HI and CR values were determined to assess the health risks to humans who consume vegetables contaminated with heavy metals. Among all the heavy metals, the highest EDI was found in *O. alismoides*. The EDI value of Pb was high in each species. A previous study found the EDI value of Pb in

rice (*Oryza sativa* L.) was 6.02 near an e-waste open dumpsite [9]. The HQ values of As, Cd and Pb in *O. alismoides*, Pb in *I. aquatic* and As and Pb in *M. crenata* were all greater than one. These results indicate that *O. alismoides* is the most unsafe for consumption and may pose potential health risks with regard to levels of heavy metals. The CR values of the three edible aquatic plant species contaminated with As, Cd, Cr and Pb indicate that the consumption of these species might lead to the development of cancer. The USEPA [63] reported that the chance of additional human cancer over a 70-year lifespan ( $1 \times 10^{-6}$ - $1 \times 10^{-4}$ ) is between 1-100 and 1-1,000,000, which is regarded as a passable or an unimportant risk. The CRt values of *O. alismoides*, *I. aquatic* and *M. crenata* were 394, 49 and 32 times greater than that of the quality standard. These results indicated that the consumption of edible aquatic plants contaminated with heavy metals leads to a great carcinogenic risk. In addition, the analysis of the carcinogenic risk revealed that the concentrations of As and Cr in the three edible aquatic plant species were above the range for relatively negligible cancer risk.

**Table 3** Bioaccumulation factors of heavy metals in three edible aquatic plant species

Heavy metal	BAFs based on sediment		
	<i>O. alismoides</i>	<i>I. aquatic</i>	<i>M. crenata</i>
As	2.302±0.03	0.238±0.05	0.14±0.05
Cd	1.479±0.11	0.032±0.02	0.05±0.03
Cr	0.622±0.08	0.139±0.06	0.08±0.06
Pb	0.097±0.005	0.034±0.01	0.02±0.004

**Table 4** The EDI, HQ, HI and CR values of heavy metals in three edible aquatic plant species

Heavy metal	EDI ( $\mu\text{g kg}^{-1}\text{d}^{-1}$ )	HQ	CR
<i>O. alismoides</i>			
As	16.701	5.568	$2.50 \times 10^{-2}$
Cd	10.004	10.006	$3.80 \times 10^{-3}$
Cr	20.797	0.014	$1.03 \times 10^{-2}$
Pb	18.101	5.029	$1.53 \times 10^{-4}$
		$\sum\text{HQ}=\text{HI}=20.617$	$\sum\text{CR}_i=3.94 \times 10^{-2}$

**Table 4** The EDI, HQ, HI and CR values of heavy metals in three edible aquatic plant species (continued)

Heavy metal	EDI ( $\mu\text{g kg}^{-1}\text{d}^{-1}$ )	HQ	CR
<i>I. aquatic</i>			
As	1.727	0.576	$2.59 \times 10^{-3}$
Cd	0.216	0.216	$8.20 \times 10^{-5}$
Cr	4.490	0.003	$2.24 \times 10^{-3}$
Pb	6.298	1.750	$5.35 \times 10^{-5}$
		$\sum\text{HQ}=\text{HI}=2.545$	$\sum\text{CR}_i=4.97 \times 10^{-3}$
<i>M. crenata</i>			
As	1.076	3.58	$1.61 \times 10^{-3}$
Cd	0.401	0.40	$1.52 \times 10^{-4}$
Cr	2.843	0.001	$1.42 \times 10^{-3}$
Pb	4.342	1.20	$3.69 \times 10^{-5}$
		$\sum\text{HQ}=\text{HI}=5.181$	$\sum\text{CR}_i=3.22 \times 10^{-3}$
Unsuitable critical threshold	-	<1	$1 \times 10^{-6}$ - $1 \times 10^{-4}$ [62]

## Conclusions

E-waste open dumpsites are an important source of heavy metal pollution, and heavy metals can be detected in the water, sediment and edible aquatic plants surrounding these areas. In this study, the Pb concentration exceeded the water quality standard. The concentrations of heavy metals in the sediment were within the limits of the quality standard. The highest As, Cr, Cd and Pb concentrations were found in *O. alismoides*, and these values exceeded the quality standard for food consumption. The human health risk assessment found that the EDI, HQ, HI and CR values in the three edible aquatic plant species exceeded the values of the quality standard. The results of this study showed that the study site presents potential non-carcinogenic as well as carcinogenic threats to human health. Local people should avoid consuming aquatic plants growing near the e-waste open dumpsite, especially *O. alismoides*, *I. aquatic* and *M. crenata*. The proper management of e-waste open dumpsites and the proper separation of e-waste components are important to reducing the human health risks related to heavy metal exposure.

## References

- [1] Ramesh, B.B., Parande, A.K., Ahmed, B.C. Electrical and electronic waste: A global environmental problem. *Waste Management & Research*, 2007, 25(4), 307–318.
- [2] Pollution Control Department, Ministry of Natural Resources and Environment. Thailand state of pollution report 2015. PCD. Bangkok, Thailand. 2015. [Online] Available from: [http://www.infofile.pcd.go.th/mgt/PollutionReport2015\\_en.pdf](http://www.infofile.pcd.go.th/mgt/PollutionReport2015_en.pdf) [Accessed 12 January 2020].
- [3] Pollution Control Department, Ministry of Natural Resources and Environment. Thailand state of pollution report 2016. PCD. Bangkok, Thailand. 2016. [Online] Available from: [https://www.stkc.go.th/sites/default/files/flip\\_ebook/catalogs/61\\_05PollutionReport2016/pdf/complete.pdf](https://www.stkc.go.th/sites/default/files/flip_ebook/catalogs/61_05PollutionReport2016/pdf/complete.pdf) [Accessed 9 January 2020].
- [4] Tansel, B. From electronic consumer products to e-wastes: Global outlook, waste quantities, recycling challenges. *Environment International*, 2017, 98, 35–45.
- [5] Thailand Development Research Institute. E-waste management in Thailand. Thailand Development Research Institute, Bangkok,

- Thailand, 2019. [Online] Available from: <https://www.tdri.or.th/2018/04/electronic-waste-management-in-thailand/> [Accessed 20 March 2020].
- [6] Kyere, V.N., Greve, K., Atiemo, S.M., Ephraim, J. Spatial assessment of potential ecological risk of heavy metal in soils from informal e-waste recycling in Ghana. *Environmental Health and Toxicology*, 2017, 32, 1–7.
- [7] Jira, S. Blood lead levels in children aged 0-5 years at Khong Chai district, Kalasin province of Thailand. *Maharakham Hospital Journal*, 2014, 11(2), 6–15.
- [8] Saetang, P., Rojanaprawong, S., Muksuwan, W. A Preliminary survey of impact and solution towards participatory waste management: A case of Khok Sa Ard subdistrict, Khong Chai District, Kalasin Province. Preliminary Report Submitted to Asia Foundation, Thailand, 2009.
- [9] Neeratanaphan, L., Khamma, S., Benchawattananon, R., Ruchuwarak, P., Appamaraka, S., Intamat, S. Heavy metal accumulation in rice (*Oryza sativa*) near electronic waste dumps and related human health risk assessment. *Human Ecological Risk Assessment*, 2017, 23, 1086–1098.
- [10] Thanomsangad, P., Tengjaroenkul, B., Sriuttha, M., Neeratanaphan, L. Heavy metal accumulation in frogs surrounding an e-waste dump site and human health risk assessment. *Human Ecological Risk Assessment*, 2019, 26(5), 1313–1328.
- [11] Caravanos, J., Clark, E., Richard, F.R., Lambertson, C. Assessing worker and environmental chemical exposure risks at an e-waste recycling and disposal site in Accra Ghana. *Journal of Health and Pollution*, 2011, 1, 16–25.
- [12] Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N. Toxicity, mechanism and health effects of some heavy metal. *Interdisciplinary Toxicology*, 2014, 7, 60–72.
- [13] Jarup, L. Hazards of heavy metal contamination. *British Medical Bulletin*, 2003, 68, 167–182.
- [14] Kakker, P., Jaffery, F.N. Biological markers for metals toxicity. *Environmental Toxicology and Pharmacology*, 2005, 19(2), 335–349
- [15] Nordberg, G.F. Biomarkers of exposure, effects and susceptibility in humans and their application in studies of interactions among metals in China. *Toxicology Letters*, 2010, 192(1), 45–49.
- [16] Yourtchi, M.S., Bayat, H.R. Effect of cadmium toxicity on growth, cadmium accumulation and macronutrient content of durum wheat (Dena CV.). *International Journal of Agriculture and Crop Sciences*, 2013, 6(15), 1099–1103.
- [17] Fodor, E., Szabo-Nagy, A., Erdei, L. The effects of cadmium on the fluidity and H<sup>+</sup>-ATPase activity of plasma membrane from sunflower and wheat roots. *The Journal of Plant Physiology*, 1995, 147 (1), 87–92.
- [18] De Filippis, L.F., Ziegler, H. Effect of sublethal concentrations of zinc, cadmium and mercury on the photosynthetic carbon reduction cycle of *Euglena*. *Journal of Plant Physiology*, 1993, 142(2), 167–172.
- [19] Jain, R., Srivastava, S., Madan, V.K. Influence of chromium on growth and cell division of sugarcane. *Indian Journal of Plant Physiology*, 2000, 5, 228–231.
- [20] Morzck, E.J., Funicelli, N.A. Effect of lead and on germination of *Spartina alterniflora* losiel seeds at various salinities. *Environmental and Experimental Botany*, 1982, 22(1), 23–32.
- [21] Reddy, A.M., Kumar, S.G., Jyotsnakumari, G., Thimmanayak, S., Sudhakar, C. Lead induced changes in antioxidant metabolism of horsegram (*Macrotyloma uniflorum*

- (Lam.) Verdc.) and bengalgram (*Cicer arietinum* L.). *Chemosphere*, 2005, 60(1), 97–104.
- [22] Abedin, M.J., Cotter-Howells, J., Meharg, A.A. Arsenic uptake and accumulation in rice (*Oryza sativa* L.) irrigated with contaminated water. *Plant and Soil*, 2002, 240(2), 311–319.
- [23] Gupta, M., Sarin, N.B. Heavy metal induced DNA changes in aquatic macrophytes: Random amplified polymorphic DNA analysis and identification of sequence characterized amplified region marker. *Journal of Environmental Science*, 2009, 21(5), 686–690.
- [24] Shahid, M., Dumat, C., Khalid, S., Schreck, E., Xiong, T., Niazi, N.K. Foliar heavy metals uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. *Journal of Hazardous Materials*, 2017, 325, 36–58.
- [25] Neeratanaphan, L., Sudmoon, R., Chaveerach, A. Assessment of genotoxicity through ISSR marker in *Pistia stratiotes* induced by lead. *Environment Asia*, 2014, 7(2), 99–107.
- [26] Thanee, T., Sudmoon, R., Thamsenapap, P., Chaveerach, A. Effect of cadmium on DNA changes in *Ipomoea aquatica* Forssk. *Polish Journal of Environmental Studies*, 2016, 25(1), 311–315.
- [27] Tao, Y., Yuan, Z., Xiaona, H., Wei, M. Distribution and bioaccumulation of heavy metal in aquatic organisms of different trophic levels and potential health risk assessment from Taihu lake, China. *Ecotoxicology and Environmental Safety*, 2012, 81, 55–64.
- [28] Harguinteguy, C.A., Cirelli, A.F., Pignata, M.L. Heavy metal accumulation in leaves of aquatic plant *Stuckenia filiformis* and its relationship with sediment and water in the Suquia river (Argentina). *Microchemical Journal*, 2014, 114, 111–118.
- [29] Wesley-Smith, J. Freeze-substitution of dehydrated plant tissues: Artefacts of aqueous fixation revisited. *Protoplasma*, 2001, 218(3), 154–167.
- [30] Kularbthong, S., Kanlapaphruek, S., Saiphattana, P. *Ottelia alismoides*: A distinctive vegetation of the Phetchaburi River. *Journal South Technology*, 2013, 6, 69–76.
- [31] Thailand Pollution Control Department (TPCD). Manual of procedures for collecting sediment and water samples from water source. Ministry of Natural Resources and Environment, Thailand, 2010.
- [32] Olafisoye, O.B., Adefioye, T., Osibote, O.A. Heavy metal contamination of water, soil, and plants around an electronic waste dump site. *Polish Journal of Environmental Studies*, 2013, 22(5), 1431–1439.
- [33] Chand, V., Prasad, S. ICP-OES assessment of heavy metal contamination in tropical marine sediments: A comparative study of two digestion techniques. *Microchemical Journal*, 2013, 111, 53–61.
- [34] American Public Health Association (APHA). Standard methods for the examination of water and wastewater. American Public Health Association, Washington DC, USA, 2005.
- [35] Keith, L.H. Compilation of EPA's sampling and analysis methods. 2<sup>nd</sup> Edition. USA: Lewis Publishers, 1998.
- [36] Khamlerd, C., Tengjaroenkul, B., Neeratanaphan, L. Abnormal chromosome assessment of snakehead fish (*Channa striata*) affected by heavy metals from a reservoir near an industrial factory. *International Journal of Environmental Studies*, 2019, 76, 1–15.
- [37] US Environmental Protection Agency (USEPA). Method 6010: Inductive coupled plasma atomic emission spectrometry. US Environmental Protection Agency, Washington DC, USA, 2007.

- [38] Chamannejadian, A., Sayyad, G., Moezzi, A., Jahangiri, A. Evaluation of estimated daily intake (EDI) of cadmium and lead for rice (*Oryza sativa* L.) in calcareous soils. *Journal of Environmental Health Science and Engineering*, 2013, 10(1), 1–5.
- [39] Chonokhuu, S., Batbold, C., Chuluunpurev, B., Battsengel, E., Dorjsuren, B., Byambaa, B. Contamination and health risk assessment of heavy metals in the soil of major cities in Mongolia. *International Journal of Environmental Research and Public Health*, 2019, 16(14), 1–15.
- [40] Cao, S., Duan, X., Zhao, X., Wang, B., Ma, J., Fan, D., ..., Jiang, G. Haassessment of various metal(loid)s via multiple exposure pathways on children living near a typical lead-acid battery plant. *China Environment Pollution*, 2015, 200, 16–23.
- [41] US Environmental Protection Agency (USEPA). Regional screening level (RSL) summary table (TR=1E-06, HQ=1). 2017. [Online] Available from: <https://sempub.epa.gov/work/03/2245059.pdf> [Accessed 21 January 2020].
- [42] Thailand Pollution Control Department (TPCD). Surface water quality standard. Notification of the National Environmental Board; No. 8. Bangkok, 2001.
- [43] Thailand Pollution Control Department (TPCD). Soil quality standards for habitat and agriculture. Notification of the National Environmental Board; in the Royal Gazette on 11 March 2021.
- [44] Huang, L., Rad, S., Xu, L., Gui, L., Song, X., Li, Y., ..., Chen, Z. Heavy metals distribution, sources, and ecological risk assessment in Huixian wetland, South China. *Water*, 2020, 12(2), 1–14.
- [45] Nnorom, I.C., Osibanjo, O. Electronic waste (e-waste): Material flows and management practices in Nigeria. *Waste Management*, 2008, 28(8), 1472–1479.
- [46] Nnorom, I.C., Osibanjo, O., Okechukwu K., Nkwachukwu, O., Chukwuma, R.C. Evaluation of heavy metal release from the disposal of waste computer monitors at an open dump. *International Journal of Environmental Science and Development*, 2010, 1(3), 227–233.
- [47] Wu, Q., Leung, J.Y., Geng, X., Chen, S., Huang, X., Li, H., ..., Lu, Y. Heavy metal contamination of soil and water in the vicinity of an abandoned e-waste recycling site: Implications for dissemination of heavy metal. *Science of the Total Environment*, 2015, 506, 217–225.
- [48] Regional Environment Office 10 of Thailand. Summary report for environmental problems from electrical and electronic products, Khong Chai District, Kalasin Province. Pollution Control Department, Thailand. 2014.
- [49] Vassanadumrongdee, S. The situation of electronic waste problem. *Environmental Journal*, 2015, 19, 1–18.
- [50] Codex Alimentarius Commission. Working document for information and use in discussions related to contaminants and toxins in the GSCTFF. Joint FAO/WHO food standards programme. Codex Committee on Contaminants in Foods. 5<sup>th</sup> Edition. The Hague, The Netherlands, 2011, 21–25.
- [51] Food and Agriculture Organization (FAO). Codex Alimentarius Commission Food Additives and Contaminants, FAO/WHO, Rome, Italy, ALINORM 01/12A, 2001, 1–289.
- [52] Tangahu, B.V., Sheikh Abdullah, S.R., Basri, H., Idris, M., Anuar, N., Mukhlisin, M. A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering*, 2011, 1–32.
- [53] Wenzel, W.W., Unterbrunner, R., Sommer, P., Socco, P. Chelate assisted phytoextraction using canola (*Brassica napus* L.)

- in outdoors pot and lysimeter experiments. *Plant and Soil*, 2003, 249(1), 83–96.
- [54] Suman, J., Uhlík, O., Viktorova, J., Macek, T. Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment. *Frontiers in Plant Science*, 2018, 9, 1476.
- [55] Fritioff, A., Greger, M. Aquatic and terrestrial plant species with potential to remove heavy metals from stormwater. *International Journal of Phytoremediation*, 2003, 5(3), 211–224.
- [56] Putshaka, J.D., Akyengo, O., Yakubu, A., Adejube, A.A.H. Bioaccumulation of heavy metal in fish (*Tilapia zilli*) and bullfrog (*Pyxicephalus edulis*) from river Challawa Kano State Nigeria citation. *International Journal of Systematic and Evolutionary Microbiology*, 2015, 2(4), 30–34.
- [57] US Environmental Protection Agency (USEPA). Risk base concentration table. US Environmental Protection Agency, Washington DC, USA, 2000.
- [58] Pilon-Smits, E.A., Hwang, S., Mel Lytle, C., Zhu, Y., Tai, J.C., Bravo, R.C., Terry, N. Overexpression of ATP sulfurylase in Indian mustard leads to increased selenate uptake, reduction and tolerance. *Plant Physiology*, 1990, 119(1), 123–132.
- [59] Van der Ent, A., Baker, A.J., Reeves, R.D., Pollard, A.J., Schat, H. Hyper-accumulators of metal and metalloid trace elements: facts and fiction. *Plant and Soil*, 2013, 362(1), 319–334.
- [60] Liu, W.J., Wood, B.A., Raab, A., McGrath, S.P., Zhao, F.J., Feldmann, J. Complexation of arsenite with phytochelatin reduces arsenite efflux and translocation from roots to shoots in *Arabidopsis*. *Plant Physiology*, 2010, 152(4), 2211–2221.
- [61] Gao, J., Garrison, A.W., Hoehamer, C., Mazur, C.S., Wolfe, N.L. Uptake and phytotransformation of organophosphorus pesticides by axenically cultivated aquatic plants. *Journal of Agricultural and Food Chemistry*, 2000, 48(12), 6114–6120.
- [62] US Environmental Protection Agency (USEPA). Risk based screening table. Composite Table: Summary Tab 0615, 2015. [Online] Available from: <http://www2.epa.gov/risk/basedscreening-table-generic-tables> [Accessed 12 January 2020].
- [63] US Environmental Protection Agency (USEPA). Risk assessment guidance for superfund (Part E, Part F). EPA. Washington DC, USA, 2011.