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Heavy metal accumulation in rice (*Oryza sativa*) near electronic waste dumps and related human health risk assessment

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ABSTRACT

This research was conducted to assess heavy metal contamination in the environment and within *Oryza sativa*. The translocation factors (TFs) and bioaccumulation factors (BAFs) for heavy metals in *O. sativa* and estimated daily intake (EDI) and health risk index (HRI) were measured. The samples were analyzed for heavy metals using inductively coupled plasma optical emission spectrometry (ICP-OES). Pb and Cr concentrations in water samples within and near the electronic-waste dumping area exceeded water quality standards for surface water sources from the Pollution Control Department in the Ministry of Natural Resources and Environment of Thailand (PCD). The Pb concentration in soil samples within the area also exceeded soil quality standards for habitat and agriculture from PCD. Most of the metals were highly concentrated in roots, except for Mn which has the highest concentration in leaves. Pb concentrations in rice grains exceeded the FAO/WHO standard (0.2 mg/kg). The average TF values for heavy metals from the soil to roots, roots to stems, stems to leaves, and stems to grains were Mn > Pb > Ni > Cr, Mn > Cr > Ni > Pb, Ni > Pb > Mn > Cr, and Pb > Ni > Cr > Mn, respectively. The average BAF values in *O. sativa* were Mn > Ni > Pb > Cr. The EDI for Cr, Pb, Mn, and Ni via *O. sativa* consumption were 6.19, 6.02, 370.57, and 3.80 μg/kg/day, respectively. The HRI for Cr, Pb, Mn, and Ni via *O. sativa* consumption were 0.30, 1.50, 2.60, and 0.002, respectively.

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KEYWORDS
electronic waste; heavy metal; *Oryza sativa*; translocation factor; bioaccumulation factor

Introduction

Electronic waste (E-waste) is a new management problem in many countries, especially in developing countries (Robinson 2009). E-waste is the fastest growing waste stream. The amount of E-waste is expected to grow to 49.8 metric tons (Mt) in 2018, with an annual growth rate of 4–5% (Balde *et al.* 2015). About 40 million tonnes of E-waste is created each year (Schluep *et al.* 2009). It is estimated that the total of global quantity of E-waste generated in 2014 was

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41.8 million Mt. It is forecasted to increase to 50 Mt of E-waste in 2018. This E-waste comprises 1.0 Mt of lamps, 6.3 Mt of screens, 3.0 Mt of small information technology equipment (such as mobile phones, pocket calculators, personal computers, printers), 12.8 Mt of small equipment (such as vacuum cleaners, microwaves, toasters, electric shavers, video cameras), 11.8 Mt of large equipment (such as washing machines, clothes dryers, dishwashers, electric stoves, photovoltaic panels), and 7.0 Mt of cooling and freezing equipment (temperature exchange equipment), (Balde *et al.* 2015). E-waste disposal methods include landfill and incineration, both of which pose considerable contamination risks. Landfill leachates can potentially transport toxic substances into groundwater, while combustion in an incinerator can emit toxic gases into the atmosphere. Recycling of E-waste can also distribute hazardous substances into the environment and may affect human health. While there are more than 1000 toxic substances (Puckett and Smith 2002) associated with E-waste, the more commonly reported substances include: arsenic (As), lead (Pb), cadmium (Cd), hexavalent chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), brominated flame retardants (BFRs), and phthalate esters (Schmidt 2002; Soderstrom and Marklund 2002; Jang and Townsend 2003; Deng *et al.* 2006; Wang and Guo 2006; Wong *et al.* 2007; Ha *et al.* 2009; Tang *et al.* 2010). These metals pose adverse risks to human health regardless of occupational or environmental exposure. The environmental impact of E-waste involves the leaching of hazardous electronic components into the surrounding areas and the proper recycling of these materials (Leung *et al.* 2006; Luo *et al.* 2011).

In Thailand, hazardous waste has recently become a problem. The estimated tonnages of household hazardous waste generated in 2012–2014 were 712,760, 562,834, and 576,316 tons, respectively. These data do not include illegal imports (PCD 2012–2014). The majority of household waste was electrical and electronic equipment. The Khok Sa Ard sub-district of the Khong Chai district in the Kalasin Province of Thailand has the largest open E-waste dumping area in Thailand, and this site has been operating for more than a decade. The majority of local people in this area are working as E-waste segregators. After stripping the device for valuable parts, such as metals and copper, workers deposit the useless device in community dumpsites. The amount of E-waste brought into the Khok Sa Ard sub-district is over 72,000 tonnes per year, and 20,000 tonnes of useless devices are left in the community every year. However, landfills currently employ improper management systems. Garbage, including E-waste, is burned and has resulted in environmental pollution and adverse health effects in people living in surrounding the area. Several studies (Saetang *et al.* 2009) found high Pb (79,520 mg/kg), Ni (75 mg/kg), and Mn (1,519 mg/kg) concentrations in the soil of E-waste dumping areas. Furthermore, a previous study reported that 12 out of 124 children in the Khok Sa Ard sub-district had blood Pb levels exceeding the recommended limits for human health (15 μg/dL), (Jira 2014). In addition to occupational and environmental exposure, food consumption is another source of pollutant exposure. Rice, *Oryza sativa*, is the main crop consumed by the local people. Furthermore, this crop is sold throughout Thailand.

Thus, individuals that eat rice regularly are at risk of heavy metal exposure. The remaining parts of the rice plant are often used to feed animals. The stems and leaves are used to feed buffaloes and cows, and the bran is used to feed pigs. Moreover, rice husks are used as fertilizer. Thus, animals and certain vegetables are also at risk of heavy metal exposure and contamination. Exposure to heavy metals can cause a variety of adverse health effects, such as genotoxic, mutagenic, and carcinogenic illnesses, in multiple body systems, including dermal, respiratory, cardiovascular, gastrointestinal, urinary, hepatic, reproductive, and central nervous systems (Godt *et al.* 2006; Duruibe *et al.* 2007; Nordberg 2010).

In this study, we examined heavy metal contamination in the environment and within *O. sativa*, and measured the TFs and bioaccumulation factors (BAFs) for heavy metals in *O. sativa* and the estimated daily intake (EDI) and health risk index (HRI). The samples were collected within and near open E-waste dumping areas in the Khong Chai district of the Kalasin Province of Thailand. These data should be used for future improvements in the environmental management of E-waste.

Methods and materials

Study site

The study site is located in the Khong Chai district of the Kalasin Province in Thailand, from latitude N16.31364°–N16.313636° and longitude E103.42443°–E103.42572°. E-waste dump site was located in former rice field. The amount of E-waste is loaded over 72,000 tonnes per year. The main E-waste includes television and personal computer displays, refrigerators and washing machines. The E-waste was improperly separated in household. Then E-waste was deposited and burnt in community dumping area. The rice field was located near an open E-waste dumping area (Figure 1). The majority of the land near the E-waste area is used for planting crops, such as rice and cassavas.

Sample collection

Random sampling was carried out in this study. Fifteen water and soil samples near the open E-waste dumping site (around 100 m) were collected surrounding *O. sativa* samples. While within the open E-waste dumping site, nine water samples were collected since the area of the pond is small.

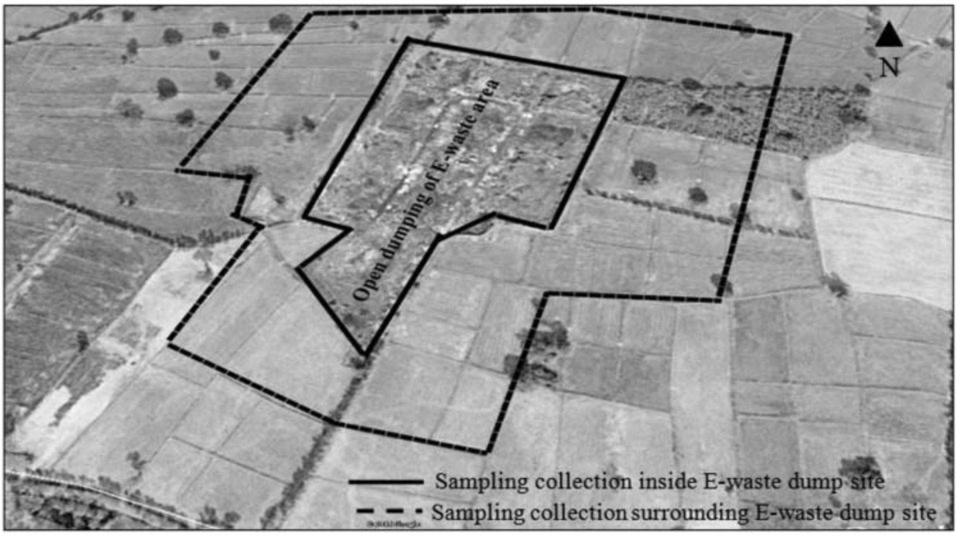

Figure 1. The E-waste dump site and the locations of the sampling collection sites are shown by the bounded areas.

Water sample collection

Water samples from the leachate pond within the E-waste dumping area and surrounding the *O. sativa* samples from the rice field were collected in glass bottle samplers that were previously washed and rinsed with deionized water. Water samples were taken with the bottle's mouth facing directly into the flow of the stream water. For the subsequent analysis of the metal content, the samples were immediately acidified by adding concentrated nitric acid until the pH was less than 2. The filled sample bottles were labeled according to the sampling point and time. The samples were stored in a cool box and transported to the laboratory for metal analyses.

Soil sample collection

The soil samples within the E-waste area and surrounding the roots of the *O. sativa* plants from the rice field were collected using a Ponar Grab sampler at a depth of 15 cm from the soil surface (Machiwa 2010). Sampling errors associated with the heterogeneous characteristic of heavy metal concentrations in soils were minimized by collecting five soil cores combined as a single composite sample. The soil samples were dried in the open air, crushed by hand in a porcelain mortar, and then sifted through a 2-mm screen. Soil samples ($<$2 mm) were stored in polyethylene bags for metal analyses.

O. sativa *plant sample collection*

Each plant sample was uprooted together with its roots, stems, leaves, and grains. Next, the samples were washed with deionized water to remove impurities and separated into the following 4 parts: roots, stems, leaves, and grains. Each part was cut to smaller pieces for easier digestion. The grains were finely ground using a mortar and pestle to separate the rice from its husk and then dried in an oven at 70°C for 24 h. Samples were stored in polyethylene bags for metal analyses.

Sample preparation and analysis

Water sample preparation and analysis

Each water sample (25 mL) was poured into a beaker. Next, 1.25 mL of nitric acid was added, and the beaker was covered with a watch glass. The beaker was then placed in a water bath at 90 ± 5°C for 30 min. After cooling, the digested samples were adjusted to a final volume of 25 mL with deionized water. The final suspended mixture was filtered using 11-μm standard quantitative cellulose paper. The samples were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES) (Chand and Prasad 2013).

Soil sample preparation and analysis

To determine the total concentrations of heavy metals in the soil, the dry samples were digested using EPA method 6010 (USEPA, 2007). After the dry samples were ground into fine powder, they were sifted through a 0.2-mm sieve and thoroughly homogenized. One gram of the sample was sequentially digested with 5 mL of HNO_3, 15 mL of HCl, and 10 mL of H_2O_2. Next, the sample was heated in a water bath for 2 h at a range of 180–220°C. After cooling, the digested samples were adjusted to a volume of 50 mL with deionized water. The final suspended mixture was filtered through 2.5 μm ashless quantitative cellulose filter paper. The soil samples were analyzed using ICP-OES (Chand and Prasad 2013).

O. sativa plant sample preparation and analysis

One gram of dried root, stem, leaf and grain samples from *O. sativa* were placed into a 50-mL conical flask. Each part of the *O. sativa* was digested by with the sequential addition of 7 mL of nitric acid and 1 mL of hydrogen peroxide. The samples were heated in a water bath for 2 h at 90 ± 5°C. After cooling, the digested samples were adjusted with deionized water to a final volume of 25 mL. The final suspended mixture was filtered through 2.5-μm standard quantitative cellulose filter paper. The plant samples were analyzed using ICP-OES (Chand and Prasad 2013). The detection limits of each element analyzed were Cr and Ni: 0.001 mg/L, Pb: 0.005 mg/L, and Mn: 0.002 mg/L. The ICP-OES wavelength analyses for Cr, Pb, Ni, and Mn were set to 267.716, 220.353, 324.752, and 259.327 nm, respectively.

Quality control and quality assurance

Blanks and quality control standards were measured at every tenth samples to detect contamination and drift. The elemental concentrations of procedural blanks were generally $< 5\%$ of the mean analyzed concentrations for all the metals. Precision and accuracy of analyses were also ensured through replicate analyses of samples against standards reference material for all the heavy metals. The results were found to be within ± 2% of certified values, thus demonstrating the accuracy of our findings.

Translocation factors (TF) of heavy metals in *O. sativa*

The TF was calculated for each metal according to the formula $\text{TF} = \text{Cs (mg/kg)}/\text{Cr (mg/kg)}$, where Cs is the heavy metal concentration in soil, root, and stem and Cr is the heavy metal concentration in root, stem, and leaves (Lokeshwari and Chamdrappa 2006).

Bioaccumulation factors (BAF) of heavy metals in *O. sativa*

Heavy metal concentrations in soil and sticky rice samples were calculated based on their dry weight. The bioaccumulation factor (BAF), an index of the ability of the vegetable to accumulate a particular metal with respect to its concentration in the soil, was calculated with the following formula: $\text{BAF} = C_{\text{grains}}/C_{\text{soil}}$, where C_{grains} and C_{soil} represent the heavy metal concentration in the grains of the rice and the soil, respectively (Abdul and Thomas 2009).

Potential health risks of heavy metals via *O. sativa* consumption

Estimated daily intake (EDI) of heavy metals via *O. sativa* consumption

The EDI of metals depends on the metal concentration in the food and amount of the food consumed daily. In addition, the body weight of the subject can influence the tolerance to pollutants. The EDI is a concept introduced to take these factors into account. The EDI was calculated with the following formula (Fu *et al.* 2008):

$$\text{EDI} = \frac{\text{C} \times \text{Con}}{\text{BW}}$$

where C (mg/kg) is the heavy metal concentration in *O. sativa*, Con (kg/day) is the average daily consumption of *O. sativa* in the region (0.372 kg/day); and BW (kg/person) is the average body weight of people in the region (65.45 kg).

Health risk index (HRI) for heavy metals via O. sativa *consumption*

In this study, the HRI associated with *O. sativa* consumption was defined as the ratio of the EDI of metals to the oral reference dose (RfDo) for each metal. The oral reference doses were 0.004, 0.02, 0.14, and 1.5 mg/kg/day for Pb, Ni, Mn, and Cr, respectively (USEPA 1997). The HRI was calculated with the following formula (USEPA 2000):

$$\mathrm{HRI} = \frac{\mathrm{EDI}}{\mathrm{RfDo}}$$

Data analysis

STATA version 11.0 software was used to describe the concentration of heavy metals in the environment and within *O. sativa*. We also determined the TF, BAF, EDI, and HRI, including the percentage, mean, standard deviation, and 95th percentiles. The concentrations of water and soil samples within and near the E-waste dump site were analyzed using a Mann–Whitney U-test. All of the statistical tests were conducted using a 95% confidence level.

Results

Heavy metal concentrations in water and soil samples

The heavy metal concentrations in water samples are shown in Table 1. The relative order of the average concentrations of heavy metals in the water samples within and near the E-waste dump site were Mn > Ni > Pb > Cr and Mn > Pb > Ni > Cr, respectively. The heavy metal concentrations in soil samples are shown in Table 2. The relative order of the average concentrations of heavy metals in the soil samples within and near the E-waste dump site were Pb > Mn > Ni > Cr and Mn > Cr > Pb > Ni, respectively.

Heavy metal concentrations in different parts of the O. sativa *plant*

The mean concentrations of heavy metals in *O. sativa* in this study showed that all metals were present in all parts of the *O. sativa* at different levels as shown in Table 3. Most of the metals were highly concentrated in roots, except for Mn which has the highest concentration in leaves. Concentrations of Pb in rice grains exceeded FAO/WHO (1972) permissible limits for human consumption.

Table 1. Heavy metal concentrations in water samples within and near the E-waste dump site.

Heavy metals	Water samples within the E-waste area (mg/L) (N = 9)	Water samples near the E-waste area (mg/L) (N = 15)	Standard[a]	*p*-value	Detection limit (mg/L)
Cr	0.31 ± 0.02	0.10 ± 0.01	0.005	0.01	0.001
Pb	0.59 ± 0.01	0.34 ± 0.05	0.05	0.04	0.05
Mn	18.25 ± 0.23	4.85 ± 0.61	—	0.01	0.002
Ni	1.44 ± 0.12	0.21 ± 0.03	—	0.003	0.001

[a] Water quality standards for surface water sources from the Pollution Control Department in the Ministry of Natural Resources and Environment of Thailand (PCD 1994).

Table 2. Heavy metal concentrations in soil samples within and near the E-waste dump site.

Heavy metals	Soil samples within the E-waste area (mg/kg, dry weight) (N = 15)	Soil samples near the E-waste area (mg/kg, dry weight) (N = 15)	Standard[b]	*p*-value	Detection limit (mg/L)
Cr	18.97 ± 1.92	11.98 ± 1.65	300	0.45	0.001
Pb	577.68 ± 1.60	6.81 ± 0.10	400	<0.001	0.05
Mn	70.56 ± 1.36	41.13 ± 1.57	1800	0.01	0.002
Ni	35.41 ± 1.91	2.42 ± 0.31	1600	<0.001	0.001

[b] Soil quality standards for habitat and agriculture from the Pollution Control Department in the Ministry of Natural Resources and Environment of Thailand (PCD 2004)

The TF for heavy metals in **O. sativa**

The TF values for Cr, Pb, Mn, and Ni from the soil to roots, roots to stems, stems to leaves, and stems to grains are shown in Table 4. The relative average TF values of the heavy metals from the soil to roots were Mn (2.76 ± 1.68). The relative average TF values of heavy metals from roots to stems were Mn (3.80 ± 2.24). The relative average TF values of heavy metals from stems to leaves were Ni (4.58 ± 0.29). The relative order of the average translocation values of heavy metals from stems to grains was Pb (1.67 ± 0.67) > Ni (1.32 ± 0.67) > Cr (1.14 ± 1.01) > Mn (0.22 ± 0.07).

The BAF for heavy metals in **O. sativa**

The mean BAF values for Cr, Pb, Mn, and Ni are shown in Table 5. The mean BAF values for Cr, Pb, Mn, and Ni were 0.10 ± 0.06, 0.23 ± 0.20, 1.88 ± 1.03, and 0.34 ± 0.19, respectively. The relative order of the average of the BAFs was Mn > Ni > Pb > Cr.

Potential health risks from heavy metal exposure via **O. sativa** *consumption*

The EDI and HRI values for heavy metal exposure via *O. sativa* consumption are shown in Table 6. The EDI for Cr, Pb, Mn, and Ni via *O. sativa* consumption were 6.19, 6.02, 370.57, and 3.80 μg/kg/day, respectively. The relative order of the EDI was Mn > Cr > Pb > Ni. The HRIs for Cr, Pb, Mn, and Ni were 0.30, 1.50, 2.60, and 0.002, respectively. The relative order of the HRI was Mn > Pb > Cr > Ni.

Table 3. Mean concentrations (Mean ± SD) of heavy metals in *O. sativa* (dry weight).

Heavy metals/parts of plant (N = 15)	Cr (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Ni (mg/kg)
Roots	3.22 ± 0.26	14.67 ± 0.56	96.72 ± 37.64	2.20 ± 0.52
Stems	1.47 ± 0.89	0.67 ± 0.29	310.72 ± 88.21	0.53 ± 0.20
Leaves	1.74 ± 1.30	2.04 ± 1.08	531.90 ± 155.14	1.85 ± 0.96
Husks	0.95 ± 0.46	1.53 ± 0.95	152.50 ± 36.26	0.63 ± 0.02
Grains	1.09 ± 0.50	1.06 ± 0.50	65.21 ± 12.22	0.67 ± 0.24
Standard[c]	—	0.2	—	—

[c] Maximum for contaminants and toxins in food (FAO/WHO 1972)

Table 4. Mean TF values (Mean ± SD) (N = 15) from soil to roots, roots to stems, stems to leaves, and stems to grains in *O. sativa*.

	Translocation factors			
Heavy metals	soil to roots	roots to stems	stems to leaves	stems to grains
Cr	0.28 ± 0.10	0.49 ± 0.36	1.40 ± 0.92	1.14 ± 1.01
Pb	2.10 ± 1.97	0.11 ± 0.10	3.23 ± 1.50	1.67 ± 0.67
Mn	2.76 ± 1.68	3.80 ± 2.24	1.90 ± 0.89	0.22 ± 0.07
Ni	1.09 ± 0.55	0.25 ± 0.09	4.58 ± 0.29	1.32 ± 0.67

Discussion

Heavy metal concentrations in water and soil samples

The relative order of the average concentrations of heavy metals in water samples was Mn > Pb > Ni > Cr. The Cr and Pb concentrations exceeded water quality standards for surface water sources from the pollution control department (PCD) in the Ministry of Natural Resources and Environment of Thailand (PCD), (PCD 1994). The highest concentration was Mn (4.85 ± 0.61 mg/L), followed by Pb (0.34 ± 0.05 mg/L). Pb is a toxic metal. The major source of Pb in this study came from computer monitors. For disposal, the computer monitors were crushed. Thus, the particulate matter from the neck glass of colored cathode ray tubes contains about 30% Pb by mass; while panel glass, funnel glass, and frit glass, which contain approximately 0–3%, 24%, and 70% Pb by mass, respectively, was released into the environment (Lee *et al.* 2000; Nnorom and Osibanjo 2008; Nnorom *et al.* 2010). Rain runoff is the probable mechanism for heavy metal contamination in water sources. The Cr, Pb, Mn, and Ni concentrations in water samples from within the E-waste dump site were significantly higher than those in the water samples collected near the E-waste dump site ($p = 0.01$, 0.04, 0.01 and 0.003, respectively). E-waste dump sites can release heavy metals that are toxic to aquatic life and plants, especially Pb, into the water supply, which can affect the food chain and ecosystem (Luo *et al.* 2011). Local communities tend to be affected directly and/or indirectly by heavy metals. Rice fields near the E-waste dump site use the contaminated water for gardening, which results in the accumulation of heavy metals in the rice crop. Furthermore, heavy metals in water can condense into the sediment, resulting in high concentrations.

The heavy metals present in the soil surrounding the E-waste dump site is a major concern because rice is grown near this site. The relative order of the average heavy metal concentration in the soil samples near the E-waste dump site was Mn > Cr > Pb > Ni. All heavy metal concentrations were within soil standard for habitat and agriculture from the PCD (PCD 2004). The relative order of the average heavy metal concentration in the soil samples within the E-waste dump site was Pb > Mn>Ni > Cr. The Pb, Mn, and Ni concentrations within the E-waste dump site were significantly higher than those in the soil samples

Table 5. Mean BAF values (Mean ± SD) in *O. sativa*.

Heavy metals	Bioaccumulation factor
Cr	0.10 ± 0.06
Pb	0.23 ± 0.20
Mn	1.88 ± 1.03
Ni	0.34 ± 0.19

Table 6. The EDI and HRI of heavy metals via *O. sativa* consumption.

Heavy metal	EDI (μg/kg/day)	HRI	RfDo* (mg/kg/day)
Cr	6.19	0.30	0.02
Pb	6.02	1.50	0.004
Mn	370.57	2.60	0.14
Ni	3.80	0.002	1.50

*USEPA 1997.

surrounding the dump site (p-value = < 0.001, 0.01, and < 0.001, respectively). These results may explain the heavy metal translocation to the rice crop. The rice plant has a high potential for phytoremediation of heavy metals from the soil (Abedin *et al.* 2002; Du *et al.* 2005). There are no plants within the E-waste dump site. The major E-waste in this study included computer monitors and television displays, which contain mainly Pb. Nnorom *et al.* (2010) reported that the total Pb concentration (mg/kg) in the cathode ray tubes, plastic, and printed writing boards of computer monitors ranged 645–2,892 mg/kg (mean: 1,271 ± 918), 11.1–117 mg/kg (mean: 45.6 ± 44.2), and 3,860–4,581 mg/kg (mean: 4,129 ± 290), respectively. The heavy metals released into the rice field from the E-waste dump site resulted in the contamination of the water, soil, and *O. sativa*.

Heavy metal concentrations in different parts of the O. sativa *plant*

In this study, the mean heavy metal concentrations showed that all metals were present at different levels in all parts of the *O. sativa* plant. Most of the metals were concentrated in the roots, except for Mn which had the highest concentration in the leaves. The Pb concentrations in the grain and husk of the plant exceeded the FAO/WHO permissible limits (0.2 mg/kg) for human consumption (FAO/WHO 1972). In this study, the highest Mn concentration was found in the leaves. Mn is used in plants as a major contributor to various biological systems, including photosynthesis, and this metal aids in chlorophyll synthesis and nitrate assimilation. Mn also plays a role in chlorophyll production, and its presence is essential in photosystem II (Millaleo *et al.* 2010). Even through Mn is an essential element, excessive Mn concentrations in plant tissues can alter various processes, such as enzyme activity, absorption, translocation, and utilization of other minerals (Ducic and Polle 2005; Lei *et al.* 2007). The high levels of heavy metal in the *O. sativa* plant increase the risk of heavy metal exposure to livestock, birds, and humans. Sticky rice is consumed by humans and birds, and the rice husk is consumed by livestock. The results of this study indicate that Pb contamination in grains is a major problem. The reasons for higher Pb contents in rice are complex. The high levels of Pb in *O. sativa* are mostly due to high Pb concentrations in soil. Moreover, heavy metals showed differential accumulation in the various parts of the *O. sativa* plant. The subcellular distribution of heavy metals in plant tissue and its relationship with phytotoxicology has recently attracted a great deal of attention, and the distribution may play an important role in the transfer of metals to plants (Geffard *et al.* 2010).

The TF for heavy metals in O. sativa

The translocation factor is one of the key components of human and animal exposure to metals through the food chain (Lokeshwari and Chamdrappa 2006). In this study, the metals with the highest TF values from the soil to roots, roots to stems, stems to leaves, and stems to grains were Mn, Mn, Ni, and Pb, respectively. Pb, Mn, and Ni had a TF value from the soil to roots that was greater than 1. Mn had a TF value from the roots to stems that was greater than 1, and the TF value from the stems to leaves and stems to grains of all heavy metals except Mn was greater than 1. These results indicate that *O. sativa* hyperaccumulated Cr, Pb, and Ni from the stems to grains. Thus, rice consumption should be concerned in public health risk management. The TF value of Pb in this study (0.11–3.23) was higher than that in previous study (0.29) (Payus *et al.* 2015). The results of this study show that heavy metals concentration in soil samples. The root plants exudates to stabilize, demobilize, and bind the contaminants in the soil matrix, thereby reducing their bioavailability. Certain plant species are capable of removing heavy metals from the soil and ground water through absorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone (Prasad and De Oliverira Freitas 2003). The metal translocation process in *O. sativa* is a crucial factor for determining the relative metal concentrations in different parts of the *O. sativa* plant.

The BAF for heavy metals in O. sativa

BAF are used to determine the degree of intake and storage areas for toxic compounds in plants and animals. The relative order of the BAF for the heavy metals was Mn > Ni > Pb > Cr. The results of this study are similar to those reported by Majid *et al.* (2014). Majid *et al.* found that Mn had the highest BAF value in *Typha angustifolia* and *Phragmites australis*. In this study, we found that only the BAF of Mn was greater than 1, indicating that *O. sativa* accumulates Mn more than other heavy metals. Accordingly, Mn showed the highest TF value and concentration in *O. sativa*.

The potential health risks from heavy metal exposure via O. sativa *consumption*

To assess the potential health risks associated with the heavy metal contamination of *O. sativa* grown near the E-waste dump site, the EDI and HRI were calculated. Rice consumption has been identified as one of the major sources of human exposure to toxic heavy metals due to its accumulation in rice grains (Sapathy *et al.* 2014). The EDIs of heavy metals in this study were higher than those in a previously published study (Huang *et al.* 2005). This study show that the local inhabitants who consume *O. sativa* are likely exposed to heavy metal contamination. The HRIs of Pb and Mn were greater than 1; however, Mn is an essential micronutrient. The result of this study is in accordance with the study by Fu *et al.* (2008) and Huang *et al.* (2009) who found that Pb had the highest EDI value (3.70 and 1.20) in rice (*Oryza sativa* L.) from a typical E-waste recycling area in Taizhou and Changshu city of China. Furthermore, Sapathy *et al.* (2014) found that Pb had the highest HRI value (3.25) in *O. sativa* grown near the E-waste dump site. Notably, Pb was also the major contaminant of *O. sativa* in this study. If consumed, Pb can enter the human body. Jira (2014) reported that children living in a village near the E-waste dump site in Khong Chai district of the Kalasin Province in Thailand had blood Pb levels that exceeded the recommended limits for human health (<15 μg/dL). In China, Huo *et al.* (2007) reported that children living in Guiyu (E-waste recycling town) had significantly higher blood Pb levels when compared with controls. Thus, people near E-waste sites may be at risk for exposure to several toxic heavy metals. Food consumption is the major source of heavy metal exposure in the general population (Bjermo *et al.* 2013; Lye *et al.* 2013; Srathonghon *et al.* 2016). Not only ingestion but also direct exposure since E-waste separators do dismantle and separation by using their bare hand without any personal protective equipment and improper methods which lead to hazard substance emission to environment and harm to their health. Exposure to heavy metals adversely affects multiple organ systems, including the nervous, hematopoietic, renal, endocrine, and reproductive systems (Jarup 2003; Kakkar and Jaffery 2004). With regard to import or illegal transmigration of E-waste from developed country to Thailand, the laws are either not sufficient to handle E-waste purposefully or have been left loose so that piling E-waste can find easy access to Thailand. The method to solving this problem is ban or restriction of import or illegal transboundary migration of E-waste, but it seems less likely since it will be difficult and costly to implement and might destroy a potentially beneficial source of income for local people who depend on these activities. Efforts for finding ways to address the root causes behind the imports and the illegal recycling sector may be concerned.

Conclusion

The improper management of E-waste dump sites has resulted in the release of large amounts of heavy metals in the local environment, including the surrounding soil and water. The *O. sativa* grown near an E-waste dump site was found to be contaminated by heavy metals, especially Pb. This contamination is a potential health concern for local residents. The Pb concentration in the rice grains exceeded the maximum permissible value. In addition, the HRI value of Pb was greater than 1, which indicates that the local inhabitants may experience future adverse health effects. Heavy metal contamination from E-waste dump sites needs to be better regulated, and increased public awareness is needed to reduce the risks to human health.

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