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E-waste environmental contamination and harm to public health in China

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Abstract The adverse effects of electronic waste (e-waste) on the human body have stirred up concern in recent years. China is one of the countries that confront serious pollution and human exposure of e-waste, and the majority of the population is exposed to potentially hazardous substances that are derived from informal e-waste recycling processes. This study reviews recent reports on human exposure to e-waste in China, with particular focus on exposure routes (e.g., inhalation and ingestion) and several toxicities of human (e.g., endocrine system, respiratory system, reproductive system, developmental toxicity, neurotoxicity, and genetic toxicity). Pieces of evidence that associate e-waste exposure with human health effects in China are assessed. The role of toxic heavy metals (e.g., lead, cadmium, chromium, mercury, and nickel) and organic pollutants (e.g., polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyl (PCBs), polycyclic aromatic hydrocarbons (PAHs), polybrominated biphenyls (PBBs), polyhalogenated aromatic hydrocarbons (PHAHs), bisphenol A (BPA)) on human health is also briefly discussed.

Keywords e-waste; heavy metal; organic pollutant; hazardous; toxicity; human health; China

Introduction

Electronic waste (e-waste) refers to end-of-life electronic products, including computers, mobile phones, washing machines, air conditioners, television sets, and others, which are composed of sophisticated blends of plastics and metals, among other materials. In recent years, e-waste pollution has been one of the most discussed global environmental issues. China (Guiyu and Taizhou), India (Delhi and Bengaluru), Nigeria (Lagos), and Ghana (Accra) are the most serious e-waste-contaminated countries, with little or no regulation for e-waste recycling or disposal [1]. Approximately 80% of the e-waste is exported to Asia, and 90% of that is transported to China, which means that China is the largest destination of e-waste from developed countries [2]. Meanwhile, China

itself has generated considerable e-waste, which exceeds one million tons per year [3]. Hazardous chemicals can be discharged as a mixture from e-waste through irregular disposal or recycling processes, threatening the health of local residents [4]. This study compiles information from the literature about the effect of pollutants released from e-waste recycling areas of China on human health.

Environmental residue of pollutants from e-waste

Currently, the e-waste dismantling industry in China is mainly distributed among coastal areas, such as Guiyu and Taizhou, which are crucial international e-waste dismantling base and key research areas. Heavy metals and organic pollutants are released into such medium as the atmosphere, soil, dust, and water, and residues of these harmful toxins are left in the environment. Specific e-waste-associated chemical elements and compounds exist in the form of components of the equipment, target

product, and by-products during the recycling process. The main elements include lead, mercury, chromium, cadmium, zinc, copper, nickel, and other dozens of metals, mainly plastic components that contain polyvinyl chloride, polyethylene, acrylonitrile-butadiene-styrene polymers, polystyrene, polypropylene, polyethylene terephthalate esters, brominated flame retardants, toner, surface coatings, and other harmful substances [5]. The risk of e-waste to the general population and surrounding environment steeply increases with the lack of guidelines of health and safety and improper recycling techniques, such as dumping, dismantling, inappropriate shredding, roasting, burning, and acid leaching from complex components of e-waste and high-cost recycle (Fig. 1).

Studies show that a variety of heavy metals and organic pollutants has been detected in the scene of the e-waste dismantling site and its surrounding environmental media

(air, water, and soil) of China. A survey conducted in Guiyu revealed elevated mean heavy metal concentrations in dust of a workshop (Pb 110 000, Cu 8360, Zn 4420, and Ni 1500 mg/kg) and in dust of adjacent roads (Pb 22 600, Cu 6170, Zn 2370, and Ni 304 mg/kg). The Pb and Cu in road dust from the e-waste site were 330, 106, and 371, 155 times higher than non-e-waste sites located 8 and 30 km away, respectively [6]. Another study evaluated the effect of e-waste recycling activities in Guiyu. Heavy metal concentrations in surface water and sediment samples from the Lianjiang River decreased from Guiyu (upstream) to Haimen Bay (downstream, the estuary), Cu concentrations in surface water of Guiyu were 2.4 to 131 times higher than the reference Cu background concentration of water, and Cu concentrations in sediment samples from Guiyu were 3.2 to 429 times larger than those from the reference background [7]. The total concentration of 13



Fig. 1 Informal e-waste recycling activities in Guiyu, including roasting, burning, dismantling, acid leaching, inappropriate shredding, and dumping.

polybrominated diphenyl ethers (PBDEs) in atmosphere from an e-waste dismantling area in Taizhou was 506 pg/m³ in summer and 1662 pg/m³ in winter, which was 7 times higher than that of the reference urban region [8]. The total polycyclic aromatic hydrocarbons in soil from an e-waste recycling site in Taizhou ranged from 371.8 µg/kg to 1231.2 µg/kg, and the total polychlorinated biphenyl (PCB) concentrations ranged from 52.0 g/kg to 5789.5 µg/kg, which were 2.1 to 232.5 times higher than that from the reference site [9]. Thus, mixture pollutants will release to environmental media from informal e-waste recycling activities.

Human exposure to heavy metals and organic pollutants derived from e-waste

Exposure routes can vary dependent on the substance and recycling process. Humans can become exposed to the hazardous components of e-waste in air, soil, dust, water, and food sources through several routes, including ingestion, inhalation, and dermal absorption (Table 1). To date, surveys of pollution level of the human body were mostly concentrated in the Guiyu area. A long-term study conducted by our research team in Guiyu showed that 81.8%, 70.8%, and 69.9% blood lead level of local children exceeded the limit (10 µg/dl) in 2004, 2006, and 2008, respectively [4,10,11]. Median umbilical cord blood chromium levels of neonates from Guiyu in 2006 and 2007 were 93.89 and 70.60 µg/L, respectively, whereas the normal range of blood chromium is 0 µg/L to 0.2 µg/L [12]. From 2004 to 2007, the median cord blood and mean placental cadmium (3.61 µg/L and 0.17 µg/g, respectively) from Guiyu was higher than those from the reference (1.25 µg/L and 0.10 µg/g, respectively) [13]. The informal e-waste recycling not only leads to serious heavy metal pollution but also causes grievous organic pollution, which severely affects the health and daily life of local residents. Concentrations of PBDEs and dechlorane plus (DP) in serum from local residents of Guiyu were measured, and the result showed that the median concentrations of total PBDE was three times higher than that of the reference group. The DP concentration from Guiyu (median, interquartile range; 42.6 ng/g, 7.8 ng/g to 465 ng/g lipid) was larger than that from the reference (median, interquartile range; 13.7 ng/g, 0.93 ng/g to 50.5 ng/g lipid) [14,15]. A study conducted to explore the burdens of polybrominated biphenyls (PBBs), PBDEs, and PCBs among cancer patients from an e-waste disassembly area in Taizhou showed that BDE-47 was the most predominant PBDE congeners, and concentrations of PCB were the highest among the three subfamilies of polyhalogenated aromatic hydrocarbons measured, suggesting that a high cancer incidence in the e-waste disassembly sites may be related to the higher burdens of PBBs, PBDEs, and PCBs

in tissue of local residents [16]. Toxic substances released from e-waste may enrich through animals and plants and finally enter the human body through the food chain, which will definitely harm the health of local populations.

Health effects caused by e-waste pollution

Pollutants that stay in the human body can damage multiple systems, such as endocrine, respiratory, nervous, and reproductive systems, with a genetic toxicity (Table 1). For instance, lead can accumulate long term in the environment and then affect multiple systems, especially the nervous, blood, and digestive systems. Cadmium can also accumulate long term in multiple organs, such as kidney and liver, with apparent chronic toxicity. Inorganic mercury tends to transform into methylmercury under the action of microorganisms, and this action leads to the enrichment of mercury in the food chains. Consequently, coastal populations with traditionally high dietary intake of freshwater fish or seafood have the highest dietary exposure to mercury, and low dose of mercury may affect the nervous system of adults [17]. Chromium mainly exists in the form of trivalent and hexavalent chromium in nature. The toxicity of hexavalent chromium is largest among many valence of chromium, which can cause respiratory inflammation and even mutation or canceration of cells caused by DNA damage. PBDEs with high durability and lipophilicity are used for the flame-retardant additives in plastics, electrical appliances, and television sets. PBDEs are easy to accumulate in the body fat that they can cause adverse effects on neural development and disrupt endocrine function. Dioxins are a group of chlorinated or brominated organic chemicals or a mix of them, and the main form usually includes chlorinated dioxins (PCDD/F/Bs), brominated dioxins (BBDD/F/Bs), and mixed bromo-chloro dioxins (PXDD/F/Bs). They are found in human carcinogens and can cause noncancerous effects, such as atherosclerosis, hypertension, and diabetes. Long-term exposures to dioxins will lead to the disruption of the nervous, immune, reproductive, and endocrine systems [18].

Endocrine toxicity

Most environmental endocrine disruptors have estrogen-like effects, and these pollutants interfere with the endocrine function of animals to produce acute or potential toxic effects. Xenobiotics, such as PBDEs, PCDDs, and PCDFs, can be combined with hormone receptor in the organism, affecting the synthesis, secretion, transport, metabolism, and combination of hormones and interfering with normal hormone levels in the human body to disrupt the endocrine system. Endocrine disturbances are associated with various human diseases, such as obesity, heart

Table 1 Classification, sources, and routes of e-waste components

Pollutant categories	Health effects and potential toxic mechanism	Commercial sources of exposure	Ecological source of exposure	Route of exposure
Persistent organic pollutants				
Polybrominated diphenyl ethers (PBDEs)	Carcinogenic, genotoxic, endocrine disrupting, metabolic syndromes, low birth weight, decrease in IQ, decreased psychomotor and mental development, neurobehavioral development, and decreased female fertility	Fire retardants for electronic equipment	Air, dust, food, water, soil, and food	Ingestion, inhalation, and transplacental
Polychlorinated biphenyls (PCBs)	Probably carcinogenic, thyroid function, cognitive function and development, neuropsychological development, attention deficits, decrease in IQ, intellectual impairment, low birth weight, and reduced growth	Dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Air, dust, soil, and food (bioaccumulative in fish and seafood)	Ingestion, inhalation or dermal contact, and transplacental
Polychlorinated dibenzodioxins and dibenzofurans (PCDD/PCDFs)	Carcinogenic, thyroid function, type II diabetes, obesity, cardiovascular disease, fetal toxicity, reproductive toxicity, feminization, changes in sex ratio at birth, and infantile autism	Released as a combustion by-product but also found in dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Air, dust, soil, food, water, and vapor	Ingestion, inhalation, dermal contact, and transplacental
Polycyclic aromatic hydrocarbons (PAHs)	Carcinogenic, mutagenic, teratogenic, toxicity of development and reproduction, DNA damage, lung, skin, bladder, and potentially larynx and kidney	Released as combustion by-product	Released as combustion by-product, air, dust, soil, and food	Ingestion, inhalation, and dermal contact
Elements				
Lead (Pb)	Affects enzyme activity, membrane ion channel, signal molecules, gene expression, neurogenesis, neurodegeneration, decrease in IQ, impaired cognitive function, anemia, neuropsychological function, nephrotoxic, and adult hearing loss	Printed circuit boards, cathode ray tubes, lightbulbs, televisions, and batteries	Air, dust, water, and soil	Inhalation, ingestion, and dermal contact
Cadmium (Cd)	Affects enzyme activity, kidney injury, decreased bone density, lung damage, carcinogenic, mutagenetic, decrease in IQ, neurodevelopment, adult hearing loss, low birth weight, cell apoptosis, and gene expression	Switches, springs, connectors, printed circuit boards, batteries, infrared detectors, semiconductor chips, ink or toner photocopying machines, cathode ray tubes, and mobile phones	Air, dust, soil, water, and food (especially rice and vegetables)	Inhalation and ingestion
Mercury (Hg)	Induction of oxidative stress, inflammatory, nerve cell apoptosis; affects enzyme activity and genetic modification, nephrotoxic, memory loss, immune system toxicity, decrease in IQ, genotoxic, and decreased fertility	Thermostats, sensors, monitors, cells, printed circuit boards, and cold cathode fluorescent lamps	Air, vapor, water, soil, and food (bioaccumulative in fish)	Inhalation, ingestion, and dermal contact
Chromium (Cr)	Carcinogenic, genotoxic, mutagenetic, ovotoxic, lung function, allergic reaction and contact dermatitis, glycometabolism, and reproductive developmental anomalies	Printed circuit boards, cathode ray tubes, lightbulbs, televisions, pigment, and batteries	Air, dust, water, and soil	Inhalation and ingestion

disease, diabetes, infertility, cancer, and neurological defects. Several studies show that e-waste contaminant exposure interferes with the balance of thyroid hormones and sex hormones in the local population. The reported effects on thyroid-stimulating hormone (TSH) are inconsistent, with some studies reporting higher TSH levels in the exposed populations [19,20] and other studies indicating lower TSH levels with e-waste exposure [21–24]. Tetraiodothyronine (T4) levels in the exposed population were not higher than those of the reference population. Thus, an inverse relationship existed between PBDEs and T4 [19,21–23]. Given that different findings may be caused by insufficient sample sizes (most studies have sample sizes less than 100 persons), studies with larger sample size and control of confounding factors are required to accurately investigate the effect of e-waste on thyroid function. Meanwhile, a study conducted to 187 men in an e-waste dismantling area in China found that the levels of male hormone, such as follicle-stimulating and luteinizing hormones, were higher than those in the reference group, and testosterone was lower than that in the reference group in male population aged 31 to 60 [25]. Similarly, the levels of sex hormones estradiol and progesterone were disrupted in pregnant women from the e-waste recycling site [26]. Therefore, the organic toxicity of e-waste on the endocrine system of the body should be focused on. Although the above-mentioned studies reveal that e-waste pollution has influenced the levels of thyroid and sex hormones, its mechanism is unclear at present and still requires further study.

Respiratory system toxicity

Harmful substances mainly enter the human body through respiratory inhalation, and their adverse effects include respiratory stimulation, airway inflammation, and lung function damage. Particles can stimulate macrophages to produce reactive oxygen species and inflammation medium, and this action results in injury of the trachea and lung tissue, thereby affecting the elasticity of the lung tissue and the respiratory function. However, the precise mechanism of lung damage caused by particles is unclear [27]. Associations between exposure to metals (Cr, Mn, and Ni) and lung function were examined in primary school children from our previous survey in Guiyu and a control town. Living in Guiyu was associated with a decreased forced vital capacity (FVC) in 8- to 9-year-old boys. Height-adjusted multivariate regression analysis showed significant negative associations between blood chromium levels and FVC in 11- and 13-year-olds and serum nickel levels and FVC in 10-year-olds [28]. Children who breathe in polluted air for a long time, especially children in the stage of rapid development, will experience lung function decline.

Developmental toxicity

The fetal period is the key period of growth and development, and extremely sensitive to the toxic substance such as heavy metal and organic pollutants. Our previous studies demonstrated that heavy metals and organic pollutants from e-waste were associated with stillbirth, premature delivery, and anencephaly, and the neonatal Apgar score, height, and weight were lower than those of children from the reference area [29–33]. Growth hormones, such as placental insulin-like growth factor-1 (IGF-1) and insulin-like growth factor binding protein-3 (IGFBP-3) from an e-waste-exposed area, were higher than those from the reference group. This result shows that IGF-1 and IGFBP-3 can be used as monitoring indicators of fetal intrauterine growth and development [34]. Children are susceptible to environmental pollution, and their normal growth and development are disturbed when they are exposed to harmful substances. Lead inhibits the synthesis and utilization of hormones, such as TSH and IGF, in stunting the physical development of children by disturbing the absorption of calcium, iron, and zinc. A negative correlation was found among height, weight, and child blood lead in Guiyu, and exposure to manganese or nickel will reduce the height, weight, and body mass index of local children [35]. The weight and chest circumference were larger from the high-chromium group than those from the low-chromium group [36]. Handling and disposal of unwanted electronic products is frequently unsafe and unregulated. Thus, extensive e-waste dismantling and recycling activities pose a potential risk and an expanding challenge to the growth and development of local neonates and children.

Reproduction toxicity

The frequent occurrence of reproductive diseases has stirred up wide public concern on environmental pollution. A study found that the estrogen-like effect of bisphenol A (BPA) may cause reproductive toxicity to the body [37]. Specifically, BPA can cause female precocious puberty and reproductive system tumor to affect fertility, and it can reduce sperm quality and quantity. Outpatient data were collected from a Guiyu hospital and a reference hospital from 2001 to 2009. The statistical results show that the incidence of male reproductive disease was 0.753% and 0.355% in 2004 and 2009, respectively. The incidence of azoospermia, asthenozoospermia, and epididymitis from the Guiyu hospital was higher than those from the reference hospital [38]. The results indicate that male reproductive health may be affected by environmental pollutants, and this finding requires confirmation in further epidemiological investigation.

Neurotoxicity

A study from China found that every 10 µg/L increase of blood Pb concentration is associated with a deficit of 0.71 IQ points [39]. A neonatal behavioral neurological assessment (NBNA) study conducted in Guiyu by our group showed that neonatal exposure to high lead was associated with low NBNA scores. The temperament questionnaires for 3- to 7-year-old children were used to assess the temperament of children, and the results indicated that Guiyu children showed higher activity level, approach withdrawal, and adaptability than those from the reference group. Blood lead levels among Guiyu children were much higher than those in children from the reference group, which demonstrated that high lead load influenced the temperament of children, and temperament characteristics are associated with some intelligence area in the development of the intelligence of children [40]. Thus, high lead load affects the intellectual, psychological, and behavioral health of children.

Genetic toxicity

Hazardous materials released from the e-waste dismantling process could damage human health and even pose toxic effects to genetic materials, resulting in DNA damage, gene expression, and alteration of chromosome structure.

DNA damage

Oxidative damage is an important aspect among several DNA damage mechanisms. It reflects an imbalance between the systemic manifestation of reactive oxygen species and the ability of a biological system to readily detoxify the reactive intermediates or to repair the resulting damage, with an imbalance in the oxidant/anti-oxidant system [41]. Heavy metal can induce the body to produce a large number of free radicals that contribute to oxidative stress and destroy the metabolic balance of oxygen-free radicals found in the body. A Chinese study showed that the levels of reactive oxygen species in white blood cell from the residents of Guiyu were higher than those from the reference group [42]. Another study demonstrated that super oxide dismutase and glutathione peroxidase from Guiyu pregnant women were lower than those from the reference group, and malondialdehyde from Guiyu pregnant women were higher than that from the reference group [26]. The DNA injury rate and tail length of lymphocytes in neonates from Guiyu were higher than those from the reference group, and positive correlations were found between blood chromium and DNA injury rate and tail length of lymphocytes. This result implies that exposure to chromium can lead to DNA and cell damage [12]. The frequency distribution of the aminolevulinic acid

dehydratase type 2 allele in newborns from Guiyu was lower than that of the reference group [43,44]. Other studies also indicated that chromosome aberration rate, micronucleus rate, lymphocyte percentage of tail DNA, lymphocyte lengths of tail, and lymphocyte olive lengths of tail from Guiyu were higher than those from the reference group [43,44]. Telomere of DNA shortening may cause adverse birth outcomes and increase cancer risk. Placental cadmium was also negatively correlated with telomere length from Guiyu samples based on a previous study [45].

Alterations in gene expression

MicroRNA (miRNA) is a small non-coding RNA molecule (containing approximately 22 nucleotides), which functions in RNA silencing and post-transcriptional regulation of expression, modification, translation, and transcription of gene. It is important in the response process of cell to environment. A study from China obtained the miRNA expression profiling of male from Guiyu and the reference group, and 109 downregulated and 73 upregulated expression miRNAs were found based on the comparison of the two groups of miRNA expression profiling [46]. Mother placental cadmium levels and metallothionein (MT) from Guiyu were higher than those from the reference group, and the calcium binding protein S100P level of Guiyu was lower than that from the reference group. The placental cadmium was negatively correlated with S100P and positively correlated with MT [47]. Another study found that the positive expression rate of MT in placenta tissue from Guiyu was 67.0%, which is significantly higher than that in placenta tissue from the reference group (32.7%). The expression quantity of MT in placenta was positively correlated with placental and umbilical cord cadmium levels [13]. Therefore, the biological activity of S100P and MT expression in the placenta is likely to be affected upon exposure to heavy metals.

Alterations of chromosome structure

Telomere is a terminal structure of eukaryotic chromosomes. It is composed of hundreds of thousands of highly repetitive tandem repeats (TTAGGG in human) and associated proteins. Telomere serves as a cap on the end of chromosomes to maintain integrity of the chromosomes and stability of the genome and to prevent end-to-end chromosomal fusion [48]. Telomere is important in placental development and maturation. Shortened placental telomere is believed to cause adverse birth outcomes, such as fetal growth restriction and low birth weight [49,50]. Shortened telomere is also related to increased cancer risk and aging [51–54]. One of our previous studies

found that placental telomere length was negatively correlated with placental cadmium concentration. Placental cadmium concentration of 0.0294 µg/g may also be a critical point at which attrition of placental telomere commenced. Exposure to cadmium pollution during pregnancy may be a risk factor for shortened placental telomere length [45]. Several biomarkers, such as monomers, fragments, translocations, satellites, quadriradials, total aberrations, and micronuclear rates, were used to perform chromosomal aberrations and cytokinesis blocking for each subject in a study conducted in Tianjin, China. The total chromosome aberration rates (5.50%) and micronuclear rates (16.99%) of the exposure group were higher than those of the reference group, and the chromosome aberration and micronucleus rates were higher in women than those in men [55].

Perspectives

E-waste pollution of China adversely affects the health of dismantling workers and nearby residents based on the above-mentioned literature. The research results from various studies are inconsistent, which may be caused by lack of sufficient sample size and inappropriate adjustment of confounding factors. Most of the studies are descriptive, with usual information about exposure collected at the same time as the health effects are measured in a group of individuals during a specific period. Thus, identifying clear temporal relations between exposures and health effects is difficult. By contrast, cohort studies are generally suitable in exploring the association between e-waste exposures and health effects. The types and compositions of e-waste are diverse and complex and may provide joint toxicity on the human body rather than single e-waste pollutant damage. Most of the current research focuses on the toxic effect of a certain toxic substance. Thus, future studies should pay more attention to the joint toxicity of a variety of toxic substances from e-waste. Multinational and multi-region research on the health effect of e-waste should be conducted to obtain accurate scientific conclusions.

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Compliance with ethics guidelines

Xijin Xu, Xiang Zeng, H. Marike Boezen, and Xia Huo declare that they have no conflict of interest. This manuscript is a review article and does not involve a research protocol requiring approval by the relevant institutional review board or ethics committee.

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