RUSSIAN JOURNAL *of* EARTH SCIENCES

SPECIAL ISSUE: "FUNDAMENTAL AND APPLIED ASPECTS OF GEOLOGY, GEOPHYSICS AND GEOECOLOGY"

E-WASTE: A CONCISE UPDATE ON GLOBAL MOVEMENT, IMPACTS, MANAGEMENT, AND SITE REMEDIATION

Ming Hung Wong[1,2]

[1]Soil Health Laboratory, Southern Federal University, Rostov-on-Don, Russia
[2]Consortium on Health, Environment, Education, and Research (CHEER), The Education University of Hong Kong, Tai Po, Hong Kong, China
* **Correspondence to:** Ming H. Wong, minghwong@eduhk.hk

Abstract: The rapid rise of electronic waste (e-waste) worldwide has become a public health concern. Wealthy countries are disposing of their e-waste to other countries taking advantage of their less stringent environmental laws and regulations. China used to receive large amounts of e-waste through Hong Kong (a free port) but banned the entry of e-waste in 2013. Salvaging or recycling different parts of the e-waste using primitive and uncontrolled techniques generated a wide range of toxic chemicals (mainly heavy metals and persistent organic pollutants). Most studies concerning the environmental and health impacts of the emitted toxic chemicals were conducted in China. The principal aim of this short article is to review the various environmental problems and health impacts of e-waste recycling, policies, management, and remediation of contaminated sites. Out of the primitive methods used for recycling, the two most destructive ones causing harm to the environment and human health are (1) Open-burning of e-waste for disposing of the salvaged e-waste and (2) Acid-stripping of electronic boards for collecting precious metals (gold, silver, platinum). There is sufficient evidence showing the associations between the toxic chemicals in different media (i.e., water, soil/sediment, air) and local food items (i.e., fish, meat, vegetables), linking with body burdens (hair, milk, placenta) of workers and residents. The epidemiological data further demonstrated the abrupt rise of several significant diseases (i.e., respiratory disease, cardiovascular disease, malignant tumors) in Taizhou (China), one of the two e-waste recycling sites. Effective policies and vigorous enforcement in managing e-waste are essential. International cooperation is necessary to prohibit the transboundary movement of e-waste. Sites contaminated by e-waste recycling contain incredibly high concentrations of toxic pollutants, which should be removed using excavation, degradation (via microbes, nanoparticles, biochar), soil washing, etc. Planting appropriate plants with associated rhizospheric microbes would achieve longer-term stability.

Keywords: ecological and human health, open burning, persistent toxic substances, primitive recycling techniques.

Citation: Wong M. H. (2023), E-Waste: a Concise Update On Global Movement, Impacts, Management, and Site Remediation, *Russian Journal of Earth Sciences*, Vol. 23, ES0208, https://doi.org/10.2205/2023ES02SI08

RESEARCH ARTICLE

Received: 20 October 2023
Accepted: 27 November 2023
Published: 15 December 2023

1. Introduction

End-of-life electrical and electronic equipment (EEE) is called waste electrical, electronic equipment, WEEE, or simply electronic waste (e-waste). E-waste contained personal computers, mobile phones, and entertainment electronics made of plastic, metals, glass, and other materials. The total annual global e-waste generation rose from 44.4 metric tonnes (Mt) in 2014 to 57.4 Mt in 2021, expected to reach 74.7 Mt in 2030, growing by 2 Mt yearly. One primary reason for the rapid rise of e-waste is various products' shorter lifespans. The ever-growing number of new models for attracting buyers, especially in more affluent countries, has aggravated the problem. The Europeans produced the most e-waste per person (16.2 kg), followed by Oceania (16.1 kg) and the Americas (13.3 kg). In terms of the amount of e-waste by countries, China tops the list (10,129 kilo tonnes [Kt]), followed by the USA (6918 kt) and India (3230 kt). Less than one-fifth of e-waste is recycled globally, although the amount varies by region. About 17.4% of the total e-waste has been collected and properly recycled, but the figure has decreased in the past 5 years due to more e-waste generated [*Roundup.com*, 2022]. Table 1 indicates the top 10 e-waste-producing countries with the total volumes of e-waste produced in Kt and the recycling rates.

Table 1. The amounts of e-waste and recycling rates of the world's top 10 e-waste-producing countries [*Roundup.com*, 2022].

Rank	Country	E-Waste Produced (Kt)	Recycling Rate
1	China	10129	16%
2	USA	6918	15%
3	India	3230	1%
4	Japan	2569	22%
5	Brazil	2143	0%
6	Russia	1631	6%
7	Indonesia	1618	Not Available
8	Germany	1607	52%
9	UK	1598	57%
10	France	1362	56%

This fast-growing waste stream imposes severe environmental issues, especially in China in the past. In addition to many domestically produced and discarded products, China received about 70% of worldwide e-waste illegally imported from developed countries. As a free port, Hong Kong Self Administrative Region (HKSAR) received a large amount of e-waste from the USA, EU, Japan, and Korea and smuggled to mainland China from the 1990s to 2010s, ending up in two mega e-waste recycling sites: Guiyu (Guangdong Province) and Taizhou (Zhejiang Province). The disposal, recycling, and part salvaging of discarded electronic devices (computers, printers, televisions, and toys) using primitive techniques severely impacted the environment and human health around the recycling sites for almost three decades [*Lin et al.*, 2019].

A food consumption survey was conducted to find out the consumption pattern of workers and residents in Guiyu and Taizhou. This was followed by the food basket analyses, quantifying the toxic chemicals entering human bodies through oral intake. There were significant correlations between poisonous substances (Hg, PCDD/Fs, PCBs, PBDEs, etc.) in the food items they consumed daily and the high body burdens (i.e., different human tissues such as milk, placenta, and hair) of these toxic chemicals. The human health impacts were further demonstrated by a local hospital's higher morbidities of several significant diseases [*Chan et al.*, 2007; *Lin et al.*, 2022a].

China exerted stringent border control in 2012, prohibiting the entry of e-waste. As such, e-waste has been stored in Hong Kong or diverted to other countries. Placing trackers on e-waste by the Basal Action Convention Network on various e-waste items revealed that e-waste originating from the USA is illegally transferred to Hong Kong SAR and other places [*Lin et al.*, 2019; *Purchase et al.*, 2020].

The principal objective of this presentation is to update the recent status of the international movement of e-waste, the environmental and health impacts of uncontrolled e-waste recycling, the management and policy of e-waste, and the remediation strategies of contaminated sites. This article focused on the two mega e-waste recycling sites (i.e., Guiyu and Taizhou, China), where most environmental and human health impact studies were conducted. Now that the e-waste is diverted to other countries due to the entry ban imposed by China, it is hoped that these receiving countries of e-waste will not repeat the same mistakes made in these two sites and also learn from the achievements made towards solving the problem.

2. Transboundary Movement of E-waste

2.1. 2.1 China Received Large Amounts of E-waste Before 2010

China was the world's major country receiving incredibly high quantities of e-waste from abroad for over two decades in the 2000s, mainly through Hong Kong. Most of this imported e-waste was sent to two mega e-waste sites for uncontrolled recycling. China started to amend and enforce import regulations in 2010 and has achieved positive outcomes, with the quantities of illegal importation gradually decreasing since the 2020s. The import quantities will sharply shrink and disappear in the coming decades if China keeps tightening import regulations. Substantial amounts of displaced e-waste divert to other countries due to China's entry ban on e-waste.

Hong Kong is China's Self Administrative Region (SAR) with an independent judiciary, the rule of law, and a free trading policy. A substantial amount of e-waste has entered Hong Kong. Based on the e-trash transparency project conducted by The Basel Action Network (BAN), a watchdog of the Basel Convention, it has been noted that most exported tracked devices from the USA (57%), Canada (50%) and Australia (67%) ended up in Hong Kong in 2016/17, adding up to about 335,084 t e-waste entering Hong Kong. Therefore, Hong Kong's role as an entry pot for mainland China's ewaste has now changed to an alternative e-waste receiving center [*Lin et al.*, 2019].

2.2. The Consequences After China Banned E-waste Entry

This large quantity of e-waste has been stored and even recycled in the northern part (the New Territories) of Hong Kong at about 70 sites, mainly abandoned farm soils, with some close to the RAMSAR site (Tai Po) [*Lin et al.*, 2019]. These areas had active agricultural activities in the past (before the 1980s), mainly producing vegetables and fruits for local consumption. However, due to socio-economic development and the change in land use, large stretches of farmland have been converted to car repairing workshops and e-waste storage. Some simple disassembling and recycling are also carried out on-site, leading to severe soil pollution with high concentrations of heavy metals (HMs): cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), zinc (Zn), mercury (Hg), and nickel (Ni), and persistent organic pollutants (POPs): polychlorinated biphenyls (PCBs), aromatic hydrocarbons (PAHs), dioxins/furans: polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), and flame retardants: polybrominated diphenyl ethers (PBDEs) in abandoned farm soils, incredibly open burning sites [*Lopez et al.*, 2010].

It was demonstrated that the high concentrations of HMs of air particulates and floor dust inside e-waste recycling workshops posed potential health risks linked to the workers' elevated blood Pb levels [*Lau et al.*, 2013]. In addition, POPs such as PAHs and PCDD/Fs in open burning sites of these abandoned farm soils may also pose detrimental health effects: mutagenicity and genotoxicity to the general public [*Man et al.*, 2014].

As some of the e-waste storage and recycling sites are close to the RAMSAR site (Tai Po), there are concerns about whether the water birds have been safely protected. These included the endangered species: black-face spoonbills visiting the sites every winter from Siberia [*Man et al.*, 2021]. Ecological risk assessments were conducted based on Cd, Cu, Hg, Pb, Zn, and arsenic (As) concentrations in biota (two fish and one shrimp species), water, and sediment. Results showed that the common sandpiper (*Actitis hypoleucos*) was at risk as the small-sized bird sought food from the sediments, reflecting that other juvenile birds with similar ecological and feeding habits may also be at risk.

3. Two Mega E-Waste Sites and the Primitive Techniques Used for Recycling

Most of the e-waste shipped to Hong Kong ended up in two e-waste recycling sites in China through smuggling through the China and Hong Kong border in the past. As most of the studies were conducted in these two sites, understanding more about the two mega sites for e-waste recycling and the techniques employed for dismantling, salvaging, and recycling various parts of end-of-life electronic products is essential.

3.1. Two Mega E-Waste Recycling Sites in China

Guiyu town (N23° E116°), located in the south-eastern part of Guangdong Province, with a population of 150,000 and a land area of 52.4 km^2, has been a significant e-waste dumping site for e-waste exported from North America since the 1980s. E-waste recycling was also conducted in Luqiao City, in the southern part of Taizhou (N28° E112°), along the central coastal section of Zhejiang Province, with a population of 400,000 and a land area of 274 km^2. The city has handled e-waste, especially those containing PCBs, generated domestically since the 1970s and started to process different kinds of e-waste imported from other countries since the 1990s. It was China's largest center for dismantling obsolete transformers and capacitors [*Lin et al.*, 2022a].

3.2. Primitive Techniques Used in Recycling E-Waste

In general, the primitive and unsafe techniques used included: (1) Manual separation of different products of the e-waste; (2) Stripping of metals in open-pit acid baths to collect precious metals (gold, silver, and platinum); (3) Removing electronic components from a circuit board by heating it over a grill, and chipping and melting plastics indoor, without proper ventilation; (4) Burning electronic cables to collect copper; and (4) Open burning all unsalvageable materials in the field, to reduce the waste volume and dispose of the waste (with ash flushed into nearby waterways) [*Wong et al.*, 2007].

4. Toxic Chemicals Emitted During Uncontrolled E-waste Recycling

Our recent review [*Lin et al.*, 2022a] summarized the published results on sources and types of various heavy metals and POPs derived from uncontrolled e-waste recycling obtained in Guiyu and Taizhou (China), compared with studies carried out in other countries. There is no intention to repeat the detailed discussion in the current article. Listed below highlighted the sources and extent of pollution derived from e-waste recycling linking to the next section on health implications.

The primary sources of toxic chemicals were the incomplete combustion (open burning) of various components of e-waste (e.g., plastic chips, wire insulations, PVC materials, and metal scraps), acid treatment of printed circuit boards and uncontrolled disposal of processed materials (including the acid baths after stripping electronic boards). All the environmental media (i.e., air, soil/sediment, water) are highly contaminated with extremely toxic chemicals, including HMs: Hg, Cu, Zn, and Pb and POPs: PBDEs, PCDD/Fs, PCBs, and PAHs in air, soil/sediment, water, and fish. In general, the concentrations of these toxic chemicals were extremely high compared with guidelines adopted in different countries [*Lin et al.*, 2022b].

4.1. Heavy Metals (HMs)

Printed circuit boards are heated on top of an open fire indoors to remove different components more efficiently, and they are also treated with strong acids to collect more precious metals like gold, silver, and platinum. Leung et al. [*Leung et al.*, 2008] investigated heavy metal pollution inside and close to these workshops in Guiyu. They noted high mean concentrations of HMs in the workshop dust and roadside dust near the workshops: Pb (110,000, 22,600 mg/kg), Cu (8360, 6170 mg/kg), Zn (4420, 2370 mg/kg), and Ni (1500, 304 mg/kg). Schoolyards and food markets were also affected though to a lesser extent.

Printed circuit boards were also treated with strong acids for collecting precious metals, and the acid residues were disposed of along river banks. The river sediments in Guiyu were contaminated with Pb (28.6–590 mg/kg), Cu (17.0–4540 mg/kg), Zn (51.3–324 mg/kg), Ni (12.4–543 mg/kg) and Cd (ND–10.3 mg/kg). The local and downstream aquatic and terrestrial environment is expected to be severely impacted.

4.2. Persistent Organic Pollutants (POPs)

The combustion of e-waste generated a relatively high concentration of PCDD/Fs (0.65 pg WHO-TEQ/m^3) (TEQ = the toxic equivalent) in air particles (PM2.5) at Guiyu, slightly exceeding the Japanese guideline of 0.6 pg TEQ/m^3. However, the concentration of the most toxic congener: 2,3,7,8-TCDD (54 fg/m^3) (TCDD=2,3,7,8-tetrachlorodibenzo-p-dioxin, the most toxic congener of PCDDs) was substantially higher than the USA (Indiana, Kansas, and Washington) guideline (of 30 fg/m^3). The air particles also contained extremely high concentrations of total PBDEs (11,226 pg/m^3), 100 times higher than any published data. The particles also had predominately lower brominated PBDEs (1-5 bromine atoms contributed to over 94% of the PBDEs generated), which are known to adversely affect hormonal (thyroid gland), reproductive, and neurological systems [*Leung et al.*, 2007].

Opening burning sites also contained the highest concentrations of PCDD/Fs (14,500 pg WHO-TEQ/g) and PBDEs (883,000 pg/g) ever recorded in soil/sediment, which greatly exceeded various guidelines for agriculture imposed by different countries (Canada: 4 pg TEQ/g, New Zealand, and Sweden: 10 pg-TEQ/g, Japan: 1000 pg WHO-TEQ/g). Deca-BDE (BDE-209) was the most dominant congener (35–82% of total PBDEs) found in combusted residues at the open burning site as well as the dumpsites (at riverbanks). PBDEs are commonly found in various parts of e-waste. It was alarming to note that the monthly concentration of 22 PBDE congeners of 16.8 ng m^{-3} contained in the air particulates PM2.5 at Guiyu was 100 times higher than any published data [*Leung et al.*, 2007].

5. Ecological Effects

The e-waste recycling sites also serve as toxic transformers. An example is the burning of cables to extract the embedded copper. Burning PVC (cable casing) can emit dioxins, and Cu will catalyze to enhance the generation of more dioxins. Furthermore, various toxic chemicals emitted interact, forming new poisonous chemicals that our equipment cannot detect. Due to air and water movement, toxic chemicals from open-burning and acid treatment residues will be diverted to the surrounding environment. They will affect local living organisms such as fish and ducks in rivers, ponds, vegetables, and rice cultivated in local small farms. Some toxic elements, especially POPs (e.g., PBDEs), are expected to enter living organisms by bioaccumulation. Their concentrations will be biomagnified along food chains, posing health hazards to residents.

5.1. Toxic Effects on Different Trophic Organisms

Bioassay tests using different living organisms can indicate the toxicity of various environmental pollutants. Our early study [*Wang et al.*, 2009] employed organisms of three trophic levels: a bacterium *Vibrio fishceri*, a microalga *Selenastrum capricornutum* (elutriate toxicity tests), and a crustacean *Heterocypris incongruens* (whole sediment toxicity test) to characterize the sediment toxicity of the Guiyu site. The sediment received ashes from the open-burning of e-waste and acid residues after acid-tripping metals from electronic boards. Therefore, it is acidic and highly contaminated by HMs and POPs. Results revealed that most sediments exhibited acute toxicity on various trophic organisms due to elevated Cu, Zn, Pb, PAHs, and low pH caused by uncontrolled acid discharge.

5.2. Toxic Chemicals Entering into Food Chains and Biomagnified

It was revealed that rice (*Oryza sativa*) grown (in six areas) near e-waste recycling sites at Taizhou was contaminated with various HMs [*Fu et al.*, 2008]. The daily uptake of Pb through rice consumption of 3.7 µg/day/kg body wt exceeded the FAO Tolerable Daily Intake (TDI). In comparison, the Cd daily uptake of 0.7 µg/day/kg body wt had taken up 70% of the TDI of 1 µg/day/kg body wt. Therefore, long-term locally-produced rice consumption may pose health hazards. Recently, Wu et al. [*Wu et al.*, 2016] carried out a similar study at Guiyu and noted that rice plants could absorb some metals, such as molybdenum (Mo), Cr, and Mn, more efficiently (bioconcentration factor [BCF>1]) than POPs, such as PBDEs and alternative halogenated flame retardants (AHFRs) (BCF<0.15). Rice is the staple diet in South China. A stringent monitoring program of farmland near e-waste sites should be in place to safeguard public health.

Furthermore, POPs are generally lipophilic and can be stored in the lipid of biota efficiently. Therefore, the tissues with high lipid content had higher concentrations of PBDEs in several fish species (e.g., common carp, *Cyprinus carpio*) collected from the local rivers in Guiyu [*Luo et al.*, 2007a]. The distributions of different PBDE congeners in various sampling locations reflected the predominant commercial PBDE products and their subsequent degradation. A significant correlation of concentration of each PBDE conger between sediment and fish muscle was also demonstrated. It was alarming that the total PBDEs in tilapia (*Oreochromis* spp.) collected from local rivers were 600 times and 15,000 times higher than those from Canadian (0.18 ng/g wet wt) and US markets (0.0085 ng/g wet wt), accordingly [*Luo et al.*, 2007b]. Based on the above results, there is an urgent need for a more comprehensive investigation into everyday food items consumed locally.

6. Health Impacts

Lin et al. [*Lin et al.*, 2022a] reviewed the toxic chemicals emitted from uncontrolled e-waste recycling related to the wide range of harmful substances, their transfer to various ecological compartments, and subsequent environmental and health impacts. It was observed that the local biota was grossly polluted, which included food items with vegetables, rice, fish, and seafood contaminated by HMs and livestock by POPs.

6.1. Case Studies (Food Intake, Body Loadings of POPs, and Disease Morbidities)

The workers and residents of e-waste recycling sites are exposed to various toxic chemicals emitted during recycling processes: (1) Oral intake of contaminated food and water, and also contaminated soil and dust unintentionally, (2) Inhalation of aerosol gases and particles, and (3) Dermal contact. In addition, fetuses and children can be exposed through ingesting human milk and placental transfer. The residents of Guiyu and Taizhou drink bottled water to minimize intake of toxic chemicals, but it is expected that some food items they consume daily may be highly contaminated.

The current review focuses on the associations of toxic chemicals entering into human bodies through oral ingestion of locally produced food, linking with body burdens of workers and residents, by analyzing various tissues as bioindicators. Several studies were conducted in the two Mega sites [*Chan and Wong*, 2013; *Man et al.*, 2017; *Xing et al.*, 2010] using exact sampling and chemical analysis protocols. Therefore, they are used as examples to show the adverse health impacts on workers/residents and infants residing in these two mega sites for e-waste recycling.

After gaining information on the food consumption patterns of workers and residents, a food basket analysis was conducted by analyzing POPs (PCDD/Fs, PCBs, and PBDEs) contained in their food items. The oral intake of toxic chemicals was quantified based on the food consumed in these two areas compared with the control site: Lin'an, without any e-waste recycling activities. In general, results showed that over 90% of POPs were through oral intake of contaminated food. The toxic chemicals in local food items were linked with workers' and residents' high body loadings (milk, placenta, hair).

6.1.1. PCDD/Fs (Guiyu and Taizhou)

PCDD/Fs are generated from waste combustion, especially burning materials containing plastics under relatively low temperatures. Heating electronic boards on an open fire indoor and open-burning of savaged e-waste to reduce its volume will undoubtedly generate PCDD/Fs. The ashes and residues derived from these operations were disposed of around burned sites and flushed into waterways spreading the highly toxic substances around [*Lin et al.*, 2019].

The data on PCDD/Fs generated from the uncontrolled operations on the environmental fate, body burdens, and human health risk assessments and detected levels in environmental compartments: air, soil/sediment, dust, and biota (including food) and the human body (milk, placenta and hair of workers/residents) demonstrated extreme environmental and health hazards of the e-waste site. The Estimated Daily Intakes (EDIs) via oral intake, inhalation, soil/dust ingestion, and dermal contacts estimated for adults, children, and breastfed infants ranged from 5.59 to 105.16 pg WHO-TEQ/kg bw/day. All values well-exceeded the TDIs recommended by WHO (1–4 pg WHO-TEQ/kg bw/day). Dietary intake and inhalation are the most critical exposure pathways for infants, children, and adults, with 60–99% and 12–30% of the total exposure doses of intakes [*Chan and Wong*, 2013].

6.1.2. PCBs (Taizhou)

Taizhou has been the primary site for recycling transforms; therefore, PCBs emitted from recycling are a significant public health concern. Results showed a high EDI of PCBs of lactating mothers of 12.9 pg WHO-PCB-TEQ/kg bw/day). This reflected that the PCB-contaminated food (primarily PCB-216 derived from transformers) resulted in high total PCBs detected in these mothers: milk, placenta, and hair of 363, 224, and 386 ng/g dry wt., three times higher than samples of the control site (Lin'an).

Compared with the 3rd round WHO-coordinated study on POPs in human milk, in terms of TEQ levels in human milk, Taizhou topped the list in terms of TEQ levels. If these mothers breastfeed, the infants will lead an extraordinarily high EDI of PCBs of 438 pg WHO-PCB-TEQ/kg. The EDIs of PCBs of 12.9 and 438 pg WHO-PCB-TEQ/kg were higher than the DTI stipulated by WHO of 1–4 pg WHO-PCB-TEQ/kg by 3 and 110 times, respectively, for mothers and infants. This raised a severe health concern as the extremely high body burdens reflected the e-waste recycling activities (mainly recycling transformers) imposed on workers, residents, and the second generation in Taizhou [*Man et al.*, 2017; *Xing et al.*, 2010].

6.1.3. PBDEs (Taizhou)

The pregnant mothers from the e-waste site contained high PBDEs in their tissues (milk 117±191, 8.89–457 ng/g fat, placenta 19.5±29.9, 1.28–72.1 ng/g fat, hair 110±210, 8.47–486 ng/g dry wt.) which were significantly higher than those from the control site (milk 2.06±0.94, 1.0–3.56 ng/g fat, placenta 1.02±0.36, 0.59–1.42 ng/g fat, hair 3.57±2.03, 1.56–5.61 ng/g dry wt.). The following trend was observed in terms of dry weight basis: hair>milk>placenta. A 6-month-old breastfed baby would be exposed to PBDEs orally (572±839 ng/kg body wt/day), 57 times higher than infants from the control site (Lin'an). The maximum calculated value (2240 ng/kg body wt/day) exceeded US EPA's chronic oral reference dose for penta-BDE (2000 ng/kg/day) [*Leung et al.*, 2010].

6.1.4. Lessons Learned From These Cases

Though the long-term health effects are unknown, the 3-year data provided by the Centre for Disease Control in Taizhou showed an abrupt increase in morbidity of a few major diseases (cancer, respiratory, and cardiovascular) [*Lin et al.*, 2022a]. This reflected the seriousness of the problem showing that e-waste recycling activities severely affected human health and the second generation. These and associated socio-economic loss can better convince policymakers to formulate and enforce control policies.

These studies indicated that local food items: vegetables, rice, livestock, seafood, and in particular, fish, were heavily polluted by HMs and POPs. Dietary exposure is the most important exposure pathway. The associations between exposure to e-waste and high body burdens of these pollutants were evident. Furthermore, the exceedance of national and international standards showed the seriousness of PCDD/Fs, PCBs, and PBDEs on their adverse impacts on the environment and human health. It seems apparent that toxic chemicals emitted from e-waste activities are causing several major illnesses mentioned above.

There are potential dangers of toxic chemicals passing on to the next generation via placental transfer and lactation. Following the development and health status of infants and children born and brought up in the e-waste sites is essential. Knowledge gaps exist, including more comprehensive and accurate dietary exposure data, body burdens (mothers, infants, and children), and kinetics about POPs partitions among different human tissues. More epidemiological and clinical studies are essential to address all these problems and make them available to the general public.

6.2. Modes of Action and Effects of Toxic Chemicals

According to experimental and human studies, Table 2 [*Frazzoli et al.*, 2019] provides a more comprehensive of all the toxic chemicals emitted during various recycling processes and their long-term toxicological impacts. The mixtures of poisonous substances cover both chemicals present in multiple e-waste, i.e., HMs and POPs: brominated flame retardants (BFRs) and non-dioxin-like polychlorinated biphenyls (NDL PCBs) and chemicals emitted during e-waste combustion: PAHs, PCDD/Fs, and dioxin-like polychlorinated biphenyls (DL PCBs).

HMs enter the human body through oral ingestion, dermal contact, and inhalation. They pose severe health threats due to membrane and DNA damage, protein function, and enzyme activity disturbance. They interfere with normal protein functions by binding to free thiols or other functional groups. They also catalyze the oxidation of amino acid side chains, disturb protein folding, and/or substitute essential metal ions in enzymes. Accumulating these heavy metals in various tissues and organs may lead to critical diseases like cancer.

POPs like PCDD/Fs, PBDEs, and PCBs can be bioaccumulated and biomagnified in the food chains. Furthermore, they are considered silent killers because of their persistent and highly toxic nature. Once emitted, they enter into different ecological compartments and biota, including plants, animals, and humans, imposing severe ecological and human health impacts. The lethal diseases include diabetes, obesity, endocrine disturbance, cancer, and cardiovascular and reproductive problems [*Alharbi et al.*, 2018].

Table 2. Summary of long-term toxicological effects of e-waste-related chemicals by nonoccupational exposure; evidence collected from experimental and human studies [*Frazzoli et al.*, 2019].

Chemical	Mode(s) of action	Effects
PCDD/Fs	Interaction with the aryl hydrocarbon receptor. Significant bioaccumulation related to lipid solubility	Chloracne at high exposure levels. Disruption of reproductive, neurobehavioral, and immune development. Increased risk of chronic diseases, including cancer
PBDEs	Interaction with thyroid hormones, retinoic acid, and several nuclear receptors (e.g., pregnane-X). Significant bioaccumulation related to lipid solubility	Lower thyroid function. Impaired reproductive and neurobehavioral development
PCBs	Significant bioaccumulation related to lipid solubility. Many congeners with different modes of action: dioxin-like PCBs are similar to PCDDs/PCDFs, though generally less potent; non-dioxin-like PCB: interference with the metabolism of thyroid and estrogens, oxidative stress	Disruption of reproductive, neurobehavioral, and immune development. Increased risk of chronic diseases, including cancer

Continued on next page

Table 2. Summary of long-term toxicological effects of e-waste-related chemicals by nonoccupational exposure; evidence collected from experimental and human studies [*Frazzoli et al.*, 2019]. (Continued)

Chemical	Mode(s) of action	Effects
PAHs (high molecular wt)	Genotoxic damage, oxidative stress, and interaction with aryl hydrocarbon receptor	Carcinogenicity, mutagenicity, and teratogenicity
Al	Interaction with calcium and cell-cell communication	Skeletal development and metabolism, neurotoxicity, and fetal toxicity
Inorganic As	Oxidative stress and interaction with glucocorticoid receptor	Skin alterations, decreased nerve conduction, increased risk of diabetes and skin and other cancers
Cd	Oxidative stress and interaction with other elements (Ca and Se), the agonist of estrogen receptor alpha	Kidney damage, bone disease (osteomalacia and osteoporosis), possibly reproductive damage, and lung emphysema
Cu	An essential element at high-dose levels may cause liver damage and interfere with Zn	Liver damage
Hexavalent Cr	Cytotoxicity and oxidative DNA damage	Carcinogenicity
Fe	An essential element that may cause liver damage at high-dose levels	Liver damage
Pb	Interaction with sulfur amino acids, disturbed cell proliferation/ differentiation/communication	Impaired neurobehavioral development of children; anemia, kidney damage, and chronic neurotoxicity
Hg	Interaction with sulfur amino acids, disturbed cell proliferation/ differentiation/communication; interaction with Se. Organic methylmercury can bioaccumulate	Impaired neurobehavioral development of children (especially methylmercury). Anemia, kidney damage, and chronic neurotoxicity
Se	An essential element that may interact with sulfur amino acids at supernormal dose levels	Hair loss; nail brittleness; cardiovascular, renal, and neurological abnormalities
Zn	An essential element that may impair copper metabolism at high-dose levels	Increased risk of copper deficiency (anemia and neurological abnormalities)

6.3. Overall Health Impacts with Emphasis on Children and Pregnant Women

Grant et al. [*Grant et al.*, 2013] conducted the 1st review on the health impacts of e-waste recycling based on 23 epidemiological studies between Jan 1965 and Dec 2012. Residents of e-waste sites are exposed to elevated levels of HMs and POPs, with children and pregnant women more susceptible to the adverse effects on biological systems and organs. The neonatal growth indices and hormone levels were detrimentally affected. There were possible associations between chronic exposure to toxic chemicals and DNA lesions, telomere attrition, elevated oxidative stress, etc. A more recent follow-up review [*Parvez et al.*, 2021] based on 70 (66 in China, 2 in Vietnam, 1 in India, 1 in Ghana) studies conducted between Dec 2012 to Jan 2020 showed more detailed analyses disclosing the following adverse health impacts: (1) Growth and neurodevelopment effects, (2) Hormonal and immunological function, (3) Genetic and oxidative changes, (4) Respiratory, cardiovascular, and hematological changes, (5) Vaccine, olfactory, reproductive, and other health effects.

WHO [*WHO*, 2021] stated substances detected in e-waste recycling sites that are of significant public health concern: Pb, Cd, Hg, PCDDs, PM2.5, PCBs, PBDEs, per- and polyfluoroalkyl substances (PFAS), phthalate esters, organophosphate flame retardants (PFRs), and bisphenols. Based on various studies primarily conducted in China, it was concluded that prenatal and childhood exposure to e-waste toxic chemicals are significantly correlated with (1) impaired neurodevelopment and behavior (Pb, Hg, and some organic chemicals such as PCBs), (2) adverse birth outcomes (PAHs, Pb, Cd, Ni, and Cr), (3) damaged lung function and respiratory systems (cough, wheezing, and asthma) (Cr, Mn, and Pb), (4) impaired thyroid function (PCBs and PBDEs), (5) impaired cardiovascular system function (Pb and PAHs), (6) DNA damage (Pb, Cr, Cd, and Ni), (7) weakened immune system functions (to common infections such as from hepatitis B, ear and respiratory infections), reduced response to immunization (some organics), more susceptible to allergies and autoimmune diseases (some HMs), and suppression of immune system (Pb and Cd), and (8) increased chronic diseases (cancer and cardiovascular disease) at a later stage in life (various toxic chemicals).

Because of their hand-to-mouth activities and spending more time contacting the floor coated with dust and dirt, children are more susceptible to exposure through oral intake and dermal contact with contaminated soil/dust. Furthermore, due to their smaller size, less developed organs and immune systems, and rapid growth and development, they tend to absorb higher proportions of pollutants. They are less able to metabolize and eliminate toxic substances from their bodies than adults. For pregnant women working or residing close to e-waste sites, there are dangers of fetal exposure to various toxic chemicals, leading to short-term impacts on the pregnancy and long-term effects on the health of new-borns in childhood or adult life [*WHO*, 2021].

7. Policy and Management

Some countries, such as Australia, dispose of e-waste in landfills, generating leachates containing high concentrations of toxic metals and flame retardants [*Kiddee et al.*, 2013a]. The leached toxic chemicals may find their way into the waterways. Through bioaccumulation and biomagnification in food chains, some of our crops and aquatic products accumulate incredibly high concentrations of poisonous chemicals, posing health threats. A more effective collection, disposal, and recycling strategy should be established.

7.1. Responsibilities of Manufacturers and Recyclers

It is critical to follow the EU Regulations on Waste Electrical and Electronic Equipment (WEEE) and the Restriction of Hazardous Substances Directive (RoHS) not to use certain harmful materials (such as Hg and Cd) to manufacture the products and for recycling e-waste [*Kiddee et al.*, 2013a]. The Extended Producer Responsibility (EPR) should be in place to regulate the manufacturers' responsibilities for appropriate management. Some regions/countries, such as Hong Kong (China) and Taiwan (China), the USA, Switzerland, Japan, etc., implemented the EPR to regulate the responsibilities of various sectors: manufacturers, retailers, and relevant administrations to properly manage e-waste. Unfortunately, these policies tend to focus on pre-contamination rather than post-contamination management.

Receiving countries of e-waste should establish and implement regulations and policies to avoid illegal imports and recycling. Techniques for e-waste recycling should be improved. Centralized dismantling and treatment of e-waste using more sophisticated equipment and methods are also needed. National strategies for managing e-waste should include (1) Effective environmental education, (2) Prohibiting illegal import/transaction, (3) Forbidding illegal recycling activities, (4) Reinforcing regulations and laws, (5) Centralizing and encouraging legal recycling activities, and (6) Continuous monitoring [*Lin et al.*, 2022b].

7.2. International Conventions Should Be Revisited

The loopholes of the e-waste movement from more wealthy countries to other countries possess less stringent environmental laws, and less prosperous economies should be plugged. Unfortunately, the USA, the largest e-waste exporter, has not signed the convention. It is vital to check the effectiveness of the Basel Convention on the Control of

Transboundary Movements of Hazardous Wastes and their Disposal (entered into force in 1998). The Basel Convention intended to protect human and environmental health from hazardous wastes (including e-waste) by restricting its transboundary movement. It comprises a three-step approach: (1) minimize waste generation, (2) treat waste near where it is produced, and (3) reduce its international movement.

Under the Basel Convention, a legal loophole exists that the export of whole products is allowed to other countries if they are not purposed for recycling, e.g., for donation for reuse. As such, a substantial amount of waste is being exported as reusable equipment other than waste. One solution to close this legal loophole is only to allow the export of materials that could be used as raw materials, such as crushed glass, shredded plastic, aggregated metal, etc. [*Wong et al.*, 2012]

7.3. Tracking the Global Movement of E-waste is Essential

The global movement across international borders should be discouraged. The Basal Network has done an excellent job of tracking illegal activity, with more wealthy countries sending their trash to other countries with less developed environmental laws and regulations. Some efforts have been made to address the problem since 2010. The initiative related to 'Solving the E-waste Problem Initiative (STEP)' was jointly launched by the US Environmental Protection Agency and the United Nations University (UNU). Projects included the ‘Person-in-the-Port’ for tracking e-waste movements in Nigeria and dismantling facility improvement in Ethiopia. The EPA also made attempts in 2020, collaborating with various environmental authorities in Asia, Africa, Latin America, North America, and the Caribbean to manage e-waste more effectively. Nevertheless, the Basel Network’s recent finding on tracking the global movement of e-waste has pointed out the deficiencies [*Lin et al.*, 2019].

8. Site Remediation

There are techniques successfully developed to decontaminate soil/sediment/water contaminated by mixtures of toxic metals and POPs that we can adopt to clean up contaminated sites derived from e-waste activities. The environmental behavior of toxic chemicals derived from uncontrolled e-waste recycling should be better understood. Different contaminated environmental compartments should be remediated using various techniques [*Lin et al.*, 2022b].

8.1. Remediation of air

In-workshop air treatment facility should be installed for cleaning the e-waste processing air before discharging it into the ambient environment. The gas treatment reactor consists of a spray tower, electrostatic precipitation, and photocatalysis. It can effectively remove almost 70% of volatile organic compounds (VOC) (i.e., halogenated hydrocarbons, aromatic hydrocarbons, and ethyl acetate) after 60 days. In addition, particles of different sizes and water-soluble gaseous pollutants from the polluted air could be efficiently removed by electrostatic precipitation. The powerful and nonselective oxidants could oxidize the levels of POPs via photocatalysis [*Zhang et al.*, 2019].

8.2. Remediation of water

Low-cost permeable reactive barriers supplemented by waste materials such as coal fly ash and wood-derived biochar can prevent the leaching of toxic metals from e-waste-contaminated soils. Low-cost adsorbents, such as coal fly ash (CFA) and food waste compost (FWC), can effectively adsorb toxic metals in water. POPs in water could be degraded via integrated chemical and biological approaches [*Beiyuan et al.*, 2017].

Chelating agents can remove HMs for ex-situ wastewater treatment, while wetland plants can stabilize toxic metals for in-situ treatment. Wetland plants: water hyacinth (*Eichhornia crassipes*), common reed (*Phragmites australis*), bulrush (*Typha* sp.), and vetiver grass (*Chrysopogon zizanioides*) are potential candidates to achieve the purpose [*Deng et al.*, 2016].

8.3. Remediation of sediment/soil

8.3.1. Dredging and excavation – for removing most toxic soils

Soils/sediments serve as sinks of pollutants. POPs such as PBDEs are readily adsorbed by sediment or soil particles instead of accumulated in water. Therefore, they should be excavated and treated by stabilization (mixing with a binding agent) and reused or disposed of in landfills. For example, part of the contaminated sediment/soil (about 77,000 m^2) in Guiyu was either excavated, replaced by clean soil, or washed [*Gdut SII*, 2020].

8.3.2. 8.3.1 Soil washing – for extracting and degrading pollutants

Generally, soil washing using extractants or solvents can enhance pollutant extraction and degradation. Chemicals extract, degrade, or fix pollutants; oxidation and/or degradation could be used simultaneously. Vegetable oil and inexpensive chelants can serve the purpose. A study using hydroxypropyl-β-cyclodextrin (HPCD), citric acid (CA), and sodium persulfate (SP) achieved satisfactory results in treating e-waste contaminated soils (HPCD was effective for extraction of POPs, CA for extraction of metals, and SP for further oxidation of POPs) [*Chen et al.*, 2017]. Environmentally friendly and biodegradable solvents, e.g., sunflower and peanut oil, effectively removed HMs and POPs. The pollutant removal efficiency of soil washing can be further enhanced by different means, e.g., ultrasonication-assisted soil washing. It can strengthen the mobilization of pollutants and reduce the washing time. Soil washing and assisted/enhanced phytoremediation are effective methods for site remediation as they are cost-effective and sustainable, with more significant economic benefits in the long term. However, higher plants and associated microbes are critical components in restoring the normal soil function of the highly disturbed environment, which may require long-term stabilization after soil washing (please refer to the below section on phytoremediation).

8.3.3. Nanoparticle and biochar – for effective pollutant degradation

Nanoscale zero-valent iron (nZVI) and Pd/Fe bimetallic nanoparticles were effective in degrading PCBs (i.e., hydrodechlorination) soils from Taizhou (removal efficiencies: 50–80%) [*Chen et al.*, 2014]. A study also showed that Ni/Fe bimetallic nanoparticles can degrade PBDEs (i.e., debromination), removing PBDEs spiked into clean soil [*Xie et al.*, 2014]. Adding biochar could disperse the nanoparticles, thereby adsorbing metal ions more effectively with negatively charged carboxyl and hydroxyl groups. Debromination of PBDEs was greatly enhanced due to the closer contact between nanoparticles and PBDEs, achieving a removal efficiency of 90% in 72 h. Furthermore, biochar can effectively adsorb and immobilize degradation products and metal ions (such as Ni) investigated in the study to avoid secondary pollution [*Wu et al.*, 2016].

8.3.4. Chelates – for enhancing plant metal uptake and microbial degradation

It is a common practice to use chelates such as S,S-ethylenediamine disuccinic acid (EDDS), and ethylenediamine tetraacetic acid (EDTA) to form metal complexes to lower their toxicity and availability. EDDS is more sustainable because it is more biodegradable and less toxic to biota when compared with EDTA. Soils from a past e-waste-opening site were extracted with EDDS (1:10 ratio of soil: extractant, w/v) observed that a high concentration of EDDS solution can remove more metals, pending on soil pH and target metal. Combining organic acid with EDDS was also valuable in removing toxic metals in the highly contaminated soil with removal efficiencies between 2.7 to 78% pending on metal, acid type, and acid dosage [*Yang et al.*, 2012].

8.3.5. *Bioremediation*

Bioremediation and phytoremediation are biological processes that can maintain soil health during and after remediation, though they are slower than physical, chemical, and/or thermal approaches. Bacteria are vital to degrade and detoxify pollutants, enhancing pollutant uptake and site stabilization using higher plants. Deep tillage was employed with bioremediation, phytoremediation, or chemical remediation to clean up the contaminated farm soils (64,000 m^2) in Guiyu, significantly reducing Cu and Ni [*Gdut SII*, 2020]. The local government (Guiyu Town) launched active soil remediation projects in 2010 (via soil treatment companies) adopting the following methods: (1) Bioremediation- biopiles added with organic materials to assist microbial degradation of pollutants, (2) Phyto-microbial remediation – e.g., the use of a wetland plant (*Canna indica*) and associated microbes to degrade and detoxify PCBs, (3) Phytochemical remediation – chemical agents are added to assist the wetland pant (*Aeschynomene indica*) for removing Pb, Mn, Cr, and Zn. After the treatment, the soil quality complied with the national standard for construction lands (GB36600-2018) [*MEE (The Ministry of Ecology and Environment of the People's Republic of China)*, 2019].

8.3.6. *Phytoremediation*

Field observation and screening tests must identify suitable plant and microbial species. Plant species that are not invasive, such as infertile vetiver grass, can be used directly. Combining plant species and associated microbes can enhance plants' pollutant uptake, stabilize the contaminated sites, and degrade and detoxify toxic chemicals. Metal hyperaccumulator plants can extract toxic metals and deposit them in their above-ground tissues. The metals can be removed from the sites upon harvest. Although some plants do not take up and accumulate substantial metals in their upper plant tissues, they can stabilize and degrade pollutants when interacting with rhizospheric microbes (bacteria and fungi). Therefore, they can restore soil functions and health. As such, some residual organic pollutants can be degraded, pending on the plant species and types of pollutants.

It is essential to select suitable and native plant species before remediation. Ideally, the plants should be able to deal with multiple pollutants simultaneously. The soil collected from Taizhou was planted with five upland plants: pumpkin (*Cucurbita pepo*), tall fescue (*Festuca arundinacea*, milk vetch (*Astragalus sinicus*), alfalfa (*Medicago sativa*), and ryegrass (*Lolium perenne*), and two wetland plants: rice (*Oryza sativa*) cultivars Huanghuazhan and Xiushui 1. Results indicated that rice cv. Xiushui 134, rice cv. Huanghuazhan and ryegrass were more effective in removing BDE-209 (with removal efficiencies of 52.9, 41.9, and 38.7%, respectively) [*He et al.*, 2015]. Another study also revealed that rice was relatively efficient in removing PCBs (35–45%) [*Chen et al.*, 2010].

Vetiver grass (*C. zizanioides*), with its high tolerance to environmental stress, relatively large biomass, and extensive root system, is an excellent candidate for stabilizing riverbanks, mine tailings, and contaminated sites containing mixtures of HMs and POPs [*Chen et al.*, 2020]. Planting vetiver grass in soils (from an e-waste site after soil washing) can degrade PBDEs, PCBs, and PAHs (35–45% removal for these POP residues. The root-associated microbes enhanced the plant, subsequently reactivated microbial activities with higher microbial biomass and biodiversity, and restored soil health [*Ye et al.*, 2015].

Suitable microbes associated with higher plants can improve remediation efficiency, involving plant-regulated degradation/detoxification and direct uptake of organic pollutants and toxic metals, notably mycorrhizal fungi. Some bacteria associated with specific plant species can degrade POPs, such as PAHs, PCBs, and PBDEs. Mycorrhizal fungus-induced bacteria significantly degrade organic pollutants such as PAHs. Species combination (plants and microbes) and removal efficiency of contaminants should be tested before field application [*Chen et al.*, 2020; *Lin et al.*, 2022b].

Remediating e-waste-contaminated soils containing mixtures of POPs and HMs poses a severe challenge. Table 3 shows limited information about laboratory experiments on e-waste soils collected with e-waste sites dealing with complex pollution. In general, soil washing using cyclodextrin and tea saponin could desorb pollutants. Adding chelates could enable higher plants to take up metals. Microbes alone can degrade pollutants, notably POPs. However, higher plants associated with rhizospheric microbes (fungi and bacteria) are necessary for removing and degrading POPs and HMs for long-term sustainability. Remediating e-waste-contaminated soils using different combinations according to specific site conditions seems effective.

Table 3. Remediation of e-waste soils contaminated with mixtures of POPs and HMs.

Reference	Pollutants	Treatments	Mechanisms	Remarks
Chen et al. [2017]	PAHs, PCBs, PBDEs/Cu, Pb, Ni	HPCD, CA, SP	Extraction and oxidation	280-240 min
Ye et al. [2015a]	PBDEs/Pb, Cd	Carboxymethyl chitosan in the oil-water solvent; bacteria	Extraction and degradation	2 h
Ye et al. [2015b]	PBDEs, PCBs, PAHs/Cu, Pb, Ni	Ultrasound, cyclodextrin, tea saponin	Desorption of pollutants during soil washing	60 min
Shen et al. [2009]	PBDEs, PCBs, PAHs/Pb, Ni	Tea saponin in a peanut oil–water solvent; vetiver grass (C. zizanioides)	Extraction and degradation	Soil washing: 1 h, plant growth: 4 months
Wang et al. [2015]	PBDEs, PCBs/Cu	EDDS and corn (Zea mays)	EDDS-triggered pollutant uptake by plants	42 days
Luo et al. [2015]	PCBs/Cu, Zn	EDDS and plant growth-promoting bacterium with corn (Z mays)	Chelant- and PGPR-assisted phytoextraction and phytodegradation	1 month
Sun et al. [2016]	PAH (phenanthrene)/Cd	EDTA, ethyl lactate, willow (Salix sp.)	EDTA and ethyl lactate enhanced PAH and Cd uptake by willow	30-45 days
Li et al. [2021]	PAH (pyrene)/Cd	Urea, willow (Salix sp.)	Urea enhanced the uptake of PAH and Cd by willow	60 days

Successful strategies have been implemented since 2000 in Guiyu: (1) Biopiles incorporated with organic materials to promote the degradation of pollutants; (2) A constructed wetland consisting of *Canna indica* (an emergent wetland plant) with root-associated microbes to degrade PCB; (3) Chelates added to decontaminate Pb, Mn, Cr, and Zn by another wetland plant *Aeschynomene indica*. The soil quality complied with the national standard for construction land after treatments [*MEE (The Ministry of Ecology and Environment of the People's Republic of China)*, 2019].

The intercropping system could be employed for contaminated farm soils by planting a plant species dealing with pollutants and a crop for human consumption. Taizhou successfully used this system to treat contaminated farm soils using legume-grass cropping to remove phthalic acid esters (PAEs) [*Ma et al.*, 2013]. Including metal hyperaccumulating plants with crops could remove toxic metals from the soil, resulting in lower metal uptake in crops and simultaneously producing crops for safer consumption. A substantial amount of soil metals could be removed upon harvest. Alfred stonecrop (*Sedum alfredii*, a Cd/Zn hyperaccumulator) was planted with vegetable upland Kangkong (*Ipomoea aquatica*) in an artificial Cd/Zn contaminated soil. The vegetable contained higher biomass and lower Cd content in the intercropping system assisted with symbiotic fungi than in the monoculture [*Hu et al.*, 2013].

Other successful phytoremediation approaches on sites contaminated with complex pollutants similar to e-waste recycling sites can serve as valuable references. It is expected that the remediation techniques can apply to emerging e-waste sites in other countries/regions as the basic principle of environmental remediation is universal. In e-waste-receiving countries, confronting challenges to decontaminate such complex contamination could be a significant socioeconomic concern. It is best to start with pilot-scale remediation trials (greenhouse trials), selecting the most appropriate technique(s) at larger scales (field trials), using the above successful strategies obtained in China and elsewhere.

9. Conclusion

There is an enormous data gap between exposure quantification and possible health effects. However, we possess enough evidence that e-waste contains various toxic chemicals that cause adverse environmental impact and toxicity to the biota, including humans. Different toxic chemicals exert various negative health impacts. Using bioindicators (hair, serum, urine, blood, human milk) to indicate the extent of health damage is recommended as it can help to obtain proper knowledge of various exposure pathways. This will help design mitigation plans. Detailed toxicological and epidemiological evidence is still insufficient. Therefore, more studies are essential to elucidate and provide comprehensive information on environmental and public health risks that e-waste constituents pose. It is also vital that these studies can cover the acute and chronic health risks of toxic chemicals to set their updated reference doses. Monitoring the development and health status of infants and children born and brought up in the e-waste sites is critical.

Manufacturers should fulfill their 'Extended Producer Responsibility' and polluters pay concept. They should also follow EU Directive to stop using toxic chemicals (such as Hg) in their products. The international movement of e-waste should be solved via national and international cooperation. Wealthier countries must stop exploiting poorer countries with less stringent environmental laws and poorer economies. Imposing tighter control of e-waste movement across international borders is a top priority. The loophole of the Basel Convention should be closed by having a better definition of e-waste. The USA should ratify the conventions not to export e-waste.

Each country/region should establish its strategy for dealing with the e-waste problem. Formulating new and strengthening existing laws would greatly help. Centralized sophisticated treatment facilities for recycling e-waste should be installed in various areas to minimize extensive impacts. Environmental protection and education should be strengthened in receiving countries. China has been the primary destination. As such, the policy, management, and remediation strategies adopted in China's two e-waste mega sites could serve as valuable references for other countries receiving e-waste.

Acknowledgments

The study was carried out in the laboratory “Soil Health” of the Southern Federal University with the financial support of the Ministry of Science and Higher Education of the Russian Federation, agreement no. 075-15-2022-1122.

References

Alharbi, O. M. L., A. A. Basheer, R. A. Khattab, and I. Ali (2018), Health and environmental effects of persistent organic pollutants, *Journal of Molecular Liquids*, *263*, 442–453, https://doi.org/10.1016/j.molliq.2018.05.029.

Beiyuan, J., D. C. W. Tsang, M. Valix, W. Zhang, X. Yang, Y. S. Ok, and X.-D. Li (2017), Selective dissolution followed by EDDS washing of an e-waste contaminated soil: Extraction efficiency, fate of residual metals, and impact on soil environment, *Chemosphere*, *166*, 489–496, https://doi.org/10.1016/j.chemosphere.2016.09.110.

Chan, J. K. Y., and M. H. Wong (2013), A review of environmental fate, body burdens, and human health risk assessment of PCDD/Fs at two typical electronic waste recycling sites in China, *Science of The Total Environment*, *463-464*, 1111–1123, https://doi.org/10.1016/j.scitotenv.2012.07.098.

Chan, J. K. Y., G. H. Xing, Y. Xu, Y. Liang, L. X. Chen, S. C. Wu, C. K. C. Wong, C. K. M. Leung, and M. H. Wong (2007), Body Loadings and Health Risk Assessment of Polychlorinated Dibenzo-p-dioxins and Dibenzofurans at an Intensive Electronic Waste Recycling Site in China, *Environmental Science & Technology*, *41*(22), 7668–7674, https://doi.org/10.1021/es071492j.

Chen, F., Z. Luo, G. Liu, Y. Yang, S. Zhang, and J. Ma (2017), Remediation of electronic waste polluted soil using a combination of persulfate oxidation and chemical washing, *Journal of Environmental Management*, *204*, 170–178, https://doi.org/10.1016/j.jenvman.2017.08.050.

Chen, X., X. Yao, C. Yu, X. Su, C. Shen, C. Chen, R. Huang, and X. Xu (2014), Hydrodechlorination of polychlorinated biphenyls in contaminated soil from an e-waste recycling area, using nanoscale zerovalent iron and Pd/Fe bimetallic nanoparticles, *Environmental Science and Pollution Research*, *21*(7), 5201–5210, https://doi.org/10.1007/s11356-013-2089-8.

Chen, X. W., J. T. F. Wong, J.-J. Wang, and M. H. Wong (2020), Vetiver grass-microbe interactions for soil remediation, *Critical Reviews in Environmental Science and Technology*, *51*(9), 897–938, https://doi.org/10.1080/10643389.2020.1738193.

Chen, Y., X. Tang, S. A. Cheema, W. Liu, and C. Shen (2010), β-cyclodextrin enhanced phytoremediation of aged PCBs-contaminated soil from e-waste recycling area, *Journal of Environmental Monitoring*, *12*(7), 1482, https://doi.org/10.1039/c0em00029a.

Deng, D., J. Liu, M. Xu, G. Zheng, J. Guo, and G. Sun (2016), Uptake, translocation and metabolism of decabromodiphenyl ether (BDE-209) in seven aquatic plants, *Chemosphere*, *152*, 360–368, https://doi.org/10.1016/j.chemosphere.2016.03.013.

Frazzoli, C., O. E. Orisakwe, and E. C. Ilo (2019), Electronic Waste and Human Health, in *Encyclopedia of Environmental Health*, pp. 315–323, Elsevier, https://doi.org/10.1016/b978-0-12-409548-9.02170-9.

Fu, J., Q. Zhou, J. Liu, W. Liu, T. Wang, Q. Zhang, and G. Jiang (2008), High levels of heavy metals in rice (Oryzasativa L.) from a typical E-waste recycling area in southeast China and its potential risk to human health, *Chemosphere*, *71*(7), 1269–1275, https://doi.org/10.1016/j.chemosphere.2007.11.065.

Gdut SII (2020), Evaluation of the environmental status of Guiyu Circular Economy Industrial Park in Chaoyang District of Shantou City.

Grant, K., F. C. Goldizen, P. D. Sly, M.-N. Brune, M. Neira, M. van den Berg, and R. E. Norman (2013), Health consequences of exposure to e-waste: a systematic review, *The Lancet Global Health*, *1*(6), e350–e361, https://doi.org/10.1016/s2214-109x(13)70101-3.

He, Y., X. Li, X. Shen, Q. Jiang, J. Chen, J. Shi, X. Tang, and J. Xu (2015), Plant-assisted rhizoremediation of decabromodiphenyl ether for e-waste recycling area soil of Taizhou, China, *Environmental Science and Pollution Research*, *22*(13), 9976–9988, https://doi.org/10.1007/s11356-015-4179-2.

Hu, J., J. Li, F. Wu, S. Wu, Z. Ye, X. Lin, and M. H. Wong (2013), Arbuscular mycorrhizal fungi induced differential Cd and P phytoavailability via intercropping of upland kangkong (Ipomoea aquatica Forsk.) with Alfred stonecrop (Sedum alfredii Hance): post-harvest study, *Environmental Science and Pollution Research*, *20*(12), 8457–8463, https://doi.org/10.1007/s11356-013-1903-7.

Kiddee, P., R. Naidu, and M. H. Wong (2013a), Metals and polybrominated diphenyl ethers leaching from electronic waste in simulated landfills, *Journal of Hazardous Materials*, *252-253*, 243–249, https://doi.org/10.1016/j.jhazmat.2013.03.015.

Kiddee, P., R. Naidu, and M. H. Wong (2013b), Electronic waste management approaches: An overview, *Waste Management*, *33*(5), 1237–1250, https://doi.org/10.1016/j.wasman.2013.01.006.

Lau, W. K. Y., P. Liang, Y. B. Man, S. S. Chung, and M. H. Wong (2013), 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, *Environmental Science and Pollution Research*, *21*(5), 3813–3825, https://doi.org/10.1007/s11356-013-2372-8.

Leung, A. O. W., W. J. Luksemburg, A. S. Wong, and M. H. Wong (2007), Spatial Distribution of Polybrominated Diphenyl Ethers and Polychlorinated Dibenzo-p-dioxins and Dibenzofurans in Soil and Combusted Residue at Guiyu, an Electronic Waste Recycling Site in Southeast China, *Environmental Science & Technology*, *41*(8), 2730–2737, https://doi.org/10.1021/es0625935.

Leung, A. O. W., N. S. Duzgoren-Aydin, K. C. Cheung, and M. H. Wong (2008), Heavy Metals Concentrations of Surface Dust from e-Waste Recycling and Its Human Health Implications in Southeast China, *Environmental Science & Technology*, *42*(7), 2674–2680, https://doi.org/10.1021/es071873x.

Leung, A. O. W., J. K. Y. Chan, G. H. Xing, Y. Xu, S. C. Wu, C. K. C. Wong, C. K. M. Leung, and M. H. Wong (2010), Body burdens of polybrominated diphenyl ethers in childbearing-aged women at an intensive electronic-waste recycling site in China, *Environmental Science and Pollution Research*, *17*(7), 1300–1313, https://doi.org/10.1007/s11356-010-0310-6.

Li, W., A. Fishman, and V. Achal (2021), Ureolytic bacteria from electronic waste area, their biological robustness against potentially toxic elements and underlying mechanisms, *Journal of Environmental Management*, *289*, 112,517, https://doi.org/10.1016/j.jenvman.2021.112517.

Lin, S., Y. B. Man, K. L. Chow, C. Zheng, and M. H. Wong (2019), Impacts of the influx of e-waste into Hong Kong after China has tightened up entry regulations, *Critical Reviews in Environmental Science and Technology*, *50*(2), 105–134, https://doi.org/10.1080/10643389.2019.1619377.

Lin, S., M. U. Ali, C. Zheng, Z. Cai, and M. H. Wong (2022a), Toxic chemicals from uncontrolled e-waste recycling: Exposure, body burden, health impact, *Journal of Hazardous Materials*, *426*, 127,792, https://doi.org/10.1016/j.jhazmat.2021.127792.

Lin, S., X. W. Chen, Z. Cai, J. Shi, J. Fu, G. Jiang, and M. H. Wong (2022b), Remediation of emerging contaminated sites due to uncontrolled e-waste recycling, *Chemical Engineering Journal*, *430*, 133,169, https://doi.org/10.1016/j.cej.2021.133169.

Lopez, B. N., Y. B. Man, Y. G. Zhao, J. S. Zheng, A. O. W. Leung, J. Yao, and M. H. Wong (2010), Major Pollutants in Soils of Abandoned Agricultural Land Contaminated by e-Waste Activities in Hong Kong, *Archives of Environmental Contamination and Toxicology*, *61*(1), 101–114, https://doi.org/10.1007/s00244-010-9590-6.

Luo, C., S. Wang, Y. Wang, R. Yang, G. Zhang, and Z. Shen (2015), Effects of EDDS and plant-growth-promoting bacteria on plant uptake of trace metals and PCBs from e-waste-contaminated soil, *Journal of Hazardous Materials*, *286*, 379–385, https://doi.org/10.1016/j.jhazmat.2015.01.010.

Luo, Q., Z. W. Cai, and M. H. Wong (2007a), Polybrominated diphenyl ethers in fish and sediment from river polluted by electronic waste, *Science of The Total Environment*, *383*(1-3), 115–127, https://doi.org/10.1016/j.scitotenv.2007.05.009.

Luo, Q., M. Wong, and Z. Cai (2007b), Determination of polybrominated diphenyl ethers in freshwater fishes from a river polluted by e-wastes, *Talanta*, *72*(5), 1644–1649, https://doi.org/10.1016/j.talanta.2007.03.012.

Ma, T. T., Y. Teng, Y. M. Luo, and P. Christie (2013), Legume-grass intercropping phytoremediation of phthalic acid esters in soil near an electronic waste recycling site: a field study, *International Journal of Phytoremediation*, *15*(2), 154–167, https://doi.org/10.1080/15226514.2012.687016.

Man, Y. B., K. L. Chow, H. S. Wang, X. L. Sun, S. C. Wu, Z. W. Cai, Y. Kang, H. Li, J. S. Zheng, J. P. Giesy, and M. H. Wong (2014), Human health risk assessment of soil dioxin/furans contamination and dioxin-like activity determined by ethoxyresorufin-O-deethylase bioassay, *Environmental Science and Pollution Research*, *22*(7), 5218–5227, https://doi.org/10.1007/s11356-014-3909-1.

Man, Y. B., K. L. Chow, G. H. Xing, J. K. Y. Chan, S. C. Wu, and M. H. Wong (2017), A pilot study on health risk assessment based on body loadings of PCBs of lactating mothers at Taizhou, China, the world's major site for recycling transformers, *Environmental Pollution*, *227*, 364–371, https://doi.org/10.1016/j.envpol.2017.04.069.

Man, Y. B., K. L. Chow, F. Zhang, K. M. Lei, A. O. W. Leung, W. Y. Mo, and M. H. Wong (2021), Protecting water birds of wetlands: Using toxicological tests and ecological risk assessment, based on metal/loid (s) of water, sediment and biota samples, *Science of The Total Environment*, *778*, 146,317, https://doi.org/10.1016/j.scitotenv.2021.146317.

MEE (The Ministry of Ecology and Environment of the People's Republic of China) (2019), Dig up and Combine "Electronic Waste City" Transformation and Crossing – Comprehensive Treatment Practice of "Dispersion and Pollution" in Guiyu Town, Shantou City, Guangdong Province, (date of access: 16.05.2023).

Parvez, S. M., F. Jahan, M.-N. Brune, J. F. Gorman, M. J. Rahman, D. Carpenter, Z. Islam, M. Rahman, N. Aich, L. D. Knibbs, and P. D. Sly (2021), Health consequences of exposure to e-waste: an updated systematic review, *The Lancet Planetary Health*, *5*(12), e905–e920, https://doi.org/10.1016/S2542-5196(21)00263-1.

Purchase, D., G. Abbasi, L. Bisschop, D. Chatterjee, C. Ekberg, M. Ermolin, P. Fedotov, H. Garelick, K. Isimekhai, N. G. Kandile, M. Lundström, A. Matharu, B. W. Miller, A. Pineda, O. E. Popoola, T. Retegan, H. Ruedel, A. Serpe, Y. Sheva, K. R. Surati, F. Walsh, B. P. Wilson, and M. H. Wong (2020), Global occurrence, chemical properties, and ecological impacts of e-wastes (IUPAC Technical Report), *Pure and Applied Chemistry*, *92*(11), 1733–1767, https://doi.org/10.1515/pac-2019-0502.

Roundup.com (2022), Latest global e-waste statistics and what they tell us, https://theroundup.org/global-e-waste-statistics/, (date of access: 16.05.2023).

Shen, C., X. Tang, S. A. Cheema, C. Zhang, M. I. Khan, F. Liang, X. Chen, Y. Zhu, Q. Lin, and Y. Chen (2009), Enhanced phytoremediation potential of polychlorinated biphenyl contaminated soil from e-waste recycling area in the presence of randomly methylated-β-cyclodextrins, *Journal of Hazardous Materials*, *172*(2-3), 1671–1676, https://doi.org/10.1016/j.jhazmat.2009.08.064.

Sun, Y. Y., H. X. Xu, J. H. Li, X. Q. Shi, J. C. Wu, R. Ji, and H. Y. Guo (2015), Phytoremediation of soils contaminated with phenanthrene and cadmium by growing willow (Salix × Aureo-Pendula CL 'j1011'), *International Journal of Phytoremediation*, *18*(2), 150–156, https://doi.org/10.1080/15226514.2015.1073668.

Wang, F., A. O. W. Leung, S. C. Wu, M. S. Yang, and M. H. Wong (2009), Chemical and ecotoxicological analyses of sediments and elutriates of contaminated rivers due to e-waste recycling activities using a diverse battery of bioassays, *Environmental Pollution*, *157*(7), 2082–2090, https://doi.org/10.1016/j.envpol.2009.02.015.

Wang, S., Y. Wang, W. Lei, Y. Sun, Y. Wang, C. Luo, and G. Zhang (2015), Simultaneous enhanced removal of Cu, PCBs, and PBDEs by corn from e-waste-contaminated soil using the biodegradable chelant EDDS, *Environmental Science and Pollution Research*, *22*(22), 18,203–18,210, https://doi.org/10.1007/s11356-015-5045-y.

WHO (2021), Children and digital dumpsites: e-waste exposure and child health: web annex: literature review on the health effects of exposure to e-waste, https://www.who.int/publications/i/item/9789240024106, (date of access: 16.05.2023).

Wong, M. H., S. C. Wu, W. J. Deng, X. Z. Yu, Q. Luo, A. O. W. Leung, C. S. C. Wong, W. J. Luksemburg, and A. S. Wong (2007), Export of toxic chemicals - A review of the case of uncontrolled electronic-waste recycling, *Environmental Pollution*, *149*(2), 131–140, https://doi.org/10.1016/j.envpol.2007.01.044.

Wong, M. H., A. O. Leung, S. Wu, C. K. Leung, and R. Naidu (2012), Mitigating environmental and health risks associated with uncontrolled recycling of electronic waste: Are international and national regulations effective?, in *Environmental Contamination*, pp. 214–229, CRC Press, https://doi.org/10.1201/b12531-14.

Wu, J., Y. Q. Yi, Y. Q. Li, Z. Fang, and E. P. Tsang (2016), Excellently reactive Ni/Fe bimetallic catalyst supported by biochar for the remediation of decabromodiphenyl contaminated soil: Reactivity, mechanism, pathways and reducing secondary risks, *Journal of Hazardous Materials*, *320*, 341–349, https://doi.org/10.1016/j.jhazmat.2016.08.049.

Xie, Y., Z. Fang, W. Cheng, P. E. Tsang, and D. Zhao (2014), Remediation of polybrominated diphenyl ethers in soil using Ni/Fe bimetallic nanoparticles: Influencing factors, kinetics and mechanism, *Science of The Total Environment*, *485-486*, 363–370, https://doi.org/10.1016/j.scitotenv.2014.03.039.

Xing, G. H., S. C. Wu, and M. H. Wong (2010), Dietary exposure to PCBs based on food consumption survey and food basket analysis at Taizhou, China - The World's major site for recycling transformers, *Chemosphere*, *81*(10), 1239–1244, https://doi.org/10.1016/j.chemosphere.2010.09.032.

Yang, R., C. Luo, G. Zhang, X. Li, and Z. Shen (2012), Extraction of heavy metals from e-waste contaminated soils using EDDS, *Journal of Environmental Sciences*, *24*(11), 1985–1994, https://doi.org/10.1016/s1001-0742(11)61036-x.

Ye, M., M. Sun, J. Wan, G. Fang, H. Li, F. Hu, X. Jiang, and F. O. Kengara (2014), Evaluation of enhanced soil washing process with tea saponin in a peanut oil-water solvent system for the extraction of PBDEs/PCBs/PAHs and heavy metals from an electronic waste site followed by vetiver grass phytoremediation, *Journal of Chemical Technology & Biotechnology*, *90*(11), 2027–2035, https://doi.org/10.1002/jctb.4512.

Ye, M., M. Sun, J. Wan, G. Fang, H. Li, F. Hu, X. Jiang, and F. O. Kengara (2015), Enhanced soil washing process for the remediation of PBDEs/Pb/Cd-contaminated electronic waste site with carboxymethyl chitosan in a sunflower oil-water solvent system and microbial augmentation, *Environmental Science and Pollution Research*, *22*(4), 2687–2698, https://doi.org/10.1007/s11356-014-3518-z.

Zhang, W., G. Li, H. Liu, J. Chen, S. Ma, and T. An (2019), Micro/nano-bubble assisted synthesis of Au/TiO2@CNTs composite photocatalyst for photocatalytic degradation of gaseous styrene and its enhanced catalytic mechanism, *Environmental Science: Nano*, *6*(3), 948–958, https://doi.org/10.1039/c8en01375f.