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Risks of toxic ash from artisanal mining of discarded cellphones



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HIGHLIGHTS

- We simulated artisanal incineration of four component categories of cellphones.
- We identified metals and organic chemicals in the resulting electronic waste ash.
- We used USEtox model to demonstrate potential ecotoxicity and human health impacts.
- We identify targets for risk reduction for hazardous chemicals in cellphones.

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ABSTRACT

The potential environmental and human health impacts of artisanal mining of electronic waste through open incineration were investigated. A market-representative set of cellphones was dismantled into four component categories—batteries, circuit boards, plastics and screens. The components were shredded, sieved and incinerated at 743–818 °C. The concentrations of 17 metals were determined using U.S. EPA methods 6010C (inductively coupled plasma-atomic emission spectrometry; 6020A (inductively coupled plasma-mass spectrometry, or 7471B and 7470A (cold-vapor atomic absorption). EPA Method 8270 (gas chromatography/mass spectrometry) was used to identify polyaromatic hydrocarbon compounds and polybrominated diphenyl ethers. EPA Method 8082A was used to measure polychlorinated biphenyls and EPA Method 8290 was used for dioxin/furans in the residue ash. The life cycle assessment model USEtox[®] was used to estimate impacts of the ash residue chemicals on human health and the ecosystem. Among metals, copper in printed circuit boards had the highest ecotoxicity impact (1610–1930 PAF m³/kg); Beryllium in plastics had the highest impact on producing non-cancer diseases (0.14–0.44 cases/kg of ash); and Nickel had the largest impact on producing cancers (0.093–0.35 cases/kg of ash). Among organic chemicals, dioxins from incinerated batteries produced the largest ecotoxicological impact (1.07E–04 to 3.64E–04 PAF m³/kg). Furans in incinerated batteries can generate the largest number of cancers and non-cancer diseases, representing 8.12E–09 to 2.28E–08 and 8.96E–10 and 2.52E–09 cases/kg of ash, respectively. The results reveal hazards of burning discarded cellphones to recover precious metals, and pinpoints opportunities for manufacturers to reduce toxic materials used in specific electronic components marketed globally.

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1. Introduction

Individuals, households, corporations and institutions generate electronic waste (e-waste) from used computers, televisions, printers, phones, personal digital assistants, entertainment equipment, and other forms of communication devices. E-waste poses a global

predicament because several municipalities lack infrastructures for its collection, recycling or proper disposal of this category of hazardous materials. There are no adequate international regulations to mandate proper management of e-waste, creating a flow to poor countries where cottage industries have emerged to mine precious and semi-precious metals such as gold and copper from the waste [1–3]. Artisanal use of combustion to mine e-waste has been documented extensively in China, India, Pakistan, Ghana, and Nigeria [4–15].

Toxic pollutants from the disposal and incineration of e-waste may contaminate soils, water systems and air, potentially contributing to disease outcomes in exposed populations [7,8]. Toxic

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metals and organic compounds can leach from e-waste discarded in landfills [16–18]. Limited studies of e-waste incineration according to the best-available technology resulted in the production of toxic organic chemicals including dioxin, furan, metal, and biphenyls [19,20]. There have been no previous studies of the generation and potential effects of toxic metals and organic chemicals from e-waste incinerated through open burning using artisanal technology. The hypothesis of this research is that incineration of e-waste under conditions simulating open burning in cottage industries will produce toxic chemicals in ash that can be mobilized in aerosols or leachates, thereby putting ecosystem quality and the health of populations at risk.

Four specific objectives were pursued to test this hypothesis: (1) Collection of a diverse sample of defunct cellphones as a representative of e-waste, and we disassembled them in a process similar those employed by artisanal e-waste recyclers; (2) simulation of artisanal open burning of disassembled cellphones; (3) measurement of chemical composition of the residual ash; and (4) life cycle impact assessment of the chemicals found in the ash using a numerical model to explore the possibility of adverse impacts on human health and environmental quality due to the disposal of the e-waste ash into the open environment.

2. Experimental

2.1. E-waste samples collection and preparation

Defunct mobile phones were collected by direct solicitation between 2008 and 2011. The samples were representative of product market share of various manufacturer and models, based on data from global market sales of mobile phones from the first quarter of 2009. From an initial collection of 253, 98 representative phones were selected for the research (Supporting information, Tables A and B). All collected phones were weighed with a precision balance scale (Ohaus, Adventurer model AR 2140), measured using a digital caliper to determine physical volume, and identified according to year that the motherboard or plastic casing were manufactured. Batteries were characterized, weighed, and measured in the same manner, separately from the phones. The cell phones were then dismantled manually to simulate the process that would occur at a cottage industry by artisanal e-waste recyclers.

The phone components were separated into four categories: printed circuit boards, batteries, plastics and screens. Samples in each category were shredded with a Retsch SM 2000 cutting mill (<http://www.retsch.com/>) using a 2.5 mm sieve to collect two different particle size portions (<2.5 mm and >2.5 mm) for each category. The two portions from each category were mixed to create a homogenous shredded sample collection for each component category.

2.2. Incineration of e-waste components

Paragon model PMT-13 heat-treating furnace, with a Sentry 2.0 digital temperature controller was used to simulate artisanal incineration of dismantled e-waste samples. A porcelain crucible was used to hold shredded samples in 10 g batches. To replicate outdoor burning temperatures, the furnace was pre-heated to 799 °C (1470 °F). This temperature was chosen to match previous studies such as Stewart and Lemieux [19] where electronic components were incinerated at a kiln temperature of 649 °C to 927 °C; and Gullett [20] where kiln temperatures of 570 °C to 880 °C was used to replicate the temperature of a reddish flame and smoldering which ranges from 700 °C to 900 °C. Temperatures were recorded at times 0, 1, 2, 3, 4, and 5 min after when the sample was removed from the furnace. The temperature data for these time-points are

presented in Supporting information (Tables C–F). Samples were then re-weighed after cooling. Through this process, the incineration of 817 g of e-waste plastics yielded 218 g (26.7%) of ash; 345 g of battery samples yielded 262 g (75.9%) of ash; 340 g of screen samples yielded 258 g (75.8%) of ash; and 345 g of printed circuit board samples, yielded 275 g (79.7%) of ash for chemical analysis.

2.3. Chemical analysis

Chemical analysis was performed on duplicate samples of ash recovered from incinerating battery, screen, circuit boards, and plastics from e-waste to identify key metals and organic compounds that may pose a threat to environmental quality and human health. The project also sought to identify the presence of toxic constituents in cellphone components that may facilitate alternative assessments in product design-for-environment strategies. For all analyses, quality control parameters are reported in Supporting information, Table G. This includes the measurement limits for method detection and reporting, method blanks, and laboratory control sample analyses.

2.3.1. Metals

Seventeen metals were selected for evaluation based on a combination of factors, including the availability of regulatory standards for environmental quality, the availability of data on human health impacts, and the use of these metals in specific components of electronic products including cellphones. U.S. EPA methods 6010C (inductively coupled plasma-atomic emission spectrometry; [21]) and 6020A (inductively coupled plasma-mass spectrometry; [22]) were used to determine the concentrations of arsenic (As), antimony (Sb), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), thallium (Tl), vanadium (V), zinc (Zn). Mercury (Hg) was determined with EPA methods 7471B and 7470A (cold-vapor atomic absorption [23,24]).

2.3.2. Organic chemicals

EPA Method 8270 (gas chromatography/mass spectrometry [25]) was used to identify polyaromatic hydrocarbon (PAH) compounds and Polybrominated diphenyl ethers (PBDEs; congeners 47, 85, 99, 100, 153, 154, 183, and 209). For dioxins and furans, we used EPA Method 8290 for the following congeners: 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD), 1,2,3,7,8-pentachlorodibenzo-*p*-dioxin (PeCDD), 1,2,3,4,7,8-hexachlorodibenzo-*p*-dioxin (HxCDD), 1,2,3,6,7,8-hexachlorodibenzo-*p*-dioxin (HxCDD), 1,2,3,7,8,9-hexachlorodibenzo-*p*-dioxin (HxCDD), 1,2,3,4,6,7,8-heptachlorodibenzo-*p*-dioxin (HpCDD), octachlorodibenzo-*p*-dioxin (OCDD) (1,2,3,4,6,7,8,9), 2,3,7,8-tetrachlorodibenzofuran (TCDF), 1,2,3,7,8-pentachlorodibenzofuran (PeCDF), 2,3,4,7,8-pentachlorodibenzofuran (PeCDF), 1,2,3,4,7,8-hexachlorodibenzofuran (HxCDF), 1,2,3,6,7,8-hexachlorodibenzofuran (HxCDF), 1,2,3,7,8,9-hexachlorodibenzofuran (HxCDF), 1,2,3,4,6,7,8-heptachlorodibenzofuran (HpCDF), 1,2,3,4,7,8,9-heptachlorodibenzofuran (HpCDF), and octachlorodibenzofuran (OCDF) (1,2,3,4,6,7,8,9). EPA Method 8082A (GC) was used to identify Polychlorinated biphenyl congeners 28, 52, 77, 105, 118, 126, and 169 in the ash samples [26]. Incomplete combustion of materials can sometimes lead to the production of other types of compounds after incineration. Therefore, the presence of semi-volatile compounds in the e-waste ash was also investigated.

2.3.3. Modeling impacts on environmental quality and human health

The life cycle assessment model USEtox[®] (<http://www.usetox.org>) version 1.01 was used to identify and quantify potential

impacts of the toxic chemicals in e-waste ash on environmental quality and human health. USEtox[®] is, based on the scientific consensus of international researchers within the life cycle initiative (LCI), collaboration between the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC). The LCI supports the USEtox[®] to advance the scientific understanding of the global environmental risks and management options of chemicals in commerce. The end-points of USEtox[®] modeling include, ecotoxicity in terms of potentially affected fraction (PAF) of species due to change in concentration of toxic emissions (PAFm³ day/kg), and human toxicity criteria related to outcomes such as the incidence of cancers and non-cancer diseases associated with toxic emission concentrations and multi-media exposure assessments [27,28]. In this research, USEtox[®] was used to focus on potential impacts of chemicals that we identified in ash resulting from incinerated cellphones human health.

3. Results and discussion

3.1. Metals in ash from incinerated e-waste

Data on the quantities of 17 metals measured in ash from incinerated components of e-waste are presented in Table 1. Mercury levels are low (0.002–0.004 mg/kg) in ash from all 4 categories of e-waste components. These levels are much higher than the normal soil levels of mercury, which range from 0.02 to 0.625 ng/kg of soil [29]. Similarly, the levels of Pb are relatively high in all component categories, especially in printed circuit boards, where Sn–Pb solders are still used by some manufacturers, despite the European Unions Restriction on Hazardous Substances (RoHS) directive restricting Pb levels in electronic products [30]. The mean concentration and ranges of Pb measured in the ash were as follows: batteries 642.5 mg/kg ± 281 mg/kg; screens 134.5 mg/kg ± 57 mg/kg; circuit boards 12,000 mg/kg ± 0.0 mg/kg; and plastics 1215 mg/kg ± 50 mg/kg. Under the “Environmental Monitoring for Public Access and Community Tracking” (EMPACT) program, the U.S. EPA regulates comparable levels of Pb in soil as at least moderately high (400–2000 mg/kg); high (2000–5000 mg/kg) or very high (>5000 mg/kg) requiring removal, installation of barriers, and unsafe for gardening or as children’s play area [31].

Elevated levels of Pb in the blood of children in vicinities of artisanal e-waste mining have been documented. Huo et al. [32] showed that 135 of 165 (82%) children under 6 years old living in an artisanal e-waste mining town had blood lead levels (BLL) >10 µg/dL, a significantly higher percentage than the BLL among children in a control town where the occupation is primarily textile manufacturing.

High levels of barium and silver were also measured in circuit boards (barium—24,050 mg/kg ± 8900 mg/kg; and silver—720 mg/kg ± 32 mg/kg). Nickel, cadmium, and cobalt are expectedly high in the ash from rechargeable batteries (nickel—120,500 mg/kg ± 5000 mg/kg; cadmium—708 mg/kg ± 130 mg/kg; and cobalt—202,500 mg/kg ± 11,000 mg/kg), and copper and zinc levels were higher in ash from batteries, printed circuit boards and plastics than in screens (Table 2). Zheng et al. [9] found significantly elevated blood cadmium levels (BCLs) among 154 children younger than 8 years living in the e-waste mining town of Guiyu, China.

3.2. Organic chemicals in ash from incinerated e-waste

Several categories of potentially toxic organic chemicals were detected in the ash from incinerated e-waste. The data on dioxins and furans are presented in Table 2. Several congeners of dioxins and furans were detected in ash primarily from incinerated batteries, possibly due to their relatively high concentration of flame-retardants. OCDD and OCDF were detected in all electronic components, batteries, screens, circuit boards and plastics. HpCDD was detected in batteries and screens only; whereas TCDF was detected in ash from all components except circuit boards. Dioxins and furans are regulated as persistent organic pollutants and probably human carcinogens. TCDD is among the most toxic of this group of compounds with extensive documentation of sources and human exposure. Small amounts of TCDD were detected in ash from incinerated e-waste batteries. This observation calls into question the design of some recent electronic equipment such as smartphones where the battery is inaccessible and cannot be easily removed for recycling purposes. Dioxin and furan compounds are listed under Annex-C of the list of Persistent Organic Pollutants (POPs) under the Stockholm Convention that requires all Parties, individually or in groups to develop action and implementation

Table 1
The concentration (mg/kg) of metals in ash from incinerated e-waste components.

Metal	Control recovery (%)	Method detection limit	E-waste Component							
			Batteries		Screens		Circuit boards		Plastics	
			Mean	±Range	Mean	±Range	Mean	±Range	Mean	±Range
Antimony	97.4	3.0	103.6	24.8	45.4	10	580.5	135	9	5.4
Arsenic	99.6	0.01	269.5	19	19.7	3.2	73	22	180.12	93.94
Barium	103.0	0.3	309.5	411	9025	4877.5	24,050	8900	336	22
Beryllium	99.6	0.01	0.01	0	0.1	0.06	43	12	44.89	88.61
Cadmium	94.4	0.2	708	130	0.3	0.2	1.83	1.30	0.85	1.01
Chromium	105.0	0.4	35.4	24.7	163	20	2635	10	707.5	205
Cobalt	102.0	0.3	202,500	11,000	29.1	15.4	766.5	299	115.5	21
Copper	95.2	0.6	72,100	5400	3590	700	393,500	35,000	67,300	28,800
Lead	100.0	0.02	642.5	281	134.5	57	12,200	0	1215	50
Mercury	100.8	0.002	0.002	0	0.002	0	0.002	0	0.004	0.001
Molybdenum	98.6	0.5	7.5	1	40.15	18.5	68.5	31	2.52	3.05
Nickel	100.8	0.5	120,500	5000	4451	2474.5	244,700	141,850	31,280	21,160
Selenium	102.2	0.02	3.85	0.3	3.9	0.2	3.35	0.1	0.7	0
Silver	98.4	0.007	101.7	58.15	97.35	45.3	720	32	215	62
Thallium	100.8	3.0	2.9	0.2	11.2	8.4	2.55	1.3	0.12	0.11
Vanadium	98.4	0.4	11.8	1.6	0.5	0.2	13	4	15.7	0.6
Zinc	94.0	0.3	2625	170	33.85	18.9	8650	8100	51,050	12,500

plans to promote practical measures for reducing releases and eliminating sources of these chemicals [33].

Polychlorinated biphenyls were not detected in e-waste ash. The manufacturing of PCBs in the United States was banned in 1979, although these compounds are still authorized for use in electric transformers, fluorescent light ballasts, electromagnets, capacitors, switches, voltage regulators, circuit breakers, and as plasticizers (Code of Federal Regulations [34]). Effective May 2004, the POPs Stockholm Convention prohibited the manufacturing of new PCBs

with the aim of phasing out equipment containing high levels of these compounds by 2025 [33]. It is possible for PCBs to form de novo during incineration processes, but this reaction depends on the components of the gas phase, the size of particulate ash, and incineration temperature. The lack of detection of PCBs in the e-waste ash in this study may reflect the fact that PCBs were not used in manufacturing the components that we tested, and the chemical conditions were not adequate for de novo synthesis to occur.

Table 2

The concentration of organic chemicals in ash from incinerated E-waste components.

Organic chemicals	E-waste Component							
	Batteries		Screens		Circuit Boards		Plastics	
	Mean	±Range	Mean	±Range	Mean	±Range	Mean	±Range
Dioxins and furans	Concentrations in ng/kg							
2,3,7,8-Tetrachlorodibenzo- <i>p</i> -dioxin (TCDD)	1.59	0.03	ND	ND	ND	ND	ND	ND
1,2,3,7,8-Pentachlorodibenzo- <i>p</i> -dioxin (PeCDD)	3.41	2.1	ND	ND	ND	ND	ND	ND
1,2,3,4,7,8-Hexachlorodibenzo- <i>p</i> -dioxin (HxCDD)	1.47	0.73	ND	ND	ND	ND	ND	ND
1,2,3,6,7,8-Hexachlorodibenzo- <i>p</i> -dioxin (HxCDD)	1.82	0.94	ND	ND	ND	ND	ND	ND
1,2,3,7,8,9-Hexachlorodibenzo- <i>p</i> -dioxin (HxCDD)	5.01	3.53	ND	ND	ND	ND	ND	ND
1,2,3,4,6,7,8-Heptachlorodibenzo- <i>p</i> -dioxin (HpCDD)	5.37	0.04	0.52	0.27	ND	ND	ND	ND
Octachlorodibenzo- <i>p</i> -dioxin (OCDD)	14	5.4	2.22	0.12	2.67	1.37	0.71	0.19
1,2,3,7,8-Pentachlorodibenzofuran (PeCDF)	79.3	41	ND	ND	ND	ND	ND	ND
2,3,4,7,8-Pentachlorodibenzofuran (PeCDF)	122	60	ND	ND	ND	ND	ND	ND
1,2,3,4,7,8-Hexachlorodibenzofuran (HxCDF)	175	102	ND	ND	ND	ND	0.13	0.064
1,2,3,6,7,8-Hexachlorodibenzofuran (HxCDF)	56	34.4	ND	ND	ND	ND	ND	ND
1,2,3,7,8,9-Hexachlorodibenzofuran (HxCDF)	2.9	1.05	ND	ND	ND	ND	ND	ND
2,3,4,6,7,8-Hexachlorodibenzofuran (HxCDF)	58.45	33.1	ND	ND	ND	ND	ND	ND
1,2,3,4,6,7,8-Heptachlorodibenzofuran (HpCDF)	65.9	28	ND	ND	ND	ND	ND	ND
1,2,3,4,7,8,9-Heptachlorodibenzofuran (HpCDF)	10.06	4.29	ND	ND	ND	ND	ND	ND
Octachlorodibenzofuran (OCDF)	16.35	2.7	0.74	0.001	0.68	0.14	0.31	0.15
Total tetra-dioxins	20.15	13.7	ND	ND	ND	ND	ND	ND
Total penta-dioxins	21.55	18.1	ND	ND	ND	ND	ND	ND
Total hexa-dioxins	13.3	3	ND	ND	ND	ND	ND	ND
Total hepta-dioxins	10.42	0.97	ND	ND	ND	ND	ND	ND
Total tetra-furans	2575	1110	ND	ND	ND	ND	2.18	1.09
Total penta-furans	1555	810	ND	ND	ND	ND	ND	ND
Total hexa-furans	544	318	ND	ND	ND	ND	ND	ND
Total hepta-furans	101.6	56.8	ND	ND	ND	ND	ND	ND
2,3,7,8-Tetrachlorodibenzofuran (TCDF)	475	206	0.48	0.16	ND	ND	1.21	0.61
2,3,7,8-Tetrachlorodibenzofuran (TCDF)	82.1	31.2	ND	ND	ND	ND	0.51	0.26
Polybrominated diphenyl ethers [*]	Concentrations in µg/kg							
PBDE 17	ND	ND	ND	ND	ND	ND	0.21	0.11
PBDE 47	0.018	0.004	0.014	0.000	0.020	0.004	0.16	0.08
PBDE 99	ND	ND	ND	ND	ND	ND	0.14	0.07
PBDE 85	ND	ND	ND	ND	ND	ND	0.07	0.04
PBDE 128	ND	ND	ND	ND	ND	ND	0.09	0.04
PBDE 209	0.43	0.22	ND	ND	0.05	0.10	ND	ND
Polynuclear aromatic hydrocarbons (PAHs) ^{**}	Concentrations in µg/kg							
Naphthalene	3.9	0.4	3.2	0.4	0.41	0.1	24.5	7
2-Methylnaphthalene	ND	ND	ND	ND	ND	ND	0.62	0.15
Dibenzofuran	4.1	1.2	1.2	2.15	0.05	ND	13	6
Phenanthrene	ND	ND	ND	ND	ND	ND	6.15	3.3
Anthracene	ND	ND	ND	ND	ND	ND	0.88	0.44
Semi-volatile organic chemicals ^{***}	Concentrations in mg/kg							
Di- <i>n</i> -butyl Phthalate	ND	ND	ND	ND	ND	0.008	ND	ND
Benz(a)anthracene	0.014	ND	0	ND	ND	0.007	ND	ND
Chrysene	0.12	0.06	0.013	0.012	0.007	ND	ND	ND
Volatile organic compounds ^{****}	Concentrations in mg/kg							
Benzene	ND	ND	ND	ND	ND	ND	0.04	0.01
Chloroform	ND	ND	ND	ND	ND	ND	0.04	0.02
Methylene chloride	ND	ND	ND	ND	ND	ND	0.35	0.04

Notes: ND = not detected.

^{*} The following BDE congeners were not detected in ash from any of the components: 28, 71, 66, 100, 138, 153, 154, 183, 190, 203, and 206.

^{**} The following PAHs were not detected in ash from any of the components: acenaphthelene, acenaphthene, benzo(*b*)fluoranthene, benzo(*k*)fluoranthene, benzo(*g,h,i*)perylene, benzo(*a*)pyrene, dibenz(*a,h*)anthracene, fluoranthene, fluorene, indeno(1,2,3-*cd*)pyrene, pyrene.

^{***} The following semi-volatile organic chemicals were not detected in ash from any of the electronic components: Bis(2-ethylhexyl) phthalate, butyl benzyl phthalate, 4-bromophenyl phenyl ether, 4-chlorophenyl phenyl ether, 3,3'-dichlorobenzidine, 2,4-dinitrotoluene, diethyl phthalate, di-*n*-octyl phthalate, hexachlorobenzene, 2-methyl-4,6-dinitrophenol, 4-nitroaniline, *N*-nitrosodiphenylamine, pentachlorophenol.

^{****} The following volatile organic compounds were not detected in ash from plastic components: acetone, bromochloromethane, bromodichloromethane, bromomethane, 2-butanone, carbon disulfide, carbon tetrachloride, chloroethane, chloromethane, dibromomethane, 1,1-dichloroethane, 1,2-dichloroethane, 1,1-dichloroethene, dichlorodifluoromethane, 1,2-dichloropropane, cis-1,3-dichloropropene, 2,2-dichloropropane, 1,1-dichloropropene, cis-1,2-dichloroethene, trans-1,2-dichloroethene, trans-1,3-dichloropropene, 4-methyl-2-pentanone, tetrachloroethene, toluene, 1,1,1-trichloroethane, 1,1,2-trichloroethane, trichloroethene, trichlorofluoromethane, vinyl chloride.

PBDEs are structurally similar to PCBs and they are used widely as flame-retardants in electronic products. BDE-47 (2,2',4,4'-tetrabromodiphenyl ether) was detected in ash from all four components of e-waste tested, with the highest levels in plastics and circuit boards. BDE-209 or decabromodiphenyl ether (2,3,4,5,6-pentabromo-1-(2,3,4,5,6-pentabromophenoxy)benzene) were also found in ash from batteries and circuit boards. Bi and colleagues [35] showed that artisanal e-waste miners in Guiyu, China, have significantly elevated body burdens of PBDEs, including up to 300 ng of BDE-209/g of lipid, the highest dose ever reported in humans. In 2008, the U.S. EPA [36] released the report from a broad-based stakeholder partnership with the agency's Design for the Environment (DfE) Program on the use of flame-retardants in printed circuit boards. New production of tetrabromodiphenyl ether and pentabromodiphenyl ether was banned under modification of the Stockholm Convention, effective in August 2010, with exemptions permitted for recycling and reuse of products containing these two congeners.

Polynuclear aromatic hydrocarbons (PAHs) from combustion processes are notorious air pollutants that are recognized carcinogens and teratogens. Naphthalene was detected in all four e-waste components, with the highest levels in ash from plastics where significant levels of dibenzofuran, phenanthrene and anthracene were also present. Tang and colleagues [37] reported very high levels (up to 3.4 mg/kg) of PAHs in agricultural soils in an e-waste recycling town in Taizhou area, China, where open burning of electronic components is practiced. More recently, Wang et al. [38] found a predominance of phenanthrene and other low molecular weight PAHs in soil and high molecular weight PAHs such as fluoanthene, pyrene, and benzo[*a*]anthracene were bio-accumulated in vegetation near e-waste recycling sites in South China. They further estimated that the human daily intake of total and carcinogenic PAHs through vegetables in the area were 279 and 108 ng/kg/d, respectively.

The data on semi-volatile chemicals in ash from incinerated e-waste show that Di-*n*-butyl phthalate was detected in ash from printed circuit boards; benz[*a*]anthracene in batteries and printed circuit boards; and chrysene in batteries and screens. Volatile organic chemicals were detected only in ash from plastic components of e-waste, including methylene chloride, chloroform and benzene. Although it is impossible to rule out the possibility that some of these volatile organic chemicals were absorbed into the e-waste ash after incineration, it is more likely that they are products of incomplete combustion of other e-waste chemicals at the temperatures used in this study [39]. These chemicals are known toxicants that have been associated with disease conditions such as cancers (e.g. chrysene), neurological damage (e.g. chloroform) immune deficiency (e.g. benzene) and respiratory illnesses (e.g. methylene chloride) through occupational exposures [40].

3.3. Assessment of environmental and human health Impacts of e-waste ash

Data obtained from chemical analyses of the ash samples (Tables 1 and 2) were used to transform ecotoxicity characterization factors (PAF m³ day/kg) and human health characterization factors generated with the USEtox[®] model to derive potential ecological and human disease impacts of toxic chemicals at the concentrations measured in e-waste ash. The model results should also assist product designers and manufacturers pinpoint opportunities to reduce the level of hazards associated with electronic products at the end of their useful lives, and to inform strategies for regulating e-waste processing, including the provision of risk management tools for artisanal e-waste mining [41].

Figs. 1 and 2 represent the results from USEtox[®] modeling. Among the metals identified, copper levels in ash from all

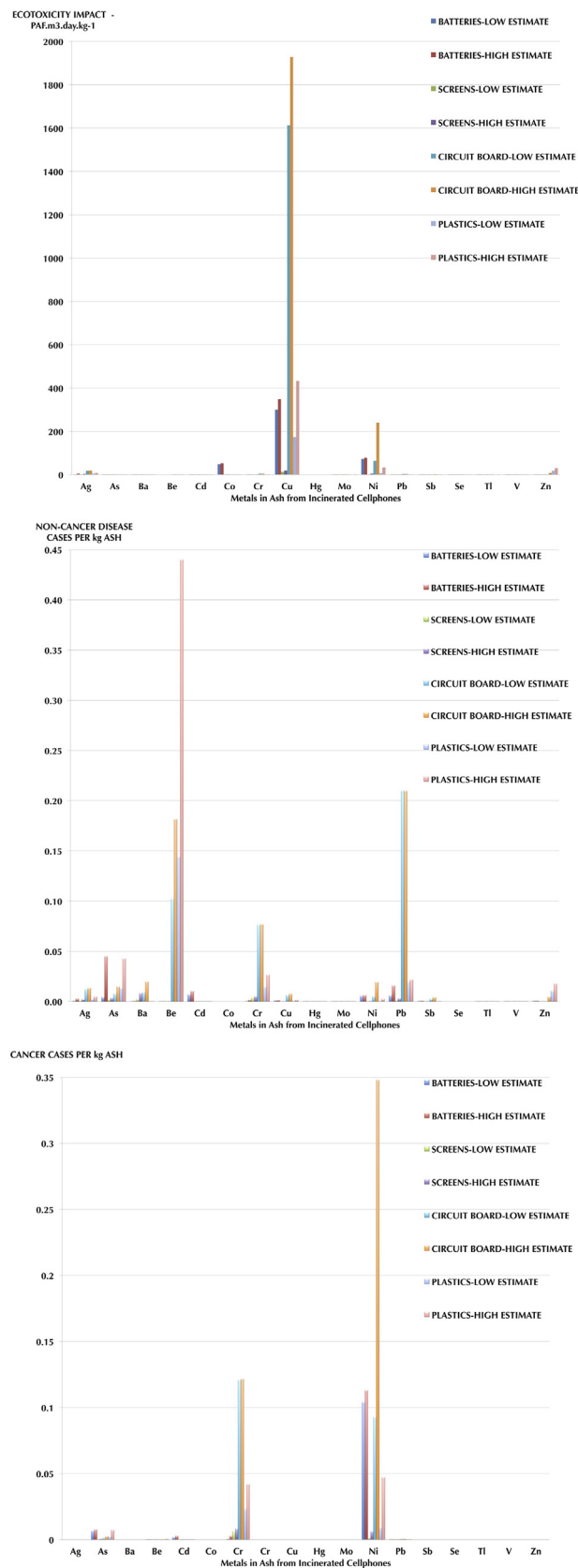


Fig. 1. Results of USEtox[®] chemical life cycle assessment modeling of the ecotoxicological (Panel A), and human non-cancer (Panel B) and cancer (Panel C) impacts of metals identified in ash from incinerated e-waste components.

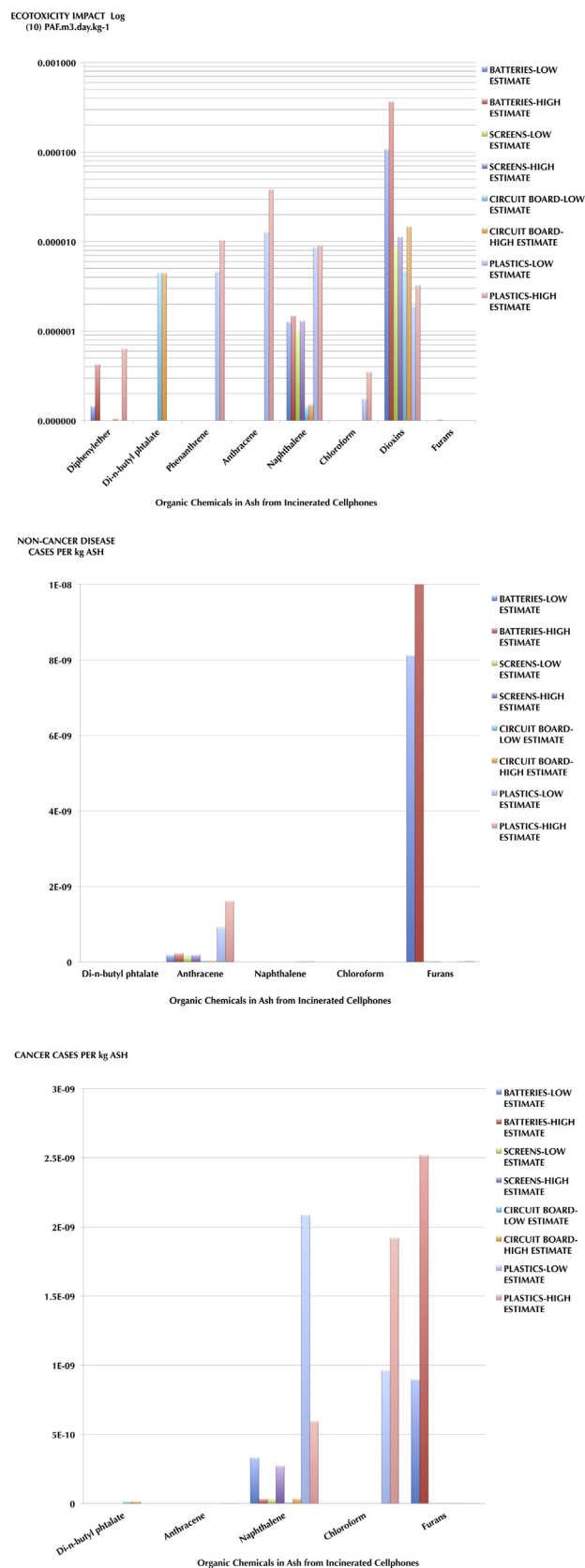


Fig. 2. Results of USEtox® chemical life cycle assessment modeling of the ecotoxicological (Panel A), and human non-cancer (Panel B) and cancer (Panel C) impacts of organic chemicals identified in ash from incinerated e-waste components.

components, but mainly from printed circuit boards posed the most significant ecotoxicity risks, followed by nickel and cobalt in batteries (Fig. 1A). Beryllium in incinerated e-waste plastics posed the most significant risk of producing non-cancer diseases, likely because of the use of beryllium alloy in molding plastics. In addition to beryllium, lead (Pb), mainly from printed circuit boards, chromium from circuit boards and plastics, arsenic from batteries and plastics, and barium and silver from circuit boards, in respective order of magnitude, also pose considerable risk of producing non-cancer diseases (Fig. 1B). Nickel in ash from incinerated printed circuit boards, batteries, and plastics; and chromium from incinerated printed circuit boards, plastics, and screens, in decreasing order of magnitude are all potentially capable of producing cancers in exposed populations (Fig. 1C).

Among the organic chemicals detected in the ash from incinerated e-waste, dioxins were present in all components, and modeling results showed that this category of toxicants, particularly from incinerated batteries, is most likely to be responsible for adverse ecotoxicity impacts. Anthracene, naphthalene, and phenanthrene from e-waste plastics also have the potential to produce ecotoxicity impacts. Phthalates from printed circuit board and diphenyl ether from batteries also contribute substantial ecotoxicity impacts (Fig. 2A). Furans from incinerated batteries contributed most to produce non-cancer diseases (Fig. 2B). Furans from incinerated batteries are also risky for carcinogenesis in populations exposed to incinerated e-waste ash. Similarly, chloroform and naphthalene from plastics are also culpable carcinogens in e-waste ash (Fig. 2C).

Although disease causality is difficult to ascertain, meta-analysis studies of the epidemiological consequences of human exposure to e-waste support the suspicion that various diseases of the genomic, hormonal, neurodevelopmental, reproductive, and respiratory systems have resulted from the toxic chemicals used to manufacture electronic products [42,43]. The results of the chemical life cycle impact assessment of e-waste ash presented here provides new information that may be used to support confirmatory assessments linking specific exposures to disease outcomes, and to support design-for-the-environment strategies [44].

4. Conclusions

This research presented evidence that environmental contamination and adverse public health impacts are associated with incineration of e-waste under conditions similar to those practiced by artisanal e-waste miners in many parts of the world. Populations exposed to the ash from these practices are at risk for various chronic and acute health effects. The results call for increased efforts to regulate the international management of e-waste and to encourage designers and manufacturers to reduce the toxic material content of the components assembled into electronic products.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.jhazmat.2014.05.089>.

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