

# Human health risk assessment based on trace metals in suspended air particulates, surface dust, and floor dust from e-waste recycling workshops in Hong Kong, China

Winifred Ka Yan Lau · Peng Liang · Yu Bon Man ·  
Shan Shan Chung · Ming Hung Wong

Received: 14 August 2013 / Accepted: 13 November 2013 / Published online: 28 November 2013  
© Springer-Verlag Berlin Heidelberg 2013

**Abstract** This study investigated health risks exerted on electronic waste (e-waste) recycling workers exposed to cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), mercury (Hg), and zinc (Zn) in Hong Kong. E-waste recycling workshops were classified into eight working areas: 1=office, 2=repair, 3=dismantling, 4=storage, 5=desoldering, 6=loading, 7=cable shredding, and 8=chemical waste. The aforementioned metal concentrations were analyzed in suspended air particulates, surface dust and floor dust collected from the above study areas in five workshops. Elevated Pb levels were measured in dismantling and desoldering areas (582 and 486  $\mu\text{g}/100 \text{ cm}^2$  in surface and 3,610 and 19,172 mg/kg in floor dust, respectively). Blood lead levels of 10 and 39.5  $\mu\text{g}/\text{dl}$  were estimated using United States Environmental Protection Agency's Adult Lead Model as a result of exposure to the floor dust from these two areas. Human health risk assessments were conducted to evaluate cancer and noncancer risks resulting from exposure to floor dust through the combined pathways of ingestion, dermal contact, and inhalation. Findings indicated that workers may be exposed to cancer risks above the acceptable range at 147 in a million at the 95th percentile in the dismantling area. Workers should be informed of associated risks to safeguard their health.

**Keywords** Electronic waste · Trace metal · Dust · Risk assessment · Occupational safety and health · Hong Kong

## Introduction

The electronic waste (e-waste) stream is very heterogeneous as there are multitudes of design and materials used for each type of electrical and electronic equipment (EEE) available on the market (Huisman et al. 2012). While over 1,000 different chemicals can be found in e-waste, some being toxic, metals are thought to comprise over 60.2 % of materials used in EEE (Widmer et al. 2005). Table 1 provides a summary of the toxic trace metals commonly found in e-waste components. Out of all e-waste components of concern, cathode ray tubes (CRTs) contain the greatest amount of trace metals, with 1–3 kg of lead (Pb) (Tsydenova and Bengtsson 2011). In contrast, printed circuit boards (PCBs) contain about 16 % copper, 4 % solder, and 2 % nickel along with other precious metals such as gold and palladium (Ogilvie 2004). Owing to their widespread uses, trace metal contaminants have been found in suspended air particulates and surface dust collected from e-waste recycling workshops (Leung et al. 2008; Bi et al. 2011; Xue et al. 2012). Exposure to metallic dust is one of the most significant health hazards in e-waste recycling. Fine dust may be created from loading or unloading of equipment, shredders, or from manual dismantling processes in e-waste recycling workshops (California Department of Public Health 2012). Brigden et al. (2005) collected dust samples from the floor of e-waste recycling workshops undergoing manual PCB separation and solder recovery in Guiyu and found Pb concentrations (31,300–76,000 mg/kg) hundreds of times higher than typical levels in indoor dusts. Leung et al. (2008) investigated the trace metal concentrations in surface dust from e-waste recycling workshops of Guiyu. Results indicated that Pb

Responsible editor: Gerhard Lammel

**Electronic supplementary material** The online version of this article (doi:10.1007/s11356-013-2372-8) contains supplementary material, which is available to authorized users.

W. K. Y. Lau · P. Liang · Y. B. Man · S. S. Chung (✉) ·  
M. H. Wong (✉)  
Croucher Institute for Environmental Sciences and Department of  
Biology, Hong Kong Baptist University, Hong Kong, People's  
Republic of China  
e-mail: sschung@hkbu.edu.hk  
e-mail: mhwong@hkbu.edu.hk

**Table 1** Overview of trace metals commonly found in e-waste (Ogilvie 2004; EMPA 2009; Li et al. 2011a; Tsydenova and Bengtsson 2011)

Substance	Occurrence in e-waste
Arsenic	Light emitting diodes
Barium	CRT (in electron gun getter)
Beryllium	PCB connectors
Cadmium	Rechargeable batteries (Ni-Cd), CRT (in phosphors), contacts and switches on PCBs, stabilizers in PVC (PVC is ubiquitously used as insulation coating on wires and cables), printer inks and toners
Chromium VI	Data tapes, floppy disks, additives in plastic-like pigments
Copper	Wires, PCBs
Lead	Rechargeable batteries (lead acid batteries—most commonly used in portable devices), CRT (in cone glass), solders on PCBs, wiring
Lithium	Rechargeable batteries (commonly used in portable devices)
Mercury	Relays and switches, batteries, gas discharge lamps (widely used in lighting LCD displays), capacitors, light emitting diodes attached to PCBs, thermostat
Nickel	Rechargeable batteries (Ni-Cd and NiMeH), CRT (electron gun), PCBs
Zinc	CRT (in panel), additives in plastics

levels detected ranged from 22,900 to 206,000 mg/kg which exceeded the Dutch Intervention Values for soil by 43–389 times and Cu and Zn were 6–188 and 1.4–14 times higher than the Dutch Intervention Values respectively. Similarly, Wang et al. (2012) found concentrations of Pb, Zn, and Cu in dust from an enclosed disassembly workshop to be 3,646, 3,485, and 4,050 mg/kg, respectively, levels which were higher than dust collected from the outdoor yard of the workshop.

In Hong Kong, formal and informal e-waste recycling sectors co-exist. Formal e-waste recyclers are generally regarded as those who are officially registered with the government and employs recycling methods which are cleaner with higher yields for precious metal extractions (Chatterjee and Kumar 2009). Informal e-waste recyclers, on the other hand, lack proper registration and usually practice basic, primitive recycling methods with minimal regard for the health and safety of humans and the environment (Chi et al. 2011). The Hong Kong government estimated in 2010 that approximately 80 % of locally generated e-wastes were recycled (Environment Bureau 2010).

As an affluent society, significant quantities of e-wastes are generated in Hong Kong each year. Chung et al. (2011) estimated that Hong Kong households produce approximately 80,000 tons of televisions, washing machines, air conditioners, refrigerators, and personal computers (TWARC) wastes each year. TWARC wastes from the commercial sector or foreign imports that are stored and processed within the city

were not included. Illegal transboundary shipments of e-waste from overseas countries have also been found to pass through Hong Kong before being re-exported into China (CBS News 2008; Ni and Zeng 2009) and large amounts of e-waste were discovered to be stored in open-air facilities in the northern New Territories (Lam 2001). Given that the majority of local e-wastes are handled through the informal sector (Environment Bureau 2010) where the bulk of the recycling takes place outside Hong Kong (Lau et al. 2013) and very little is known about the formal workshops, a knowledge gap exists in the current types of processes used for treatment and their potential impacts to human health and the environment.

Since there is a large amount of e-waste being handled in Hong Kong in both formal and informal workshops, there is an urgent need to understand and improve the current system to make it more sustainable. This is the first systematic study focused on local e-waste processes and estimation of associated risks. It is hypothesized that workers are exposed to trace metals in dust resulting from current e-waste recycling practices in Hong Kong at concentrations which may adversely affect their health. In this regard, the major objectives of this paper are to (1) investigate the extent of trace metal (Cd, Cr, Cu, Pb, Ni, Hg, and Zn) contamination of suspended air particulates, surface dust and floor dust associated with the eight work areas within formal e-waste recycling workshops and (2) estimate potential health risks to e-waste recycling workers as a result of exposure.

## Methodology

### Description of sampling sites

Samples were collected from four major formal e-waste recycling workshops and one informal e-waste recycling workshop in Hong Kong. Formal e-waste recycling workshops are believed to be the dominant e-waste processors in Hong Kong. The following eight individual working areas were collectively identified from the sampling sites: 1=office, 2=repair, 3=dismantling, 4=storage, 5=desoldering, 6=loading, 7=cable shredding, and 8=chemical waste. Description of each working area is summarized in Electronic supplementary material (ESM) Table S1. Suspended air particulates, surface dust and floor dust were collected from individual work areas to reflect emissions from each respective work activities.

In contrast, very limited information is available on the processes that occur in informal e-waste recycling workshops, most of which are believed to act as open storage sites for in-transit e-wastes with very limited treatment capabilities, if any. In general, the two major work processes adopted are loading and storage of e-wastes. As samples were collected from only one informal e-waste recycling workshop, the data obtained

can only serve as a crude comparison to the data obtained from the formal e-waste recycling workshops. Identical samples were also collected from a newly constructed workshop in the New Territories with no prior activities as control.

#### Sample collection and preparation

Deposited floor dust samples were collected using a plastic whisk broom and dustpan, stored in pretreated paper bags (heated at 50 °C overnight to remove volatiles) and placed in sealable polyethylene bags to be taken back to the laboratory. After each sampling, the broom and dustpan were thoroughly cleaned with paper towels. Sample locations consisted of both indoor and outdoor sites and were within a 2 m radius from work benches or areas. At the laboratory, dusts from each location were homogenized using a mechanical shaker with a stainless steel sieve (<100 µm), rid of any foreign objects and stored at -20 °C until chemical analyses.

Air samples were collected using active air samplers (XQC-15E, Jiangsu Eltong Electric Corp., China) according to The National Institute for Occupational Safety and Health (NIOSH) method 7301 with slight modifications (NIOSH 2003a). Each sampler contained a quartz filter (32 mm diameter, 21038, Supelco) to collect airborne particles at a flow rate of approximately 1.5 L/min. Samplers were placed on or near a worker's bench for 24 h (three consecutive working shifts). Flow rates of the air samplers were calibrated before and after each sampling with a calibrated flowmeter. Temperature, air pressure, and relative humidity at the sampling sites were recorded. Before and after each sampling, filters were conditioned at 25 °C and 40 % relative humidity in a desiccator for at least 48 h and then weighed on an electronic balance ( $\pm 0.00001$  precision, Shimadzu, Japan). Particle concentration was calculated as the change in weight of the filter pre- and postsampling divided by the volume of air passed through the sampler. After final weighing, the filters were individually wrapped in aluminum foil and stored at -20 °C until chemical analyses. Field blanks consisted of a filter treated identically to those used for sampling except no air was aspirated through them.

The informal e-waste recycling workshop and the workshop with the desoldering process did not permit air samples to be taken. In addition, safety concerns restricted sampling in loading areas, therefore no air sampling results were obtained from the informal workshop, desoldering, and loading areas.

Wipe sampling is regarded as a fast and simple method for determining contaminants present in the surface environment. The Ghost Wipes™ brand (Environmental Express, Mount Pleasant, SC, USA) was used in this study because it meets all criteria listed in the American Society for Testing and Materials method E 1792 for Pb and has been demonstrated by McDonald et al. (2011) to be suitable for additional

elements namely, As, Cd, Cr, Cu, Ni, and Sb as they contain very low background concentrations of the elements. However, consistent with the findings of McDonald et al. (2011), high background levels of Zn was found in blank wipes and therefore, results of this element will not be reported. Sampling was done as prescribed by NIOSH method 9102 (NIOSH 2003b) on smooth work surfaces using a 100 cm<sup>2</sup> plastic template used to constrain the wipe sampling area. Wipes were frozen at -20 °C until chemical analyses. Field blanks were collected at the beginning, middle, and end of each sampling and consisted of unexposed wipes from packaging placed directly into sample containers.

#### Analyses of metals in dust

Floor dust was oven dried at 105 °C overnight. About 0.2 g of sample was digested with 12 ml of mixed acid (conc. HNO<sub>3</sub>/conc. HCl=3:1) at 180 °C using a microwave-assisted digestion method until the reaction was complete. The solution was cooled, filtered, and diluted to 25 ml with Milli-Q water in a pretreated glass volumetric flask. Concentrations of Cd, Cr, Cu, Pb, Ni, and Zn were determined by a flame atomic absorption spectrophotometer (Varian Spectra AA-220FS) while Hg concentrations were detected by measuring about 0.1 g of floor dust into a direct Hg analyzer (Milestone, DMA-80) based on thermal decomposition, amalgamation, and atomic absorption spectrophotometry, following United States Environmental Protection Agency (USEPA) Method 7473 (USEPA 2007). Filter samples (cut into strips) and surface wipes were placed into Teflon tubes and digested with 4 ml mixed acid (conc. HNO<sub>3</sub>/conc. HCl=3:1) using the same microwave-assisted digestion program as the floor dust samples. The solution was cooled, filtered, and diluted to 10 ml using Milli-Q water into pretreated glass volumetric flasks. Concentrations of Cd, Cr, Cu, Pb, Ni, and Zn were determined using a Graphite Tube Atomizer (Varian Spectra AA-220Z).

#### Quality control

All glassware used were previously soaked overnight in HNO<sub>3</sub> (10 %) and rinsed thoroughly with Milli-Q water before use. For every eight air samples that were taken, two field blanks were collected while one to two field blanks were taken for every six wipe samples collected. Floor dusts were digested in triplicates. An average of three replicates of standard reference material (SRM) from the National Institute of Standards and Technology (NIST SRM 2584) Trace Elements in Indoor Dust and analytical blanks were included in every batch of microwave acid digest. The SRM for wipe sampling was prepared by unfolding a Ghost Wipe™ and placing 0.2 g of NIST SRM 2584 onto the center of the wipe. The wipe was then folded inward and handled in the same way as that for the

samples. SRMs were used to calculate the recoveries of all investigated elements which were considered satisfactory and ranged between 81 and 124 % for floor dust, 77 and 111 % for air filters, and 81 and 112 % for surface wipes. Hg concentrations were not measured in air and wipe samples.

#### Human health risk assessment

E-waste recycling workers can be exposed to hazardous chemicals through inadvertent ingestion of dust, dermal absorption of pollutants within floor dust, and inhalation of fugitive floor dust particles. Equations 1 and 2 below were used to estimate the average daily dose (ADD, in milligram element per kilogram weight per day) for exposure to floor dust via the ingestion and dermal contact pathways (USEPA 2011a) while the exposure concentration for exposures to the floor dust via the inhalation pathway was estimated using Eq. 3 (USEPA 2009).

$$ADD_{\text{ingest}} = \frac{C_{\text{dust}} \times \text{IngR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \times \text{CF} \quad (1)$$

where

- $C_{\text{dust}}$  concentration of the contaminant in dust (in milligram per kilogram)  
 IngR ingestion rate of dust (in milligram per day)  
 EF exposure frequency (in days per year)  
 ED exposure duration (in years)  
 BW average body weight (in kilogram)  
 AT averaging time (in days)  
 CF conversion factor ( $10^{-6}$  kg/mg)

$$ADD_{\text{dermal}} = \frac{C_{\text{dust}} \times \text{SA} \times \text{AF} \times \text{ABS} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \times \text{CF} \quad (2)$$

where

- SA surface area of skin that contacts the dust (in square centimeter per day)  
 AF skin adherence factor (in milligram per square centimeter)  
 ABS dermal absorption factor (chemical specific) (unitless)

$$EC = \frac{C_{\text{dust}} \times \text{ET} \times \text{EF} \times \text{ED}}{\text{PEF} \times \text{AT}_i} \times 1,000 \mu\text{g}/\text{mg} \quad (3)$$

where

- EC exposure concentration (in microgram per cubic meter)  
 ET exposure time (in hours per day)

- PEF particulate emission factor= $1.36 \times 10^9$  (in cubic meter per kilogram)  
 $\text{AT}_i$  Averaging time (in hours)

The parameters used in the equation are summated in ESM Table S2. In this study, dust ingestion rate and average body weight for adults were estimated to be 50 mg/day and 60 kg, respectively. The dust ingestion rate of 50 mg/day as the central tendency for soil+dust ingestion in adults (general public) was selected because it incorporated soil and dust from both indoor and outdoor sources and was considered more appropriate as work processes may take place either under covered areas outdoors or indoors with large windows opened in different e-waste recycling workshops. Workers were assumed to be exposed to the dust for 8 h per day, 300 days per year for an average of 25 years. For intake via the dermal pathway, an estimated exposed skin area of 3,300 cm<sup>2</sup> for an adult commercial/industrial receptor assumed to have the head, hands, and forearms exposed; the default skin adherence factor of 0.07 mg/cm<sup>2</sup>/day was used in estimating the human health risk as a result of exposure (USEPA 2004).

Calculated ADDs were subsequently divided by a reference dose (RfD) to yield a noncancer hazard quotient (HQ) for each element and exposure pathway. However, it is assumed that toxic risks are additive if a mixture of hazardous substances is present and calculation of the hazard index (HI), which is equal to the sum of the HQs, can be used to quantify noncarcinogenic risks. There are assumptions that simultaneous subthreshold exposures to a mixture of chemicals may result in adverse health effects and that the magnitude of adverse health effect will be proportional to the HI. When HI>1, there may be concern for potential health effects, otherwise, it is assumed to be negligible (USEPA 1989).

For cancer risk estimations to the floor dust, the lifetime average daily dose (LADD) was calculated according to RAGS (part A; USEPA 1989) as a result of ingestion and dermal contact and RAGS (part F; USEPA 2009) as a result of inhalation using Eqs. 7 and 8, respectively. Toxicity and chemical information used in the risk assessment calculation are provided in ESM Table S3

$$\text{Cancer risk} = \text{LADD} \times \text{SF} \quad (7)$$

where

- SF slope factor

$$\text{Cancer risk} = \text{IUR} \times \text{EC} \quad (8)$$

where

- IUR inhalation unit risk (in microgram per cubic meter)

The equations above could not be used for Pb because no consensus could be established in deriving a RfD for Pb. One method to relate Pb concentrations to human health is by estimating blood lead levels (BLL) of workers. The most current reference BLL for lead-exposed adults set by the Centers for Disease Control and Prevention (CDC) is 10 µg/dl while 5 µg/dl was established as a reference level to identify children with BLL higher than most children's level (CDC 2012, 2013). To fill the immediate need for a scientifically sound method to assess adult lead risks, USEPA developed the Adult Lead Model (ALM), a simple representation of lead biokinetics to predict quasi-steady state BLL among women of child-bearing age with site exposure to contaminated soil in a nonresidential setting. However, the model can also be used as an interim modeling methodology until more sophisticated methodology is available (USEPA 2003).

The basic form of the Adult Lead Model is given by Eq. 9:

$$PbB_{\text{central}} = PbB_0 + \frac{PbS \times BKSF \times IR_S \times AF_S \times EF_S}{AT} \quad (9)$$

where

$PbB_{\text{central}}$	central estimate of BLL in adults (in microgram per deciliter) who are exposed to soil/dust Pb concentration, PbS
$PbB_0$	Typical BLL in adults in microgram per deciliter in the absence of exposures to the site being assessed=1.7 µg/dl
$PbS$	Soil/dust lead concentration (in microgram per gram)
$BKSF$	Biokinetic slope factor relating quasi-steady state increase in $PbB_0$ to average daily Pb uptake=0.4 µg/dl per µg/day
$IR_S$	Intake rate of soil (in gram per day)=0.05 g/day
$AF_S$	Absolute gastrointestinal absorption fraction for ingested lead (unitless)=0.12
$EF_S$	Exposure frequency for contact (in days per year)=300 days/year
$AT$	Averaging time (days)=365 days

### Statistical analyses

All statistical analyses were performed with SPSS (version 17, SPSS, Chicago, IL, USA). All data were tested for goodness of fit to a normal distribution with Kolmogorov–Smirnov's one-sample test. Since all of the data were found to deviate from the normal distribution, the data were log-transformed prior to performing the one-way analysis of variance test. The means of different groups were compared using Duncan's multiple range test. The probability value of  $p < 0.05$  was set as the level for statistical significance.

## Results and discussion

### Trace metal concentrations in suspended air particulates

Trace metal concentrations detected in suspended air particulates are presented in Table 2. In general, air particulates in the dismantling area contained the highest concentrations of Cd (1.59–204 ng/m<sup>3</sup>), Cr (2.50–2,714 ng/m<sup>3</sup>), Pb (67.8–3,415 ng/m<sup>3</sup>), and Ni (46.4–2,717 ng/m<sup>3</sup>) with Pb and Ni concentrations being significantly higher ( $p < 0.05$ ) than the control site. The high metal concentrations detected in dismantling areas are likely attributed to dusty manual dismantling of EEE using hand-held tools. In addition, suspended air particulates from the cable shredding area were found to contain significantly higher ( $p < 0.05$ ) concentrations of Cu and Zn (429 and 8,002 ng/m<sup>3</sup>, respectively) relative to most areas of the workshop. This may be because of the ubiquitous use of Cu and Zn in cables and wires resulting in high dust emissions during shredding.

Trace metal concentrations in the suspended air particulates were compared to Occupational Safety & Health Administration (OSHA)'s permissible exposure limits, the Hong Kong Occupational Exposure Limit, and the NIOSH REL-time-weighted average (TWA) based on 8-h TWA with exposure on a 40 h/week schedule (HKLD 2002; OSHA n.d.). Owing to differences in sampling times (24 h in the present study), the guideline values can only serve as references to results obtained in the present study. Results indicated that concentrations of Cd, Cr, Cu, Pb, and Ni present in sampled suspended air particulates are at levels where occupational exposures resulting in adverse health effects are minimal. With regards to Zn, which concentrations were highest out of all metals tested but no international standards could be identified, OSHA recognizes it as an irritant to the eyes, nose, throat, and skin and can potentially cause acute lung damage (OSHA 1993).

Although the majority of samples in the present study were taken indoors or in semicovered structures and were different from those being taken from the rooftop of a three-story building in Guiyu where open burning of e-wastes and other recycling operations occur in Deng et al. (2006), it was found that Cd, Pb, and Zn concentrations from dismantling areas in the present study were five, two, and four times higher than total suspended particles (particles less than 30–60 µm) concentrations in Guiyu. Ni concentrations from the present study all exceeded those measured in Deng et al. (2006) while Cr and Cu concentrations were all below concentrations measured in the same report. In another study done by Kent et al. (2007) on airborne metal exposures in a formal cellular phone recycling plant in the USA, 8-h personal air samples were collected and analyzed for Al, As, Be, Ca, Cd, Cr, Cu, Fe, Pb, Mg, Mn, Ni, Se, Ag, Na, and Zn. With the exception of Cr which results were comparable, those obtained from personal

**Table 2** Concentration of trace metals in suspended air particulates (in nanogram per cubic meter) measured from formal e-waste recycling workshops in Hong Kong

Location		Cd	Cr	Cu	Pb	Ni	Zn
Office ( <i>n</i> =3)	Mean	5.39±2.41 ab	129±126 ab	44.6±13.5 c	115±66.4 bc	108±97.7 b	401±590 e
	Median	4.58	96.8	45.4	94.7	72.0	84.1
	Min.	2.31	2.96	23.0	10.9	18.8	28.6
	Max.	10.2	363	63.0	211	350	1,892
Repair ( <i>n</i> =5)	Mean	3.80±1.42 b	279±413 ab	54.0±27.4 bc	131±93.8 bc	220±436 ab	458±556 de
	Median	3.71	41.7	42.8	99.4	77.7	169
	Min.	2.35	0.93	26.0	1.74	29.8	32.9
	Max.	6.98	1,450	124	296	1,950	2,130
Dismantling ( <i>n</i> =7)	Mean	38.6±48.3 a	593±919 ab	142±143 b	824±801 a	485±592 a	4,456±5,207 bc
	Median	9.91	148	94.2	741	227	1,698
	Min.	1.59	2.50	23.2	67.8	46.4	39
	Max.	204	2,714	644	3,415	2,717	18,806
Storage ( <i>n</i> =2)	Mean	3.72±1.73 b	431±461 a	50.5±33.0 bc	36.0±19.3 cd	61.4±35.9 b	38.0±1.15 e
	Median	3.79	226	37.2	35.8	53.1	37.6
	Min.	1.68	157	28.1	15.7	29.9	37.0
	Max.	5.63	1,116	99.7	56.9	109	39.6
Cable shredding ( <i>n</i> =1)	Mean	4.58 ab	2.25 c	429 a	239 ab	191 ab	8,002 a
	Median	–	–	–	–	–	–
	Min.	–	–	–	–	–	–
	Max.	–	–	–	–	–	–
Chemical waste ( <i>n</i> =1)	Mean	3.57 b	1.37 c	82.6 bc	289 ab	88.9 b	6,872 ab
	Median	–	–	–	–	–	–
	Min.	–	–	–	–	–	–
	Max.	–	–	–	–	–	–
Control ( <i>n</i> =4)	Mean	4.38±4.23 b	15.4±8.34 bc	103±54.9 bc	86.8±116 d	87.4±67.2 b	1,220±637 cd
	Median	4.22	14.5	114	5.9	68.4	1,151
	Min.	0.04	6.48	24.5	0.21	24.3	493
	Max.	12.3	26.2	163	252	218	2,042
OSHA PEL-TWA <sup>a</sup>		5,000	1,000,000	1,000,000	50,000	1,000,000	n.a.
NIOSH REL-TWA <sup>a</sup>		n.a.	500,000	1,000,000	50,000	15,000	n.a.
HK OEL <sup>b</sup>		10,000 <sup>c</sup>	500,000	1,000,000	50,000	1,500,000	n.a.

Values followed by the same letter (a–e) in the same column are not significantly different at the 0.05 probability level according to Duncan's multiple range test

n.a. none established

<sup>a</sup> OSHA (n.d)

<sup>b</sup> HKLD (2002)

<sup>c</sup> Inhalable dust fraction

sampling were 1.7- to 1,338-fold higher than corresponding concentrations detected in the present study. In their study, Cu from shredding and roasting steps reached 22,000 and 38,000 ng/m<sup>3</sup>, respectively. Although Kent et al. (2007) did not conduct area samples and the type of waste and treatment capacity will have an effect on concentrations of metals on suspended particulates, the large discrepancies between personal and area sampling advocates the need to conduct personal sampling on local e-waste workers in the future.

#### Surface dust

Results from wipe samples are presented in Table 3. Large variation (with the largest percentage difference being about 200 %) was seen between samples from the same area implying that workers conducting the same processes may be exposed to varied levels of surface contaminants, even when their work benches are located in close proximity to each other. Furthermore, no significant differences ( $p > 0.05$ ) could

**Table 3** Trace metal concentrations on surface wipes (in microgram per 100 cm<sup>2</sup>) of formal and informal e-waste recycling workshops in Hong Kong

Location		Cd	Cr	Cu	Pb	Ni
Office (n=14)	Mean	0.64±0.49 a	12.8±10.1 a	14.9±11.8 cd	7.35±6.46 bc	79.5±127 bcd
	Median	0.74	8.85	9.86	8.47	9.38
	Min.	0.03	1.00	2.78	0.41	1.8
	Max.	1.31	29.3	35.8	21.5	379
Repair (n=24)	Mean	0.55±0.36 a	20.6±21.6 a	44.9±148 cd	40.5±135 bc	132±252 abc
	Median	0.39	15.0	11.2	10.7	46.3
	Min.	0.04	0.60	2.63	1.75	0.76
	Max.	1.28	81.3	735	675	1,173
Dismantling (n=26)	Mean	3.65±8.04 a	51.9±85.1 a	431±1,136 bc	582±1,748 ab	93.1±124 abc
	Median	1.36	22.0	32.8	24.6	13.3
	Min.	0.01	0.34	3.53	2.80	4.12
	Max.	41.0	335	4,816	8,562	413
Storage (n=6)	Mean	1.46±0.23 a	34.9±6.75 a	12.2±0.58 cd	12.9±4.24 b	7.77±1.76 cd
	Median	1.46	30.9	12.2	13.0	7.66
	Min.	1.24	7.40	11.4	7.88	6.20
	Max.	1.68	44.9	12.8	17.9	9.56
Desoldering (n=6)	Mean	0.49±0.09 a	13.5±6.36 a	97.7±87.9 bc	486±418 a	20.8±13.3 bcd
	Median	0.52	13.1	58.1	268	17.9
	Min.	0.35	4.58	22.5	148	7.55
	Max.	0.58	22.6	221	1,125	41.2
Cable shredding (n=3)	Mean	0.37±0.04 a	29.2±14.6 a	1,350±1,726 a	51.4±33.5 ab	174±78.2 a
	Median	0.37	34.5	394	33.6	200
	Min.	0.33	12.7	315	30.4	86.8
	Max.	0.40	40.4	3,343	90.0	237
Chemical waste (n=4)	Mean	1.89±2.59 a	20.6±7.26 a	120±47.2 b	38.6±25 ab	111±52.0 ab
	Median	0.76	20.5	103	40.7	102
	Min.	0.29	14.2	87.0	11.25	58.5
	Max.	5.73	27.4	190	61.9	183
Storage <sub>i</sub> (n=2)	Mean	0.24±0.01 a	7.53±0.18 a	4.33±0.85 d	5.87±0.37 bc	4.30±1.04 cd
	Median	0.24	7.53	4.33	5.87	4.30
	Min	0.23	7.40	3.73	5.60	3.56
	Max	0.25	7.65	4.93	6.13	5.03
Control (n=12)	Mean	0.31±2.14 b	26.8±34.9 a	84.1±147 cd	40.7±56.5 c	3.68±3.40 d
	Median	0.15	2.62	4.77	2.9	2.78
	Min.	<0.001	<0.001	1.28	<0.001	0.53
	Max.	0.5	98.4	463	159	9.3

Values followed by the same letter (a–d) in the same column are not significantly different at the 0.05 probability level according to Duncan's multiple range test

Storage<sub>i</sub>: results obtained from informal e-waste recycling workshop

be identified for Cd and Cr concentrations between different areas of the workshop. However, Cu concentrations in the cable shredding area were significantly higher ( $p < 0.05$ ) than other parts of the workshop. Significant differences between mean surface contaminant concentrations indicate that the activities of individual work processes present a different level of risk relative to other areas.

Further examination of the results found that workers in the dismantling and desoldering areas are exposed to the highest concentrations of Pb. A sample from the dismantling area of one of the workshops measured 8,562  $\mu\text{g}/100 \text{ cm}^2$ , being almost 20 times higher than US regulated limit of 431  $\mu\text{g}/100 \text{ cm}^2$  (USEPA 2001). Moreover, workers involved with cable shredding are exposed to Cu on work surfaces, with the

mean concentration being approximately 16 times higher than the control. Regarding trace metal concentrations in surface dust between formal and informal e-waste recycling workshops, trace metal concentrations measured in the storage area of the informal e-waste recycling workshop were generally lower than those measured in the formal e-waste recycling workshops. With the exception of Cd, no significant differences in trace metal concentrations were observed between surface dust in the informal e-waste recycling workshop and the control site. This may be because the sampled informal e-waste recycling workshop only stores e-waste on site with no other handling or treatment processes and that the site is open and subjected to weather influences which could potentially reduce the amount of dust within the workshop.

No previous study on trace metal analyses in e-waste recycling workshops using wipe sampling was identified in the literature. But in comparison with a study done by McDonald et al. (2010) to quantify Pb and Cd in Canadian homes where the highest median Pb concentration was  $5.64 \mu\text{g}/100 \text{ cm}^2$  and the highest Cd concentration was  $0.320 \mu\text{g}/100 \text{ cm}^2$ , results of Pb and Cd in the surface dust collected from formal e-waste recycling workshops in the present study were found to be between 1.3–103 and 1.15–11.4 times higher, respectively. Results suggest that e-waste recycling contributes significant concentrations of trace metals in surface dust exposed to workers. Pb may be absorbed through the skin to cause adverse health effects, such as causing brain and kidney damages, without being noticed by the worker (ASTDR 2007a, 2007b). In addition to skin absorption, exposure to dust on work surfaces may ingestion of dust particles appears adhere to the skin and enter the body through inadvertent ingestion. Since all samples were taken on surfaces which are regularly used by workers (e.g., desks and work benches), good housekeeping practices may significantly reduce the exposure and risk posed to the workers.

#### Workshop floor dust

Concentrations of metals in floor dust are presented in Table 4. Dust swept from office areas of the formal e-waste recycling workshops contained the lowest levels of trace metals in general, while results were varied for other work processes. Surprisingly, loading areas contained the highest mean levels of Hg and Cd where concentrations were respectively nine and two times higher than the next highest concentrations measured. In addition, mean Pb concentrations in the loading area did not differ significantly from Pb concentration in the desoldering area where the highest level of Pb ( $19,172 \text{ mg}/\text{kg}$ ) was detected. The highest mean Cr concentration was measured in the dismantling area ( $801 \text{ mg}/\text{kg}$ ) and was eight times higher than the dust collected by Brigden et al. (2005) from Chinese and Indian PCB recycling workshops where PCBs were heated over metal plates or open flames so that

components can be removed manually. Cr concentration in one of the formal e-waste recycling workshops of the present study averaged to be  $2,919 \text{ mg}/\text{kg}$  or approximately 29 times the value measured in the Chinese and Indian workshops in Brigden et al. (2005). Further comparisons with Brigden et al. (2005) found lower Cu concentrations compared to that of the Guiyu workshops where PCB were heated to extract valuable materials. Results from the present study indicate that workers are exposed to significant concentrations of trace metals in workshop floor dust of formal e-waste recycling workshops in Hong Kong which alarmingly, were comparable to those detected in workshops where uncontrolled heating and burning of PCBs are practiced. When comparing the findings obtained from the informal e-waste recycling workshop, Cd and Zn concentrations in the storage areas were found to be comparable to those obtained in PCB recycling workshops in Guiyu.

#### Human health risk assessment

It is necessary to conduct a risk assessment on the measured trace metal concentrations in floor dust to evaluate whether any potential adverse health effects are posed to e-waste recycling workers. The present findings may also contribute as baseline information should a set of specific guideline values be determined for e-waste recycling in Hong Kong. Floor dust provides information on both short- and long-term exposures in contrast to only short-term exposures for surface wipes. Therefore, health risks posed by ingestion, dermal contact, and inhalation were calculated for floor dusts only. Owing to the small sample size of informal e-waste recycling workshops, only the results obtained from the formal workshops will be presented.

For noncancer effects reported in Table 5, ingestion of dust particles appears to be the major route of exposure to workshop dust followed by dermal contact. HQ (noncancer) due to inhalation of dust particles are 2–3 orders of magnitude lower than the other two exposure pathways. The highest HI at the 95th percentile was calculated for repair ( $\text{HI}=0.72$ ) followed by cable shredding ( $\text{HI}=0.63$ ) with the largest contribution from ingestion of Cu. For all three exposure pathways, Ni concentrations in the floor dust contributed the greatest proportion to the HI for most of the processes practiced in e-waste recycling workshops in Hong Kong. But since all calculated HIs were below 1, results indicated that there are little adverse noncancer health risks due to workshop dust. But since trace metals could be retained in the body for long periods of time and cause potentially serious noncancer adverse effects to humans (Järup 2003), exposure to contaminated dust should be minimized.

Table 6 shows the calculated per million human cancer risks at 5th, median, and 95th percentiles. The median cancer risks ranged from  $2.96 \times 10^{-6}$ – $3.60 \times 10^{-5}$  for exposures to



**Table 4** Trace metal concentrations (in milligram per kilogram, dry weight) in workshop floor dust of formal and informal e-waste recycling workshops in Hong Kong

Location		Cd	Cr	Cu	Pb	Ni	Zn	Hg	Reference
Office ( <i>n</i> = 3)	Mean	5.48±2.64 d	458±198 ab	1,655±1,032 c	1,259±493 c	496±200 abc	4,392±1,081 ab	0.39±0.25 ef	Present study
	Median	5.45	364	1,259	1,231	541	4,231	0.31	
	Min.	2.14	257	529	662	200	3,000	0.15	
	Max.	8.63	698	3,143	1,953	712	5,810	0.81	
Repair ( <i>n</i> = 5)	Mean	6.99±3.98 cd	287±259 bc	1,204±624 c	2,068±1,751 bc	1,438±1,582 bd	4,663±2,595 abc	1.38±1.27 cde	Present study
	Median	5.48	192	1,155	1,427	828	4,352	1.41	
	Min.	2.85	69.4	346	440	90.7	1,089	0.17	
	Max.	16.0	786	2,266	5,602	4,436	9,038	4.93	
Dismantling ( <i>n</i> = 7)	Mean	41.4±38.7 bc	801±926 ab	3,539±1,917 b	3,610±2,133 b	1,162±817 ab	7,998±4,525 ab	17.4±26.7 bc	Present study
	Median	18.2	307	3,009	2,164	768	7,237	6.7	
	Min.	3.67	145	1,855	1,077	324	1,766	0.28	
	Max.	111	2,919	8,046	7,642	2,752	14,947	102	
Storage ( <i>n</i> = 2)	Mean	61.3±67.8 bc	268±85.1 b	1,646±425 c	1,331±1,195 c	495±60.3 bc	3,350±1,217 bcd	2.71±2.20 bcde	Present study
	Median	36.9	296	1,763	923	488	3,230	3.26	
	Min.	3.4	153	1,122	592	428	2,201	0.20	
	Max.	156	362	2,052	3,713	571	4,823	5.97	
Desoldering ( <i>n</i> = 1)	Mean	19.9 bcd	376 ab	4,830 b	19,172 a	1,099 a	3,73 8abcd	7.52 b	Present study
	Median	-	-	-	-	-	-	-	
	Min.	-	-	-	-	-	-	-	
	Max.	-	-	-	-	-	-	-	
Loading ( <i>n</i> = 1)	Mean	101 a	248 bc	3,807 b	17,266 a	599 bc	5,566 ab	148 a	Present study
	Median	-	-	-	-	-	-	-	
	Min.	-	-	-	-	-	-	-	
	Max.	-	-	-	-	-	-	-	
Cable shredding ( <i>n</i> = 1)	Mean	9.56 cd	311 ab	29,085 a	3,068 b	232 c	1,789 cd	1.81 bcde	Present study
	Median	-	-	-	-	-	-	-	
	Min.	-	-	-	-	-	-	-	
	Max.	-	-	-	-	-	-	-	
Chemical waste ( <i>n</i> = 1)	Mean	11.5 cd	716 a	4,308 b	2,019 bc	402 abc	5,146 ab	3.96 bcd	Present study
	Median	-	-	-	-	-	-	-	
	Min.	-	-	-	-	-	-	-	
	Max.	-	-	-	-	-	-	-	
Control ( <i>n</i> = 4)	Mean	1.68±1.29 e	96.9±17.1 cd	173±18.3 d	130±25.1 d	58.4±9.12 d	1,832±683 d	0.06±0.02 f	Present study
	Median	1.51	96.7	180	132	57.9	1,859	0.05	
	Min.	0.28	79.4	145	102	46.9	1,165	0.04	
	Max.	3.25	115	188	154	69.9	2,476	0.08	
Storage <sub>i</sub> ( <i>n</i> = 1)	Mean	49.0 ab	60.8 d	1,093 c	1,394 bc	234 b	8,911 a	0.55 de	Present study
	Median	-	-	-	-	-	-	-	

**Table 4** (continued)

Location	Cd	Cr	Cu	Pb	Ni	Zn	Hg	Reference
Loading, ( <i>n</i> =1)	Mean							
PCB workshop, Beilin, China ( <i>n</i> =3)	13.4 cd	51.2 d	1,622 c	954 c	207 b	1,763 cd	0.22 ef	Brigden et al. (2005)
PCB workshop, Zafarabad, India ( <i>n</i> =2)	55.3±46.7	108±33.3	13,400±10,904	52,767±22,402	605±374	5,080±3,580	2.10±3.29	Brigden et al. (2005)
PCB recycling workshop, Guiyu, China ( <i>n</i> =12)	53.5	101	3,487	4,483	283	4,470	231	Leung et al. (2008)
Road side dust, Hong Kong ( <i>n</i> =45)	n.a.	<100	1,100–36,000 <sup>a</sup>	22,900–206,000	n.a.	980–10,200 <sup>a</sup>	n.a.	Li et al. (2011b)
	3.77±2.25	n.a.	173±190	181±92.9	n.a.	1,450±869	n.a.	

Values followed by the same letter (a–f) in the same column are not significantly different at the 0.05 probability level according to Duncan's multiple range test  
Storage/ Loading<sub>i</sub> results obtained from informal e-waste recycling workshop

<sup>a</sup> Not explicitly stated in the paper and was derived from the text by the author

dust collected from the loading and chemical waste areas, respectively. According to the USEPA, a generally acceptable cancer risk ranges from  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$  (USEPA 2001). While the cancer risk at the 95th percentile for exposures to floor dust in the dismantling area was slightly above  $1 \times 10^{-4}$  at  $1.47 \times 10^{-4}$ , the upper boundary of the generally acceptable range is not a discrete line at  $1 \times 10^{-4}$ , further evaluation is necessary to assess on the site-specific conditions, including any uncertainties about the nature and extent of contamination and associated risks (USEPA 2001).

Similar to noncancer risks, ingestion and dermal contact of floor dust appears to be the most significant exposure pathway in terms of cancer risks to workers. For all three exposure pathways, Cr contributed the greatest proportion to the calculation of cancer risks as a result of exposure to the floor dust in the e-waste recycling workshops. Cancer risks above the accepted range describe the probability that an exposed individual will develop cancer as a result of that exposure by the age of 70.

The limitations of risk assessment calculation presented in the present study include that noncancer health risks are believed to be underestimated owing to the scarcity of data. For the ingestion pathway, Pb and Hg were excluded because no oral RfDs were established. In the case of Pb, the USEPA considered it inappropriate to develop an RfD for inorganic Pb because adverse health effects occurred at blood Pb levels so low as to be essentially without a threshold (USEPA 2011b). For exposure via dermal contact, USEPA recommended the use of ingestion RfDs until more appropriate dose–response factors are available for dermal exposures. Uncertainty exists because factors were derived from oral studies and intended for assessing risks from ingestion (USEPA 2004). Similarly, no reference concentration (RfC<sub>i</sub>) for inhalation was available for Cu, Pb, and Zn and therefore, no calculation of their respective HQs could be conducted.

Cancer risk estimations in this study were also believed to be an underestimation of the actual risk. USEPA typically calculates slope factors for potential carcinogens in classes A, B1, and B2 which represent human carcinogen, probable human carcinogen with limited human data, and probable human carcinogen with sufficient evidence in animals and inadequate or no evidence in humans, respectively (USEPA 1989). While Cr(VI) and Ni are classified as class A, Cd as class B1, and Pb as class B2 carcinogens, only a oral slope factor for Cr(VI) is available. Therefore, cancer risks for ingestion and dermal contact were based solely on the carcinogenicity of Cr(VI). For exposure via the inhalation pathway, IURs were available for Cd, Ni, and Cr(VI).

The use of personal protective equipment (PPE), such as face masks and gloves, and implementation of good work practices should reduce dust exposure to the workers. However, while PPE were provided in all of the formal e-waste recycling workshops studied, their use by workers were not stringently enforced. During the study period, many workers were not observed to be wearing appropriate PPE during their

**Table 5** Hazard quotients of ingestion, dermal contact, and inhalation and total hazard index of floor dust in formal e-waste recycling workshops based on trace metal concentrations at 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentiles

Location	HQ ingestion			HQ dermal contact			HQ inhalation			Total HI		
	5th percentile	Median	95th percentile	5th percentile	Median	95th percentile	5th percentile	Median	95th percentile	5th percentile	Median	95th percentile
Office	0.02	0.06	0.13	0.01	0.05	0.10	1.22E-03	7.07E-03	1.02E-02	0.04	0.12	0.24
Repair	0.03	0.11	0.33	0.02	0.08	0.33	1.49E-03	1.22E-02	6.34E-02	0.05	0.20	0.72
Dismantling	0.10	0.19	0.35	0.06	0.15	0.24	5.08E-03	1.26E-02	3.95E-02	0.17	0.35	0.57
Storage	0.07	0.08	0.10	0.03	0.04	0.05	4.27E-03	5.35E-03	6.58E-03	0.11	0.13	0.14
Desoldering	0.18	0.19	0.19	0.11	0.11	0.11	1.58E-02	1.63E-02	1.65E-02	0.31	0.31	0.32
Loading	0.01	0.06	0.20	0.01	0.02	0.08	8.76E-04	3.97E-03	1.15E-02	0.02	0.09	0.29
Cable shredding	0.51	0.52	0.56	0.06	0.06	0.06	3.42E-03	3.53E-03	3.66E-03	0.57	0.58	0.63
Chemical waste	0.13	0.14	0.15	0.07	0.08	0.08	5.41E-03	6.15E-03	6.42E-03	0.21	0.23	0.24
Control	0.01	0.01	0.02	0.01	0.01	0.01	7.30E-04	8.65E-04	1.04E-03	0.02	0.02	0.03

work shift. Since risk assessment estimations were considered to be an underestimation, use of PPE and good work practices such as washing hands before eating or regular dust removal are highly recommended.

Health risk estimation for Pb

An exposure frequency of 300 days/year and an averaging time of 365 days as recommended by USEPA (2003) for assessing continuing long-term exposures were inputted into the ALM. BLL of workers in the desoldering and loading areas were calculated to be 39.5 and 35.8 µg/dl, respectively, well above the limit of 10 µg/dl set by the CDC while the BLL of workers in the dismantling areas were estimated to be at 10 µg/dl. Under OSHA's Lead Standard (29 CFR 1910.1025; OSHA n.d.), BLLs of above 40 µg/dl requires medical intervention.

Menke et al. (2006) identified a direct association between BLL and increased mortality. The risk of cardiovascular, myocardial infarction, and stroke mortality was evident at BLLs of 2 µg/dl. BLL as low as 5–9 µg/dl were associated with increased risk of death from all causes, cardiovascular disease, and cancer in a study conducted by Schober et al. (2006). Given the association of adverse health effects at low BLLs, and its irreversible bioaccumulative effects, it is essential to minimize worker exposure to Pb in contaminated areas.

It should be mentioned that the model is estimated using a linear biokinetic slope factor which is multiplied by the estimated lead uptake. The lead uptake in turn, is based upon the overall rate of daily ingestion and the estimated AF<sub>g</sub>. Owing to insufficient research on dust-specific parameters, default soil parameters were inputted into the model for the calculations. But settled dust may have a lower dry bulk density than

**Table 6** Cancer health risks (10<sup>-6</sup>) faced by e-waste recycling workers in formal e-waste recycling workshops from exposure by ingestion, dermal contact, and inhalation to trace metals in floor dust at 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentiles

Location	Ingestion			Dermal contact			Inhalation			Total		
	5th percentile	Median	95th percentile	5th percentile	Median	95th percentile	5th percentile	Median	95th percentile	5th percentile	Median	95th percentile
Office	1.79	5.66	12.2	3.32	10.5	22.5	0.09	0.29	0.62	5.20	16.4	35.3
Repair	1.48	3.35	13.7	2.74	6.18	25.3	0.13	0.18	0.71	4.29	9.70	39.6
Dismantling	2.69	5.37	50.9	4.97	9.93	94.0	0.16	0.29	2.52	7.79	15.6	147
Storage	0.99	3.28	6.18	1.82	6.07	11.4	0.06	0.17	0.31	2.86	9.51	17.9
Desoldering	6.26	6.33	7.04	11.6	11.7	13.0	0.33	0.34	0.37	18.1	18.3	20.4
Loading	0.23	1.02	5.27	0.42	1.89	9.74	0.01	0.06	0.29	0.66	2.96	15.3
Cable shredding	5.33	5.37	5.57	9.85	9.92	10.3	0.27	0.27	0.28	15.4	15.6	16.2
Chemical waste	12.2	12.4	13.0	22.5	23.0	23.8	0.61	0.62	0.65	35.3	36.0	37.6
Control	0.93	1.13	1.34	1.71	2.08	2.47	0.05	0.06	0.07	2.69	3.26	3.87

surface soil, volumes of settled dust may weigh less than comparable volumes of surface soils such that the rate of intake may be higher than that for soil (USEPA 2008). Therefore, current calculated BLL for workers may only represent the lower range of exposure.

## Conclusion

Metals comprise a significant portion of EEE. Through collection of suspended air particulates, surface dust, and settled floor dust, it was found that Hong Kong's e-waste recycling workers are exposed to trace metal concentrations which may be detrimental to their health. Although concentrations in suspended air particulates were well below the regulatory standards, dismantling and desoldering processes were found to generate high Pb levels in surface dust. Trace metal concentrations from floor dust were also found to be comparable to those from Chinese and Indian recycling workshops where crude recycling processes are practiced. Pb concentrations were estimated to result in BLL that require medical intervention. It should also be emphasized that while most of the calculated HI and cancer risks were below the acceptable reference values (1 for HI and  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$  for cancer risks), these estimations have limitations which may have underestimated health risks. As a result, further investigation on potential health effects such as direct measurement of the body loadings of trace metals in workers is highly recommended.

**Acknowledgments** The authors would like to thank the participating e-waste recycling workshops and Mr. K.K. Ma for his help with the chemical analyses. This research is supported by a grant from the Public Policy Research Grant (HKBU 2001-PPR-5) and the Marginally Funded Post-Graduate Fund (on Persistent Toxic Substances) from the Research Grants Council of Hong Kong.

## References

- ASTDR (2007a) Lead CAS#7439-92-1 Division of Toxicology and Environmental Medicine ToxFAQs. <http://www.atsdr.cdc.gov/tfacts13.pdf>. Accessed 13 Mar 2013
- ASTDR (2007b) Lead CAS#7439-92-1 Division of Toxicology and Environmental Medicine public health statement. <http://www.atsdr.cdc.gov/ToxProfiles/tp13-c1-b.pdf>. Accessed 3 Mar 2013
- Bi X, Li Z, Zhuang X, Han Z, Yang W (2011) High levels of antimony in dust from e-waste recycling in southeastern China. *Sci Total Environ* 409:5126–5128
- Brigden K, Labunska I, Santillo D, Allsopp M (2005) Recycling of electronic wastes in China and India: workplace and environmental contamination. Technical Note: 09/2005 (Section 1). Greenpeace Research Laboratories, Department of Biological Sciences, University of Exeter, Exeter
- California Department of Public Health (2012) Electronic waste recycling: working safely. <http://www.cdph.ca.gov/programs/hesis/Documents/eWaste.pdf>. Accessed 26 Apr 2013
- CBS News (2008) Following The Toxic Trail of E-Waste. [http://www.cbsnews.com/8301-18560\\_162-4579229.html](http://www.cbsnews.com/8301-18560_162-4579229.html). Accessed 15 Jan 2013
- CDC (2012) What do parents need to know to protect their children? [http://www.cdc.gov/nceh/lead/ACCLPP/blood\\_lead\\_levels.htm](http://www.cdc.gov/nceh/lead/ACCLPP/blood_lead_levels.htm). Accessed 4 Nov 2013
- CDC (2013) Adult Blood Lead Epidemiology & Surveillance (ABLES). <http://www.cdc.gov/niosh/topics/ables/description.html>. Accessed 4 Nov 2013
- Chatterjee S, Kumar K (2009) Effective electronic waste management and recycling process involving formal and non-formal sectors. *Int J Phys Sci* 4:893–905
- Chi X, Streicher-Porte M, Wang MY, Reuter MA (2011) Informal electronic waste recycling: a sector review with special focus on China. *Waste Manag* 31:731–742
- Chung S, Lau K, Zhang C (2011) Generation of and control measures for, e-waste in Hong Kong. *Waste Manag* 31:544–554
- Deng WJ, Louie PKK, Liu WK, Bi XH, Fu JM, Wong MH (2006) Atmospheric levels and cytotoxicity of PAHs and heavy metals in TSP and PM<sub>2.5</sub> at an electronic waste recycling site in southeast China. *Atmos Environ* 40:6945–6955
- EMPA (2009) Hazardous substances in e-waste. <http://ewasteguide.info/node/219>. Accessed 4 June 2012
- Environment Bureau (2010) Safe and sustainable: a new producer responsibility scheme for waste electrical and electronic equipment, Consultation Document. <http://www.epd.gov.hk/epd/weee/en/index.html>. Accessed 3 June 2012
- HKLD (2002) Code of practice on control of air impurities (chemical substances) in the workplace. <http://www.labour.gov.hk/eng/public/oh/AirImpure.pdf>. Accessed 26 Apr 2013
- Huisman J, van der Maesen M, Erjsbouts RJJ, Wang F, Baldé CP, Wielenga CA (2012) The Dutch WEEE Flows. United Nations University, ISP-SCYCLE, Bonn
- Järup L (2003) Hazards of heavy metal contamination. *Brit Med Bull* 68:167–182
- Kent MS, Corbett ML, Glavin M (2007) Characterization and analysis of airborne metal exposures among workers recycling cellular phones. Proceedings of the 2007 I.E. International Symposium on Electronics and the Environment, Orlando, 2007, pp. 112–116
- Lam L (2001) Toxic e-waste exposed to the elements in open-air depots, South China Morning Post Online Edition. <http://citizenmap.scmp.com/reports/view/269>. Accessed 3 Jan 2013
- Lau WKY, Chung SS, Zhang C (2013) A material flow analysis on current electrical and electronic waste disposal from Hong Kong households. *Waste Manag* 33:714–721
- Leung AOW, Duzgoren-Aydin NS, Cheung KC, Wong MH (2008) Heavy metals concentrations of surface dust from e-waste recycling and its human health implications in Southeast China. *Environ Sci Technol* 42:2674–2680
- Li J, Duan H, Shi P (2011a) Heavy metal contamination of surface soil in electronic waste dismantling area: site investigation and source-apportionment analysis. *Waste Manag Res* 29:727–738
- Li X, Poon C, Liu PS (2011b) Heavy metal contamination of urban soils and street dusts in Hong Kong. *Appl Geochem* 16:1361–1368
- McDonald LT, Rasmussen PE, Chénier M, Levesque C (2010) Wipe sampling methodologies to assess exposures to lead and cadmium in urban Canadian homes. *Proc Ann Int Conf Soils Sed Wat En* 15(6):52–66
- McDonald LT, Rasmussen PE, Chénier M, Levesque C (2011) Extending wipe sampling methodologies to elements other than lead. *J Environ Monit* 13:377–383
- Menke A, Muntner P, Batuman V, Silbergeld EK, Guallar E (2006) Blood lead below 0.48  $\mu\text{mol/L}$  (10  $\mu\text{g/dL}$ ) and mortality among US adults. *Circulation* 114:1388–1394
- Ni HG, Zeng EY (2009) Law enforcement and global collaboration are the keys to containing e-waste tsunami in China. *Environ Sci Technol* 43:3991–3994

- NIOSH (2003a) Elements by ICP (Aqua Regia Ashing): method 7301. NIOSH manual of Analytical methods (NMAM), 4th ed. 3rd suppl., U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. <http://www.cdc.gov/niosh/nmam/new.html>. Accessed 2 Dec 2011
- NIOSH (2003b) Elements on wipes: method 9102. NIOSH manual of analytical methods (NMAM), 4th ed., 3rd suppl., U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. <http://www.cdc.gov/niosh/nmam/new.html>. Accessed 2 Dec 2011
- Ogilvie SM (2004) WEEE & hazardous waste: a report produced for DEFRA. <http://www.defra.gov.uk/environment/waste/producer/electrical/documents/weee-hazwaste.pdf>. Accessed 29 March 2013
- OSHA (1993) Zinc. [http://www.osha.gov/dts/chemicalsampling/data/CH\\_276790.html](http://www.osha.gov/dts/chemicalsampling/data/CH_276790.html). Accessed 4 June 2012
- OSHA (n.d) Table Z-1 limits for air contaminants. [http://www.osha.gov/pls/oshaweb/owadis.show\\_document?p\\_table=STANDARDS&p\\_id=9992](http://www.osha.gov/pls/oshaweb/owadis.show_document?p_table=STANDARDS&p_id=9992). Accessed 2 May 2013
- Schober SE, Mirel LB, Graubard BI, Brody DJ, Flegal KM (2006) Blood lead levels and death from all causes, cardiovascular disease, and cancer: results from the NHANES III mortality study. *Environ Health Perspect* 114:1538–1541
- Tsydenova O, Bengtsson M (2011) Chemical hazards associated with treatment of waste electrical and electronic equipment. *Waste Manag* 31:45–58
- USEPA (1989) Risk assessment guidance for superfund volume I human health evaluation manual (part A). Office of Emergency and Remedial Response, Washington DC
- USEPA (2001) Identifying lead hazards in residential properties, prevention, pesticides and toxic substances (7404), EPA747-F-01-002, Washington, DC
- USEPA (2003) Recommendations of the technical review workgroup for lead for an approach to assessing risks associated with adult exposures to lead in soil, EPA-540-R-03-001. <http://www.epa.gov/superfund/health/contaminants/lead/products/adultpb.pdf>. Accessed 4 June 2012
- USEPA (2004) Risk assessment guidance for superfund volume I: human health evaluation manual (part E, supplemental guidance for dermal risk assessment) final, EPA/540/R/99/005, Washington, DC
- USEPA (2007) Method 7473: mercury in solids and solutions by thermal decomposition amalgamation, and atomic absorption spectrophotometry. USEPA, New York
- USEPA (2008) Human health risk assessments. <http://cfpub.epa.gov/ncea/cfm/healthtri.cfm>. Accessed 12 May 2013
- USEPA (2009) Risk Assessment Guidance for Superfund (RAGS), volume I: human health evaluation manual (part f, supplemental guidance for inhalation risk assessment). OSWER 9285.7-82, Office of Superfund Remediation and Technology Innovation, Washington, DC
- USEPA (2011a) Exposure factors handbook: 2011 Edition. EPA/600/R-090/052F, Office of Research and Development, Washington, DC
- USEPA (2011b) Lead and compounds (inorganic) (CASRN 7439-92-1), Integrated risk information system. <http://www.epa.gov/iris/subst/0277.htm>. Accessed 4 June 2012
- Wang J, Chen H, Xia W, Chen L, Zhao J, Li G (2012) Heavy metal pollution in the surface dust from E-waste disposal place and its ecological risk assessment. *Adv Mater Res* 347–353:2360–2364
- Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M, Böni H (2005) Global perspectives on e-waste. *Environ Impact Assess Rev* 25:436–458
- Xue M, Yang Y, Ruan J, Xu Z (2012) Assessment of noise and heavy metals (Cr, Cu, Cd, Pb) in the ambience of the production line for recycling waste printed circuit boards. *Environ Sci Technol* 46:494–499