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REVIEW PAPER

A review on management practices, environmental impacts, and human exposure risks related to electrical and electronic waste in Vietnam: findings from case studies in informal e-waste recycling areas

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Abstract Electrical and electronic waste (e-waste) has become a global concern, especially in developing countries. In this review, we conducted a literature survey of e-waste management practices, processing activities, and adverse effects in Vietnam, an emerging country in Southeast Asia, by gathering data from peer-reviewed articles published between 2009 and 2021. This is the first review paper to comprehensively discuss management and research aspects regarding e-waste in an Asian developing country. Due to the lack of an effective management and recycling system, a certain portion of Vietnamese e-waste has been processed by informal sectors without appropriate recycling and pollution control technology, resulting in localized contamination and human exposure to toxic chemicals. Primitive processing activities, such as manual dismantling, open burning, and plastic recycling, have been identified as important contributors to the environmental emission and human exposure to toxic elements (notably As, Mn, Ni, Pb, Zn) and organic pollutants like flame retardants, PAHs, PCBs, and dioxin-related compounds. Informal e-waste processing from these small-scale workshops can release pollutants at similar levels compared to large-scale facilities in developed countries. This fact suggests an urgent need to develop

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management best practices for e-waste in Vietnam as well as other emerging and developing countries, in order to increase recycling efficiency and minimize their adverse impacts on environmental and human health.

Keywords Electrical and electronic waste · Environmental pollution · Heavy metals · Human exposure · Informal e-waste recycling · Organic pollutants

Abbreviations

BFRs	Brominated flame retardants
CALUX	Chemically activated luciferase gene expression
CBzs	Chlorobenzenes
DBDPE	Decabromodiphenyl ethane
EEE	Electrical and electronic equipment
DPs	Dechlorane plus
DRCs	Dioxin-related compounds
HFRs	Halogenated flame retardants
HQs	Hazard quotients
HMs	Heavy metals
NBFRs	Novel brominated flame retardants
OPEs	Organophosphorus esters
PFCs	Perfluorinated chemicals
POPs	Persistent organic pollutants
PBDD/Fs	Polybrominated dibenzo-*p*-dioxins/furans
PBDEs	Polybrominated diphenyl ethers
PCBs	Polychlorinated biphenyls
PCDD/Fs	Polychlorinated dibenzo-*p*-dioxins/furans
PAHs	Polycyclic aromatic hydrocarbons
PTWI	Provisional tolerable weekly intake
RfD	Reference dose
TDI	Tolerable daily intake
TEQ	Toxic equivalency
US EPA	US Environmental Protection Agency
WHO	World Health Organization

Introduction

Electrical and electronic waste (e-waste) has become a global concern, especially in developing countries because of several adverse effects on environmental and human health related to e-waste-containing hazardous substances (Abalansa et al., 2021; Sthiannopkao, 2013). During the past decades, the electronic demand in Vietnam, a country in Southeast Asia, has a sharp increase resulted from rapid socio-economic development (Hai et al., 2017; Quang et al., 2009). A lifetime analysis of selected electronic devices in Vietnam showed a drastic decrease in mean lifetimes of four appliances such as televisions (TVs), refrigerators, washing machines, and air conditioners in Hanoi and Ho Chi Minh City during 2006–2013, which were shorter than lifetimes estimated for the same devices in Japan in 2013 (Yamasue et al., 2017). The increase in domestic electrical and electronic equipment (EEE) quantity coupled with the trend of decreasing lifetime led to a huge amount of e-waste released. The e-waste generation rate was estimated as 1.9 kg/capita/y in 2014, and increased to 3.7 kg/capita/y in 2020, leading to a national e-waste generation of 0.24 Mt/y during this period (Salhofer, 2017; Tran & Salhofer, 2018a). These e-waste generation rates were markedly lower than those estimated for other countries in Oceania (17.3 kg/capita in 2017), Europe (16.6 kg/capita), and America (11.6 kg/capita) (Baldé et al., 2017). It should be noted that these estimates were only based on amounts of used household EEE using data of domestic sales. If other e-waste sources (e.g., office appliances, industrial devices, and discarded equipment imported illegally) were accounted, the actual e-waste amount in Vietnam is likely to be much higher (Hai et al., 2017; Tran & Salhofer, 2018a).

The Government of Vietnam banned the import of 12 good categories including e-waste after the promulgation of the Decree No. 187/2013/NĐ-CP, which has come into force since 20 February 2014 (Vietnam Government Portal, 2013). The Prime Minister of Vietnam released the Decision No. 16/2015/QĐ-TTg providing regulations on recall and treatment of discarded products including batteries, EEE, lubricant oils, tires, and vehicles. According to this decision, these waste types should be transported to designated recall points before further treatment and disposal. However, e-waste has not been completely separated from municipal solid waste in Vietnam (MONRE, 2020). In addition, improper recycling and illegal import–export of solid waste including e-waste have still occurred in Vietnam due to the limitations of legislation, management system, and treatment technology (Hai et al., 2017; Salhofer, 2017; Thai, 2009; Tran & Salhofer, 2018a). There are numerous inadequacies of e-waste management regulations in

Vietnam, for example, the absence of specific standards and guidance for collection, storage, transportation, and treatment activities of e-waste, unclear roles and responsibilities of governmental authorities established for e-waste management, and the lack of strong sanctions against violators (Thai, 2009). The knowledge of many Vietnamese people about economic benefits and negative effects of e-waste is still limited, that prevents establishing an effective management scheme. Some Asian countries such as China, Taiwan, Japan, South Korea, and the Philippines have proposed specific regulations on e-waste management and recycling (Terazono et al., 2006). In Japan, a recycling system for large home appliances (e.g., TVs, refrigerators, washing machines, and air conditioners) has been implemented since 2001, showing the responsibility of retailers and manufacturers for e-waste reuse and recycling (Terazono et al., 2006). In Vietnam, although e-waste has been collected and treated by formal sectors (e.g., registered facilities and governmental and non-governmental projects), a certain portion of e-waste has been processed in informal recycling sites located in some northern provinces (Hai et al., 2017; Salhofer, 2017; Tran & Salhofer, 2018a, 2018b).

Based on the literature review, there is no comprehensive review paper on management and environmental issues related to e-waste in Vietnam as well as Southeast Asia. To fill such information gaps, we conducted this review to provide an up-to-date overview on e-waste processing activities and their environmental impacts in Vietnam, focusing on informal e-waste recycling areas. The review contents include: (1) e-waste management and treatment technologies; (2) environmental pollution and human exposure to hazardous substances released from informal e-waste processing; (3) recommendations to establish e-waste management best practices in Vietnam, considering multiple factors such as legislation completion, public awareness propaganda, and specific technical improvements. The significance of this review includes: (1) providing an inclusive overview on e-waste in a typical emerging country; (2) characterizing environmental and human health impacts of pollution caused by informal recycling activities; (3) addressing limitations of e-waste management in Vietnam with suggestions to improve current situation; (4) addressing knowledge gaps and suggesting future researches; (5) providing useful information for policy makers, government managers, scientists, and entrepreneurs in the e-waste management field in developing and emerging countries, heading toward the environmentally sound management of e-waste in these countries.

Methods

The review method used in this study generally followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021). The review process includes four steps: identification (mainly by electronic database search), screening papers by title and abstract, eligibility evaluation by full text, and inclusion. Peer-reviewed publications between 2009 and 2021 were searched from multiple databases such as ScienceDirect, PubMed, Springer, ACS Publications, Taylor & Francis, Wiley Online Library, J-STAGE, SAGE, MDPI, Hindawi Publishing, IOP Publishing, and Organohalogen Compounds Database, by using keywords such as "e-waste," "e-waste recycling," "developing country," "Southeast Asia," "Vietnam," and pollutant names (e.g., heavy metals, toxic elements, organic pollutants, persistent organic pollutants, flame retardants, plasticizers, polycyclic aromatic hydrocarbons, dioxin-related compounds, perfluorinated compounds, etc.). The papers were selected by major criteria such as: (1) published in edited books and peer-reviewed journals/conferences by reputable publishers; (2) related to e-waste management in Vietnam; and (3) included field survey and actual monitoring results on pollutants with reliable instrumental analysis and sufficient QA/QC information. A summary of review process is provided in Fig. S1 of Supplementary data. To facilitate comparison and discussion, about 30 other papers were also included due to their relevance to e-waste management and pollution issues in developing countries or other waste processing categories in Vietnam. The additional papers were selected by using similar PRISMA approach and selection criteria (i.e., containing field survey and actual measurements of pollutant concentrations by consistent analytical methods with adequate QA/QC information). In addition, the comparison studies were also conducted for waste processing activities in similar period (i.e., 2010–2020).

A total of 31 peer-reviewed publications related to e-waste problems in Vietnam were selected, including 7 e-waste management and recycling technology studies and 24 pollution monitoring and risk assessment studies. These monitoring studies were further classified into sub-categories by pollutant classes (i.e., HFRs [12 papers], OPEs [5], PCBs [4], DRCs [3], heavy metals [3], PAHs [2], PFCs [1], chlorobenzenes [1], bromophenols [1], PAEs [1], perchlorate [1], thiocyanate [1]) and sample types (i.e., soil [10], sediment [8], dust [7], human [5], biota [4], air [2], water [1], waste [1]). Elemental analysis was performed by inductively coupled plasma with mass spectrometry (ICP-MS) and atomic emission spectroscopy (ICP-AES); and the elemental results were ensured by analysis of standard reference materials (Oguri et al., 2018; Uchida et al., 2018). Dioxin-like compounds and dioxin-like activities were analyzed by gas chromatography/high-resolution mass spectrometry (GC/HRMS) and by the dioxin-responsive chemical-activated luciferase gene expression (DR-CALUX) assay, respectively (Suzuki et al., 2016; Tue et al., 2010a). Other organic pollutants were mainly determined by gas chromatography or liquid chromatography coupled with mass spectrometry (GC/MS or LC/MS). Concentrations of target compounds were quantified by internal standard/isotope dilution method. The analysis of blank samples, standard reference materials and/or matrix-spike samples, together with strict control of labeled surrogate recovery was performed in all the selected studies. The environmental pollution and human exposure monitoring data were tabulated from the selected papers with median and range values, rearranged in tables and figures to show a certain concentration variation trend, and compared with relevant studies conducted in other countries. Concentrations of organic pollutants were mainly compared by totals of each group. The target compound lists of each group may differ between studies, leading to some uncertainties. Meanwhile, comparisons of elemental concentrations between studies were conducted for each metal.

E-waste management practices in Vietnam

In Vietnam, stakeholders of discarded EEE can be classified into several groups such as: (1) producers, importers, and sale agents; (2) consumers such as households and offices; (3) private intermediate collectors and service shops; (4) informal dismantlers and recyclers; (5) formal waste treatment facilities; and (6) illegal importers and exporters (Hai et al., 2017; Quang et al., 2017). Among them, only groups (1) and (5) are under formal control of the government in terms of waste management (Quang et al., 2017). In this section, we mainly focus on characterization of e-waste management practices by groups (2), (4), and (5), because investigated data for the remaining groups is relatively limited. These representative stakeholders are thought to cover a major portion of EEE lifetimes, and to handle a predominant amount of e-waste in Vietnam (Hai et al., 2017; Salhofer, 2017; Tran & Salhofer, 2018a). Current e-waste management practices performed by these groups in Vietnam, in comparison with similar groups in other countries, are mentioned and discussed.

Consumers

Electronic goods in Vietnam such as TVs, refrigerators, washing machines, and air conditioners, are mainly sold to private collectors, gifted to others, or stored at homes (Quang et al., 2009); whereas small appliances such as cell phones and other portable and semi-portable machines can be discarded together with domestic waste. As no extensive formal collection scheme exists, selling e-waste to private collectors or just discarding as normal waste, unintentionally raises the difficulty for e-waste management (Salhofer, 2017). Storing e-waste at homes or in offices is also a common option applied in Vietnam and other Asian countries such as Singapore (Sen & Peng, 2010) and Malaysia (Kalana, 2010; Tiep et al., 2015). However, toxic chemicals such as polybrominated diphenyl ethers (PBDEs) and other additives used in various parts of EEE can emit from their sources into the surrounding environments (i.e., indoor air and settled dust), and then potentially affect health of human and pets (Ali et al., 2013; Besis & Samara, 2012; Hahladakis et al., 2018), suggesting that keeping e-waste at homes is not safe. Therefore, formal and effective collection schemes in combination with consumer awakening about e-waste as a "double-edged sword" containing both recyclable materials and hazardous substances, are in urgent need.

Formal sectors

Although e-waste in Vietnam is predominantly handled by informal sectors, several formal programs and facilities for e-waste collecting and treating have been implemented with initially promising results. In terms of collecting schemes, the Vietnam Recycles program run by the Vietnam Recycling Platform, a consortium of some leading producers of EEE, has offered e-waste take-back services at homes or at some designated stations in Hanoi and Ho Chi Minh City (Vietnam Recyclers, 2015). According to the Vietnam Environment Administration Magazine, this program has been promoted by local residents, notably student and youth voluntary groups, through several propaganda activities such as parades and gift giving, in order to improve public knowledge and awareness about e-waste (VEM, 2017). Similar collection programs should be promoted throughout the country, not only in big cities but also in rural and remote areas affected by urbanization and modernization in Vietnam. In the long term, a synchronized collection system of e-waste should be considered by learning from developed countries such as mandatory take-back by retailers in Japan, voluntary combined collection in US, or regulated combined collection in European Union (Jofre & Morioka, 2005). Although curbside collection by local governments has been applied in Japan (Jofre & Morioka, 2005) and South Korea (Jang, 2010), this method seems to be inapplicable in Vietnam because of uncontrolled collecting activities performed by peddlers.

According to the Circular Management of Hazardous Wastes (Circular No. 36/2015/TT-BTNMT on 30 June 2015) issued by the Vietnam Ministry of Natural Resources and Environment, e-waste originated from both domestic and industrial applications are defined as hazardous wastes and should be treated at facilities licensed by the Vietnam Environment Administration (VEA). To date, there are about 15 licensed medium and large facilities that have e-waste treatment capacities from 0.25 to 30 t d^{-1} throughout the country (Hai et al., 2017). Among them, few facilities have demonstrated their abilities in material recovery from e-waste with specified technologies (Hai et al., 2017; Tran & Salhofer, 2018a). The most important recyclable materials from e-waste are metals such as Cu, Mn, Ni, Sn, Pb, Fe, and other precious metals (Hai et al., 2017). In these facilities, metals are separated and recovered from e-waste mainly by hydrometallurgical technologies (Hai et al., 2017; Tran & Salhofer, 2018a). A typical process of e-waste recycling in formal sector in Vietnam comprises three major steps as follows: (1) dismantling; (2) shredding/crushing/separating; and (3) recovering metals; and these processes are performed manually or semi-mechanically (Hai et al., 2017). Recovered metals can exist in salt (mostly sulfate) or elemental form. The recovery rate of Cu and Mn from obsolete printed circuit boards in the form of sulfate salts by hydrometallurgical method was reported up to 95% (Hai et al., 2017). Brief descriptions of metal recovery technologies in selected formal facilities are summarized in Table 1.

In the formal sectors, industrial e-waste can be treated as hazardous waste by incineration method in some facilities such as URENCO (Hanoi) and Tan Thuan Phong JSC (Hai Phong). Before incineration, e-waste is pre-treated by shredding/crushing followed by initial separation. In the URENCO company, glass from cathode ray tubes (CRTs) is separated and stored (Hai et al., 2017). E-waste is then incinerated in automatically controlled two-stage incinerators with manual or automatic waste feeding. Slag from these incinerators can be recycled for cement or brick production (Hai et al., 2017). Although these facilities have relatively high capacity for industrial waste (including e-waste) treatment, metal recovery efficiency was not reported for the e-waste treated by their pyrogenic methods. A project for recycling discarded electric and electronic devices in Vietnam has been promoted under the consultants and technical supports from Nippon Magnetic Dressing Co., Ltd and Kitakyushu Asian Center for Low Carbon Society, Japan (KACLCS, 2015). In this project, e-waste such as cell phones and personal computers (PCs) are processed by three main steps: (1) primary dismantling; (2) fine crushing and enrichment; and (3) smelting and precious metal recovery, with the final step would be performed by Japanese firms.

In brief, a portion of e-waste in Vietnam has been processed by the formal sector in terms of collection, storage, recycling, and final disposal. A relatively high recovery rate of metals from e-waste was also reported for some facilities in this sector. However, comparing to total amount of e-waste released, the fraction treated by formal facilities can be considered to be minor despite no statistical information reported (Hai et al., 2017; Tran & Salhofer, 2018a).

Table 1 Metal recovery technologies in selected formal e-waste treatment facilities in Vietnam

Facility/location	Technology	Special features	References
Green Environment Production and Trade Services Co., Ltd (GECO)/Hai Duong	Hydrometallurgy Crushing-floatation Incineration	Obsolete electric circuit boards are treated with 15% acid solution, and separated into circuit boards, plugs, integrated circuits, and solutions. These portions are then crushed/ treated to recover Cu, Fe, Au, Ag, Pd, Sn, Pb. Plastic residues are incinerated	GECO (2013)
Viet Xanh Environmental Co., Ltd (Viet Xanh)/ Binh Duong	Manual dismantling Separation Hydrometallurgy Incineration Solidification	Domestic and industrial e-waste are manually dismantled and separated into circuit boards, recyclable materials (plastic, glass, metals), and less valuable parts. Circuit boards are then dismantled and treated by hydrometallurgy to recover metals. Less valuable parts are incinerated or solidified	Viet Xanh (2013)
Hoa Binh Waste Technology Processing and Recycling JSC/Hanoi	Dismantling Shredding/crushing Hydrometallurgy Electrolysis	E-waste is dismantled and shredded before hydrometallurgy treatment. Metals (mainly Cu) were recovered from solutions by electrolysis	Hai et al. (2017)
Thuan Thanh Environment JSC/Bac Ninh	Dismantling Gravity/magnetic separation Hydrometallurgy	E-waste is dismantled and separated into ferrous/ non-ferrous metals and residues by gravimetric and magnetic methods. Precious metals are recovered by hydrometallurgy. Residues are incinerated	Tran and Salhofer (2018a)

Furthermore, to our knowledge, no investigation was conducted for the environmental release of primary (e.g., metals, flame retardants, and other additives) and secondary (e.g., dioxins and related compounds and other unintentionally produced substances) e-waste-related pollutants in the formal sector in Vietnam. The limitations of e-waste treatment in the formal sector are also found in other developing nations in Asia and Africa (Garlapati, 2016; Kumar et al., 2017). Meanwhile, high e-waste recycling rates of 75% to 82% have been reported for some Asian countries such as Japan, South Korea, and Taiwan (Garlapati, 2016), implying valuable lessons for other countries including Vietnam. In addition, extended producer responsibility (EPR) has been introduced and exhibited promising results (reviewed by Tran & Salhofer, 2018a). The technical support from foreign producers and organizations plays an important role to promote an effective and environmentally sound e-waste management and recycling system in Vietnam.

Informal sectors

As previously mentioned, the majority of e-waste in Vietnam has been handled by the informal sector (Hai et al., 2017; Salhofer, 2017; Tran & Salhofer, 2018a, 2018b). For collecting activities, it is estimated that thousands of peddlers, operating on motorcycles, bicycles, or on foot from house to house to buy disposed EEE and other recyclable materials from end users, and then they sell those items to private shops or traders with higher prices to receive premium. Some authors evaluated this informal e-waste collecting system as very active, flexible, and successful in terms of high collection rates (Quang et al., 2009; Salhofer, 2017; Tran & Salhofer, 2018a). The type of door-to-door collection is also popular in some countries such as China (Wei & Liu, 2012), Ghana (Oteng-Ababio, 2012), India (Bhat & Patil, 2014), Malaysia (Kalana, 2010; Tiep et al., 2015), and Thailand (Kunacheva et al., 2009); whereas informal sector plays an insignificant role in the e-waste collection systems of other countries like Hong Kong (Hoyng, 2018), Singapore (Sen & Peng, 2010), and South Korea (Jang, 2010).

From consumers and peddlers, a large portion of e-waste and other disposed household products has been collected and processed in informal waste recycling sites. There are about 30 craft villages involved in e-waste processing in Vietnam (Salhofer, 2017), mainly located in rural or suburban areas of cities and provinces in northern Vietnam such as Hanoi (Trieu Khuc and Xa Cau); Hai Phong (Trang Minh); Hung Yen (Bui Dau, Minh Khai, and Phan Boi); Vinh Phuc (Te Lo, Dong Mau, and Dong Van); and Bac Ninh (Man Xa) (Fig. 1). Among them, Bui Dau Village in Hung Yen Province is one of the most extensively studied areas on the aspects of recycling activities and environmental impacts. In the informal sector, e-waste has been treated by local unskilled workers using primitive technologies to recover bulk materials such as ferrous metals, copper, aluminum, and plastics (Hai et al., 2017; Salhofer, 2017). Typical processes of e-waste treatment in Bui Dau as shown in Fig. 2 and Fig. S2 comprise six main activities: (1) collection and transporting; (2) stockpiling of pre- and post-processed e-waste in both indoor and outdoor areas; (3) manual dismantling and separation materials into metals, glass, plastics, etc.; (4) plastic recycling; (5) open burning of cables and wires to recover metals mostly copper; and (6) final disposal of less valuable materials and/or domestic waste by open dumping and burning. In addition, repair, refurbishment, and resale activities of reusable EEE and their disassembled components are also existed in these recycling sites (Salhofer, 2017; Tran & Salhofer, 2018a).

Plastic recycling

Plastics separated from e-waste comprise many types, predominantly acrylonitrile butadiene styrene (ABS), polystyrene (PS), and polyethylene (PE) (Dimitrakakis et al., 2009). After separation, plastic parts are shredded and recycled mainly by extrusion technology to produce secondary plastic pellets or recycled household products (Tran & Salhofer, 2018b). A recovery rate of 93.4% of recycled products to original scraps was estimated for plastic recycling process from PCs (Tran & Salhofer, 2018b). Plastic pellets can be introduced as raw materials for plastic facilities, while recycled products might be attractive to low-income markets in the rural areas. However, the potential impacts on

Fig. 1 Map of northern Vietnam and some informal e-waste recycling areas

environmental and human health related to wastewater, solid waste, and air emission released from different stages of plastic recycling in these informal e-waste sites have not been characterized.

Metal recycling

Different from the hydrometallurgical methods used in the formal sector, e-waste-related metals in the informal recycling sites are mainly recovered by pyrometallurgical methods. Wires, cables, and other copper-containing parts are gathered in large, vacant areas, often near agricultural fields, and then are fueled, and combusted to isolate metals from coating materials. Recycled metals might be sold to other traders, handicraft villages, or industries. This method has been also applied to recover copper from e-waste in other countries such as China and India (Awasthi & Li, 2017), Ghana (Oteng-Ababio, 2012), and Nigeria (Peluola, 2016), although it is well known that these open burning processes can release a considerable amount of unintentionally produced pollutants including dioxins and related compounds (Zhang et al., 2017). Printed circuit boards are important

Fig. 2 Typical e-waste processing activities in Bui Dau, northern Vietnam: **a** collection; **b** stockpiling; **c** manual dismantling; **d** plastic recycling; **e** open burning of wires and cables to recover metals; **f** open burning of less valuable materials and domestic waste

sources of precious metals such as gold, silver, palladium, copper, and other solder metals. It was estimated that 1000 kg of circuit boards can yield 284 kg copper and 44 kg solder metals (by thermal–mechanical method), and 20.5 g gold (by aqua regia method) (Tran & Salhofer, 2018b). In case of gold recovery by aqua regia method, large amounts of residual acid solutions and toxic gases can cause adverse effects on the workers and surrounding environments. The application of amalgam method in metal recovery from e-waste has been reported in Bangalore, India, leading to serious exposure to mercury in workers of this area (Ha et al., 2009). These facts suggest that current technologies for metal recycling in the informal e-waste sector of developing countries exhibit several disadvantages, especially for environmental and occupational exposure problems.

We cannot deny the socio-economic benefits of e-waste-related materials from informal sector in rural development of the e-waste sites in northern Vietnam. The e-waste processing activities create jobs for local and neighboring residents, and probably provide them with higher income than from traditional agricultural production. However, several limitations in recycling technologies, pollution control and waste treatment systems, and labor protection conditions have resulted in environmental pollution and human exposure to hazardous substances such as heavy metals, toxic gases, and a variety of organic contaminants.

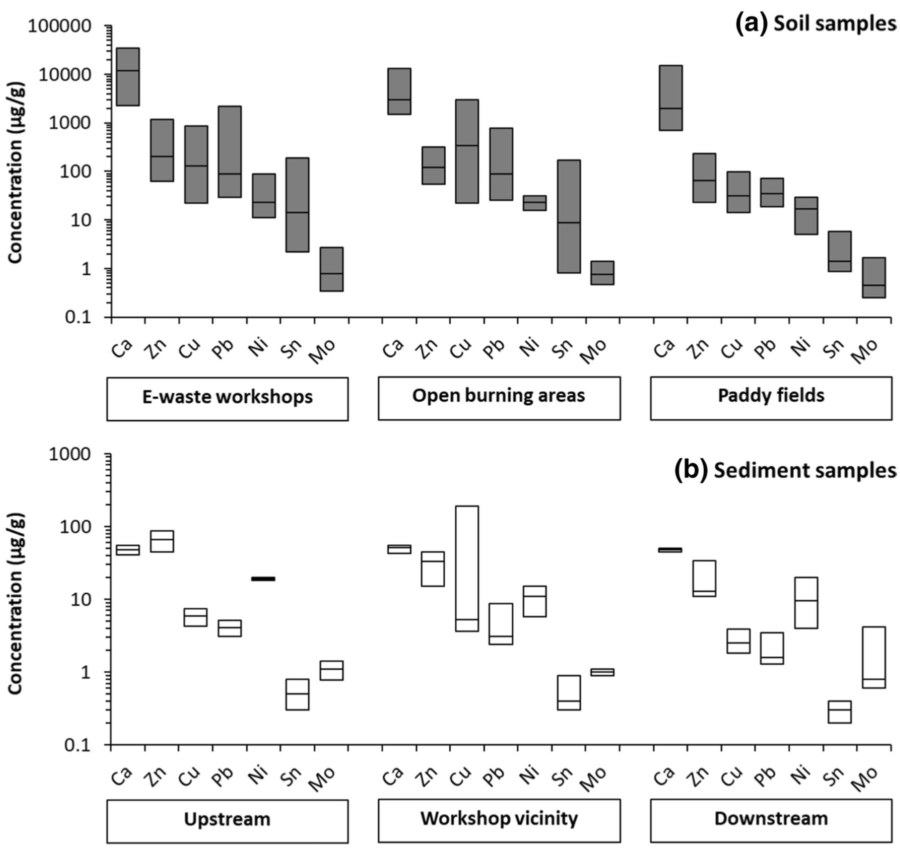
Impacts of informal e-waste processing activities on environmental and human health

Environmental pollution by hazardous elements

Concentrations of hazardous elements were determined in environmental and diet samples collected from the Bui Dau e-waste recycling area between 2012 and 2014 (Oguri et al., 2018; Uchida et al., 2018). A summary of concentrations of toxic elements in the air, water, soil, sediment, and food samples is provided in Table S1. Garden soils in Bui Dau were contaminated with moderate levels of heavy metals (HMs) such as Cd, Cu, Mn, Pb, Sb, and Zn through activities like separating metals and plastics, sorting of electric parts, and open burning of wires to recover metals (Oguri et al., 2018). The contents of some HMs such as Pb, Cu, and Zn in the Bui Dau e-waste soils exceeded the allowable limits specified by the Vietnam Ministry of Natural Resources and Environment (MONRE, 2008). A significant positive correlation between indoor dust and garden soil levels of Cu and Sb was observed, indicating a direct release of these metals from the e-waste workshops to their surroundings (Oguri et al., 2018). However, concentrations of HMs in air particulate samples collected from bedrooms and living rooms in this e-waste site were relatively low, suggesting limited diffusion of metal-containing particles from e-waste processing areas to living areas in Bui Dau (Oguri et al., 2018). There was no significant difference in concentrations of Cd, Cu, Pb, and Sb in diet samples between the Bui Dau e-waste areas and other sites, but contents of Zn and Mn were somewhat higher in the e-waste samples. However, due to limited sample size, Oguri et al. (2018) could not distinguish the sources of Zn and Mn from plant uptake or external exposure to particles (e.g., dust and soil) during the cooking process.

Uchida et al. (2018) conducted a comprehensive study on spatiotemporal trends of 23 elements in soil, sediment, and water samples collected between 2012 and 2014 from Bui Dau e-waste areas. The analytical results of soil and sediment samples indicated relatively high concentrations of 7 elements (i.e., Ca, Cu,

Fig. 3 Concentrations (median and range) of selected metals in soil (**a**) and sediment (**b**) samples collected from Bui Dau e-waste recycling areas, northern Vietnam between 2012 and 2014. Data were retrieved from Uchida et al. (2018)



Mo, Ni, Pb, Sn, and Zn) (Fig. 3), which were largely related to e-waste processing activities such as open burning of cables to recover copper wires and washing of burned materials on riverside. Concentrations of several metals (notably Cu, Pb, Sn, and Zn) were higher in samples collected from e-waste workshops, open burning sites, and their vicinity than other locations like paddy fields and upstream/downstream areas. Detection frequencies of Ag (89%) and Cd (56%) were higher in sediment samples taken from e-waste workshops' vicinity than upstream/downstream (33–58% for Ag, 0–25% for Cd); however, concentrations of these two metals were not very high in all the samples. Concentrations of As, Co, Fe, In, Li, Mg, Mn, Ni, Se, and rare-earth elements (i.e., Ce, Eu, Gd, La, Nd, and Sm) in soil and sediment samples did not show a clear spatial trend. Water concentrations of almost all elements were not high, except for one sample collected near e-waste workshops in 2012 with Cu concentration of 190 µg/L.

In general, little is known about the emission of hazardous elements including heavy metals from e-waste processing in Vietnam (Oguri et al., 2018; Uchida et al., 2018). Available data showed that some critical activities such as manual e-waste dismantling and open burning can release HMs (notably Cu, Pb, Sn, and Zn) to surface soil and river water. The main sources of these metals in the e-waste areas were largely attributed to printed circuit boards, wires, cables, and plastic casings. Concentrations of HMs like Cu, Pb, and Zn in surface soils from Bui Dau e-waste areas were within the middle ranges when compared to those measured in e-waste recycling areas in China (Li et al., 2011; Tang et al., 2010), the Philippines (Fujimori et al., 2012), Thailand (Damrongsiri et al., 2016), and Ghana (Kyere et al., 2017) (Fig. 4), largely due to small scales and capacity of the Vietnamese recycling workshops. Because of the limitation in number of studies, investigated areas, sample categories and sample sizes, further research is needed to characterize the contamination degree, distribution, transportation, and toxic effects of HMs derived from e-waste recycling in Vietnam.

Environmental pollution by organic compounds

Studies on the pollution status of organic compounds in the environments around Vietnamese informal e-waste recycling sites have been conducted since the late 2000s. The study areas are located in three informal e-waste sites in northern Vietnam comprising Bui Dau (Hung Yen), Trang Minh (Hai Phong), and

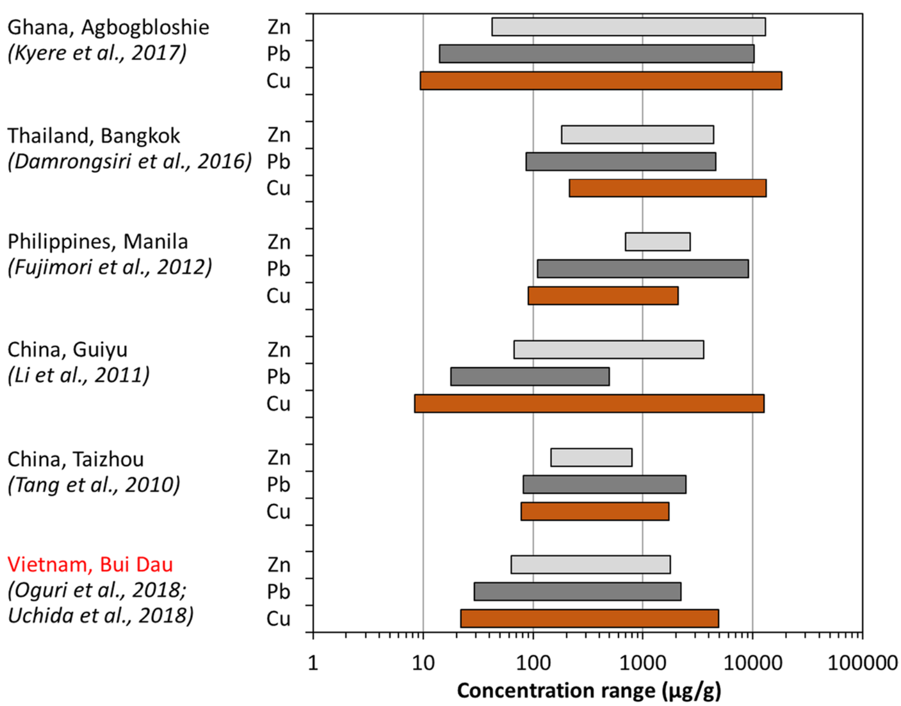


Fig. 4 Comparison of Cu, Pb, and Zn concentrations in soil samples collected from e-waste recycling areas in different countries. Data were retrieved from Tang et al. (2010), Li et al. (2011), Fujimori et al. (2012), Damrongsiri et al. (2016), Kyere et al. (2017), Oguri et al. (2018) and Uchida et al. (2018)

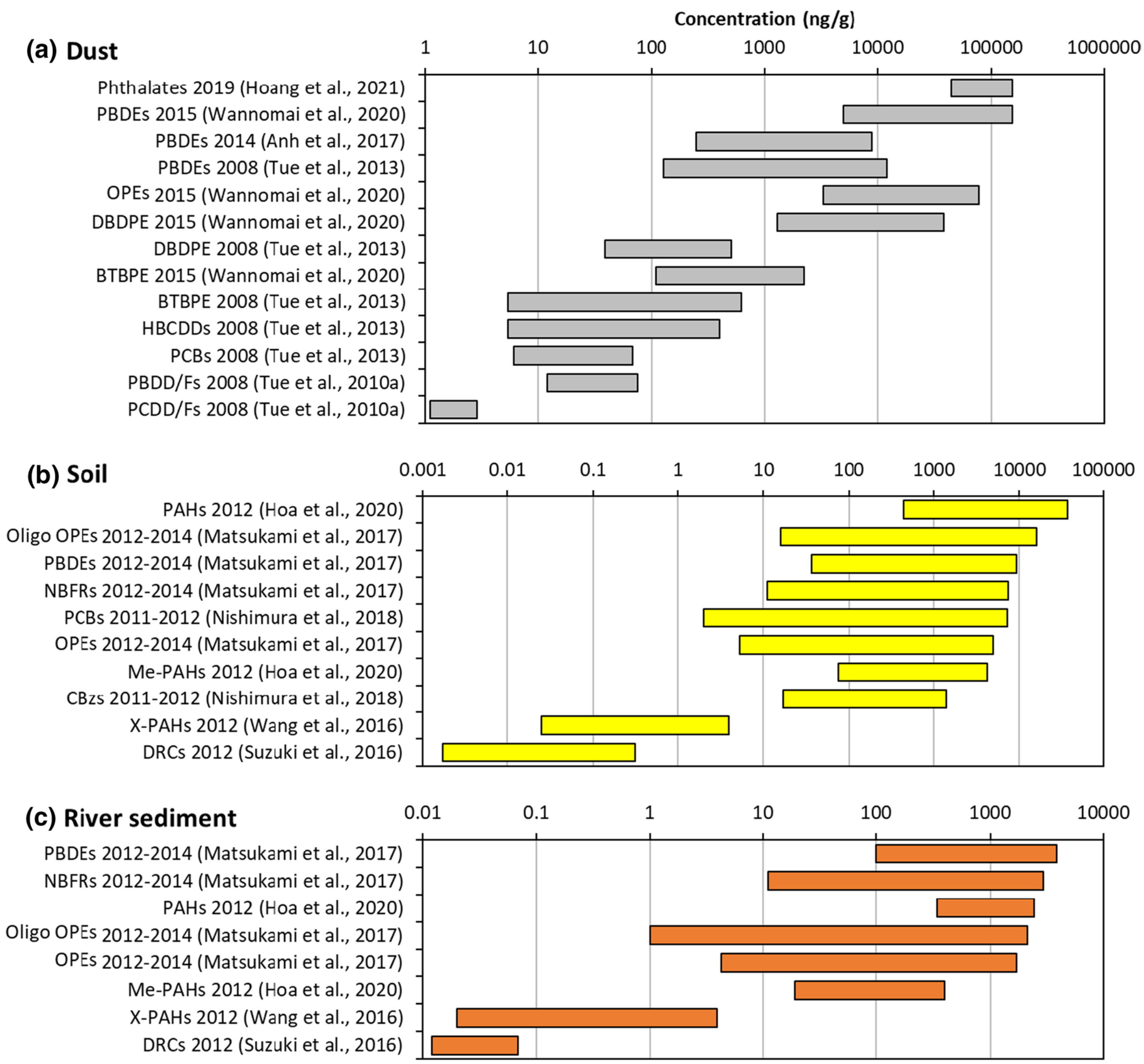


Fig. 5 Concentration ranges of organic pollutants in dust (**a**), soil (**b**), and river sediment (**c**) samples collected from Bui Dau e-waste recycling areas, northern Vietnam between 2008 and 2019. The target lists of pollutants are given in Table S2

Trieu Khuc (Hanoi), together with some rural/urban/suburban control sites. Concentrations of organic pollutants in environmental and biota samples collected from Bui Dau e-waste recycling areas are tabulated in Table S2 and S3, while a summary focusing on dust, soil, and sediment samples is presented in Fig. 5.

A localized contamination by various classes of flame retardants and other additives in plastics and polymeric materials has been evidenced in the e-waste recycling sites in northern Vietnam. Concentrations of PBDEs in settled dust samples collected from e-waste workshops in Trieu Khuc, Bui Dau, and Trang Minh (130–250,000 ng/g) were about one to three orders of magnitude higher than those detected in house dusts from control sites (26–610 ng/g) (Anh et al., 2017; Hoang et al., 2022b; Tue et al., 2013). The strong abrasion of e-waste by manual dismantling may contribute significant amounts of PBDE-containing debris and dust inside equipment to the air and settled dust of the facilities, adjacent living areas, and surrounding areas. Concentrations of dust-bound PBDEs in Vietnamese e-waste recycling areas were within the ranges reported for some e-waste facilities in Thailand (Muenhor et al., 2010, 2017), but generally higher than levels found in common house dust and road dust from other Southeast Asian countries (Fig. S3). Atmospheric concentrations of PBDEs found in backyards of the e-waste recycling households were also significantly higher than levels recorded in common houses (Tue et al., 2013). Elevated levels of PBDEs, novel BFRs (NBFRs), and OPEs were measured in soil and sediment samples obtained from the e-waste processing workshop sites, that were much greater than those observed in other locations such as dumping and open burning sites, rice paddy fields, and textile and paper craft villages in northern Vietnam (Anh et al., 2017; Eguchi et al., 2013; Matsukami et al., 2015, 2017; Someya et al., 2016). Opposite concentration trends of legacy and emerging flame retardants were reported by a 3-year study in Bui Dau from 2012 to 2014 (Matsukami et al., 2017). Levels of PBDEs in surface soils from Bui Dau e-waste sites decreased significantly between 2012 and 2014, whereas concentrations of oligo-OPEs, NBFRs, and DPs showed a clear increase during this period (Matsukami et al., 2017). PBDEs and other emerging flame retardants were detected in poultry and fish samples collected from Bui Dau at concentrations higher than those found in normal ones, reflecting bioaccumulation effects of e-waste-related pollutants (Anh et al., 2017; Matsukami et al., 2016a, 2016b).

Relatively high concentrations of phthalate plasticizers (44,700–110,000 ng/g) were detected in settled dust samples from the e-waste recycling workshops, which were generally higher than those measured in other micro-environments such as houses, offices, shops, and laboratories in Hanoi urban areas (Hoang et al., 2022a). Kim et al. (2013) have reported that total PFC concentrations in surface water near Bui Dau e-waste recycling sites (18–170 ng/L) were higher than levels measured in samples from other sites such as battery recycling area, municipal dumping site, municipal wastewater discharge station, and rural control site (not detected—23 ng/L), suggesting e-waste as potential sources of PFCs in Vietnam. These findings suggest that informal e-waste processing areas in northern Vietnam are specific and significant sources of flame retardants and plastic additives, implying considerable risks for ecosystems and human health.

Although PCBs were detected in the ambient air and settled dust samples collected from e-waste households at concentrations higher than those found in non-e-waste houses in Bui Dau and Trang Minh, no significant difference in PCB levels between the e-waste sites and urban areas was observed (Tue et al., 2013). This fact suggests that the emission of PCBs from technical mixtures in the Vietnamese e-waste sites was localized and the e-waste recycling activities were not a major pollution source of PCBs in Vietnam (Tue et al., 2013). However, relatively high PCB levels were detected in surface soil from e-waste open burning sites (1400–7300 ng/g), followed by burning sites' nearby (2.5–330 ng/g), e-waste workshops (10–15 ng/g), and rice fields (2.0–11 ng/g) in Bui Dau (Nishimura et al., 2018). Similar trend was observed for CBzs in surface soil from Bui Dau (Nishimura et al., 2018). The soil pollution with PCBs and CBzs in this area was largely attributed to unintentional formation during combustion processes. In addition, PAHs and their derivatives such as methyl PAHs (Me-PAHs) and chlorinated/brominated PAHs (X-PAHs) were found in soil and sediment samples collected from the e-waste workshops and open burning sites in Bui Dau at concentrations higher than those detected in samples obtained from locations that were not closely influenced by e-waste processing activities (Hoa et al., 2020; Wang et al., 2016). Hoa et al. (2020) indicated that the emission of PAHs and Me-PAHs in this area was mainly due to uncontrolled burning of e-waste together with waste oils and agricultural by-products to recover metals, as well as other domestic combustion activities. Concentrations of DRCs such as PCDFs, monobrominated PCDFs, PBDD/Fs, and coplanar PCBs in settled dusts from the e-waste sites in Bui Dau and Trang Minh were significantly higher than those in Hanoi urban houses with different homolog patterns (Tue et al., 2010a). Dibenzofurans (i.e., PCDFs and PBDFs) dominated WHO-TEQ levels in surface soil and river sediment samples affected by e-waste processing activities, meanwhile, PCDDs were more abundant in rice paddy soils and sediments from upstream and downstream areas in Bui Dau (Suzuki et al., 2016). Results from DR-CALUX assays have indicated the contribution of emerging and unregulated DRCs other than conventional PCDD/Fs to total dioxin-like toxicity in settled dust, surface soil, and river sediments in the e-waste sites (Suzuki et al., 2016; Tue et al., 2010a).

The surrounding environments of some informal e-waste recycling sites in northern Vietnam have been polluted by some heavy metals and a variety of organic micro-pollutants not only related to the emission from electrical and electronic equipment, but also derived from unintentional sources. E-waste-related activities such as collecting, open storing, manual dismantling, shredding plastic parts into chips, and plastic recycling operated under primitive conditions of facilities and technologies, without appropriate pollution control and waste management system have resulted in elevated environmental levels of flame retardants, plasticizers, and PFCs in the e-waste sites. Furthermore, high-thermal processes such as burning wires and circuit boards to recover metals and open burning of less valuable parts and domestic waste may lead to a considerable unintentional formation of highly toxic substances such as PBDD/Fs, mixed halogenated DRCs, PCBs, CBzs, and unsubstituted/halogenated PAHs (Hoa et al., 2020; Nishimura et al., 2018; Suzuki et al., 2016; Tue et al., 2010a; Wang et al., 2016). Ecotoxicological and human health risks associated with exposure to e-waste-related pollutants have been evaluated and the obtained results have revealed that aquatic organisms and residents in the e-waste sites, especially e-waste recyclers and children, are at greater risk of exposure to PBDEs, PCBs, DRCs, PAHs, and other emerging pollutants than the general population (Anh et al., 2017; Eguchi et al., 2015; Hoa et al., 2020; Tue et al., 2010a, 2010b, 2013; Wannomai et al., 2020). These observations suggest the need of comprehensive and continuous monitoring of toxic chemicals in the environments of e-waste recycling areas in Vietnam.

Human exposure to e-waste-related contaminants

Several risk-assessment studies have been carried out for e-waste recycling workers and residents in some e-waste sites in northern Vietnam, covering both internal and external exposures to inorganic and organic pollutants via multiple pathways such as inhalation, dust/soil ingestion, and diet (Anh et al., 2017; Eguchi et al., 2014, 2015; Ngo et al., 2021; Oguri et al., 2018; Tue et al., 2010a, 2013, 2014). Obtained results indicate that the e-waste recyclers and their offspring are estimated as high-risk groups of exposure to some specific pollutant classes such as BFRs and DRCs (Anh et al., 2017; Tue et al., 2010a, 2013, 2014). Daily intakes of heavy metals and selected organic compounds estimated for Vietnamese e-waste recycling workers and general population are summarized in Table 2.

Oguri et al. (2018) have found that the dietary intakes of Cd, Cu, Pb, and Sb estimated for residents in the Bui Dau e-waste site were similar to those reported for uncontaminated sites, whereas the intakes of Mn and Zn were two to four times higher in Bui Dau compared to control sites (Marcussen et al., 2013). In Bui Dau, soils and dusts were the major sources of human exposure to Pb and Sb, meanwhile other metals such as Cd, Cu, Mn, and Zn enter the human body mainly through food. Non-cancer risk of HMs evaluated using the bioaccessible concentrations showed insignificant adverse health effects of Cu, Cd, Mn, Sb, and Zn with hazard quotients (HQs) lower than one. Human exposure to Pb in Bui Dau showed the highest non-cancer risk compared to the remaining HMs with a maximum HQ value of 0.6. These levels were still lower than HQ values of Pb documented in e-waste sites in India (Singh et al., 2018) and China (Fang et al., 2013; Xue et al., 2012; Zhang et al., 2014). The daily intake doses of Pb (median 0.92; range 0.34–2.3 µg/kg/d) were still lower than the provisional tolerable weekly intake (PTWI) as 25 µg/kg/w (JECFA, 2000). Nevertheless, it should be re-emphasized that concentrations of Pb in the Bui Dau e-waste soils were higher than the standard level, and the current PTWI for Pb may be replaced by a lower value in the coming years (JECFA, 2011). Therefore, further studies on the exposure and human health risk associated with HMs, especially Pb, should be conducted for not only adults but also children living in Vietnamese e-waste sites.

Considering improper e-waste processing activities as a significant source of organic pollutants, human exposure to typical organic pollutants such as PBDEs, PCBs, and DRCs has been evaluated for residents living in some e-waste sites in northern Vietnam (Anh et al., 2017; Tue et al., 2010a, 2013). As presented in Table 2, the daily intakes of PCBs, PBDEs, and DR-CALUX-TEQs estimated for residents in the e-waste sites were generally higher than those of general population. Levels and patterns of human exposure to PCBs in the e-waste sites and urban areas in Vietnam

Table 2 Daily intakes of heavy metals (μg/d), perchlorate (ng/kg/d), and organic pollutants (ng/d) estimated for residents in the Vietnamese e-waste recycling areas and control sites

Pollutant	E-waste sites	Control sites	Notes and references	TDI/RfD
Cd	6.1 ± 4.6	34.1	Mean daily dietary intakes estimated for e-waste recyclers in Bui Dau (Oguri et al., 2018) and adults in urban control site Hanoi (Marcussen et al., 2013)	WHO TDI = 0.06 mg/kg/d
Cu	2670 ± 5270	3070		WHO TDI = 3 mg/kg/d
Mn	7840 ± 3320	4185		WHO TDI = 0.06 mg/kg/d
Pb	21.4 ± 11.6	26.7		WHO TDI = 0.214 mg/kg/d
Sb	1.05 ± 1.01	1.68		WHO TDI = 6 μg/kg/d
Zn	19,700 ± 9310	9000		–
Perchlorate	48	33	Derived by perchlorate serum (Eguchi et al., 2014)	US EPA RfD = 7×10^{-4} mg/kg/d
DR-CALUX-TEQ	Adults: 0.010 Children: 0.025	Adults: 0.0027 Children: 0.0068	Median daily intakes via dust ingestion estimated for residents in Bui Dau and Trang Minh e-waste sites and Hanoi (Tue et al., 2010a)	WHO TDI = 1–4 pg TEQ/kg/d
WHO-TEQ	Bui Dau: 0.037 Trang Minh: 0.047	–	Median daily intakes via breast feeding estimated for infants in Bui Dau and Trang Minh e-waste sites (Tue et al., 2014)	WHO TDI = 1–4 pg TEQ/kg/d
PCBs	Trang Minh: 56 Bui Dau: 59	Hanoi: 50	Median daily intakes via dust ingestion, inhalation, and diet for adults (Tue et al., 2013)	US EPA RfD = 20 ng/kg/d for Arochlor 1254
PBDEs	Trang Minh: 22 Bui Dau: 65	Hanoi: 5.9	Median daily intakes via dust ingestion, inhalation, and diet for adults (Tue et al., 2013)	US EPA RfD = 100, 100, 200, 7000 ng/kg/d for BDE-47, BDE-99, BDE-153, BDE-209, respectively
	Adults: 65.4 Children: 164	–	Mean daily intakes via dust ingestion and fish consumption estimated for residents in Bui Dau (Anh et al., 2017)	

were not significantly different with major sources for low-chlorinated (di- and trichloro) and higher chlorinated (tetra- to decachloro) PCBs as inhalation and diet, respectively (Tue et al., 2013). Human exposure to low-chlorinated PCBs through inhalation was important in e-waste recycling workers, which was in good agreement with specific accumulation patterns of these compounds in breast milk samples collected from women living in the e-waste areas (Tue et al., 2010a). Meanwhile, residents in the e-waste sites were estimated to receive much higher intake doses of PBDEs mainly from dust ingestion, compared to urban individuals with dominant contribution of both diet and dust, following hypothesis that the e-waste residents consumed food from the non-contaminated neighboring communes (Tue et al., 2013). However, Anh et al. (2017) have revealed that freshwater fish from sewer systems in the Bui Dau e-waste sites can be significant exposure sources of PBDEs. Daily intake doses from 1.2 to 3.3 pg CALUX-TEQ kg/d via dust ingestion estimated for children in the Bui Dau and Trang Minh e-waste sites suggest a considerable DRC exposure as compared to the range of tolerable daily intake (TDI) doses of 1–4 pg WHO-TEQ kg/d (Tue et al., 2010a). Moreover, daily intake doses of WHO-TEQs (comprising PCDD/Fs, DL-PCBs, and PBDFs) and unknown DRCs estimated for infants in the Bui Dau and Trang Minh e-waste sites through breast feeding also exceeded the TDI values (Tue et al., 2014). These observations suggest that the e-waste residents were estimated to be at greater risk

Table 3 Human levels of inorganic and organic pollutants in Vietnamese e-waste recycling and control sites

Media	Pollutant	Concentration (median and range)	References
Blood (children)	Pb (μg/dL)	BD: 4.05 (1.90–13.41); NT: 3.94 (2.06–14.11)	BD: Bui Dau; NT: Nhuan Trach control sites (Ngo et al., 2021)
	Cd (μg/L)	BD: 0.50 (0.18–2.01); NT: 0.57 (0.31–2.31)	
	Cr (μg/L)	BD: 2.25 (0.99–3.22); NT: 2.08 (0.51–7.12)	
	Ni (μg/L)	BD: 16.39 (0.59–21.7); NT: 14.31 (8.85–18.62)	
	As (μg/L)	BD: 7.09 (4.32–22.27); NT: 5.73 (0.15–17.42)	
Serum (adults)	Perchlorate (ng/mL)	BD: 0.120 (< 0.05–1.25); RC: 0.086 (< 0.05–0.660)	BD: Bui Dau; RC: rural control (Eguchi et al., 2014, 2015)
	PCBs (pg/g ww)	BD: 420 (150–6400); RC: 290 (52–2500)	
	OH-PCBs (pg/g ww)	BD: 160 (60–1100); RC: 82 (19–110)	
	PBDEs (pg/g ww)	BD: 290 (37–2300); RC: 230 (100–450)	
	OH-PBDEs (pg/g ww)	BD: 37 (7.7–140); RC: 140 (62–440)	
	Bromophenols (pg/g ww)	BD: 300 (90–1400); RC: 200 (100–400)	
Breast milk	WHO-TEQs (pg/g lw)	BD: 1.4 (0.22–5.9); TM: 1.8 (0.72–4.8); HN: 1.7 (1.1–3.3)	BD: Bui Dau; TM: Trang Minh; HN: Hanoi control (Tue et al., 2014)
	CALUX-TEQs (pg/g lw)	BD: 7.8 (3.3–10); TM: 3.2 (2.4–4.8); HN: 1.7 (1.0–4.5)	
	PCBs (ng/g lw)	BD recyclers: 34 (28–59); BD non-recyclers: 24 (8.4–28); TM: 33 (11–73); HN: 46 (20–100)	BD: Bui Dau; TM: Trang Minh; HN: Hanoi control (Tue et al., 2010b)
	PBDEs (ng/g lw)	BD recyclers: 84 (20–250); BD non-recyclers: 3.2 (2.0–4.0); TM: 2.3 (0.55–13); HN: 0.57 (0.24–0.80)	
	HBCDDs (ng/g lw)	BD recyclers: 2.0 (1.4–7.6); BD non-recyclers: 0.36 (0.29–1.2); TM: 0.38 (0.11–3.3); HN: 0.33 (0.070–1.4)	

of organic pollutants, especially BFRs and DRCs, than those of Vietnamese general population.

Human levels of hazardous elements, perchlorate, and organic pollutants in Vietnamese e-waste recycling areas and control sites are tabulated in Table 3. Ngo et al. (2021) measured concentrations of As, Cd, Cr, Ni, and Pb in blood samples of children in Bui Dau e-waste recycling areas and Nhuan Trach rural control sites, and found that blood concentrations of As, Ni, and total five metals and DNA damage levels were significantly higher in the e-waste children. Serum concentrations of perchlorate, an ionic compound that widely used as an oxidant in rocket fuel, missiles, flares, fireworks, and automobile air bag inflators, and as a dopant material in the production of polyvinyl chloride (PVC), were significantly higher in Bui Dau e-waste residents (median 0.120; range < 0.050–1.25 ng/mL) than those in rural control residents (0.086; < 0.050–0.660 ng/mL) (Eguchi et al., 2014). Based on serum levels of perchlorate, the median exposure dose of this compound estimated for residents in Bui Dau was 48 ng/kg/d, which was higher than those estimated for residents in control sites (33 ng/kg/d), but still lower than the US EPA reference dose (RfD) (700 ng/kg/d; US EPA, 2005). However, a maximum daily intake dose of 810 ng/kg/d was derived for an e-waste recycler, indicating a significant occupational exposure to perchlorate in the e-waste sites (Eguchi et al., 2014). Although the association between serum perchlorate equivalent concentrations and thyroid hormone levels was not clear, additional investigations on human exposure to perchlorate and other anionic compounds are needed, especially for pregnant women and their offspring in the e-waste sites (Eguchi et al., 2014).

Concentrations of POPs such as PCBs, PBDEs, and HBCDDs, and their metabolites such as hydroxylated PCBs (OH-PCBs) and bromophenols in human serum and breast milk samples donated by the e-waste residents, in particular persons directly involved in the e-waste processing activities, were significantly higher than those detected in normal inhabitants, providing evidence of occupational exposures to e-waste-related pollutants (Eguchi et al., 2015; Tue et al., 2010b). In females, positive associations were found between serum concentrations of PCBs/OH-PCBs and thyroid hormones (Eguchi et al., 2015). Dioxin-like activities screened by the DR-CALUX bioassays were higher in breast milk samples from the Bui Dau e-waste sites than Trang Minh e-waste sites and Hanoi control sites (Tue et al., 2014). Breast milk of women involved in e-waste recycling activities had higher accumulation of PCDFs and PBDFs than other groups (Tue et al., 2014). Although no clear association between environmental and human levels of organic pollutants and specific human diseases was reported in Vietnam, more detailed and intensive investigations on risk assessment of these contaminants, incorporating environmental and personal monitoring, questionnaire data evaluating, and epidemiological testing, should be performed in future, especially for occupationally exposed persons and children in the e-waste sites.

Residents in some Vietnamese e-waste recycling sites are estimated to be exposed to toxic chemicals (e.g., As, Cu, Mn, Ni, Pb, Zn, perchlorate, BFRs, PCBs, and DRCs) at levels higher than those found in general population. The children in e-waste sites may have higher blood concentrations of some toxic elements like As and Ni and DNA damage levels than in control sites (Ngo et al., 2021). Several exposure scenarios have been evaluated and the obtained results showed a variegated contribution of inhalation, food consumption, and dust ingestion pathways depending on the nature of pollutants and investigated groups. Among them, contaminated dust and food (e.g., poultry and fish) are considerable and specific sources of some heavy metals (e.g., Cu, Pb, and Zn), flame retardants, and DRCs in the e-waste sites (Anh et al., 2017; Matsukami et al., 2016a, 2016b; Oguri et al., 2018; Tue et al., 2010a, 2013). In addition, breast milk of some mothers directly involved in e-waste recycling were considered unsafe for breastfeeding infants in case of PBDE residues (Tue et al., 2010b). Throughout the period of investigation (i.e., 2008–2019), the labor protection conditions and human awakening of occupational exposures in the Vietnamese informal e-waste recycling areas were not sufficiently considered. Working under non-protected conditions without simplest personal protective equipment (e.g., facemask, helmets, goggles, and gloves), consuming contaminated food, and other unhealthy habits (e.g., smoking during working hours in male recyclers and taking care of children near or in the workplaces) are possible explanations for the elevated exposure to toxic chemicals in recyclers and their offspring in the e-waste sites. More attention should be paid on the improvement of working conditions and human awareness on the potential adverse effects of e-waste-related pollutants in these informal recycling sites.

Recommendations and knowledge gaps

As described in previous sections, the e-waste managing and processing system in Vietnam exhibits several limitations on both political and technical aspects. The recommendations to improve management effectiveness and recycling rates, and to reduce negative effects of e-waste-related processing activities have been suggested. These suggestions are based on literature studies (Thai, 2009), field surveys combined with modeling calculations (Hai et al., 2017; Tran & Salhofer, 2018a, 2018b), and actual monitoring data (Suzuki et al., 2016). An overview of recommendations on the e-waste management practices in Vietnam is presented in Table 4. The current management practices showed limitations and a need for improvement in all sectors such as government managers, industries, consumers, and e-waste recycling facilities. In case of informal recycling sites, if the barrier of technologies and waste control is too difficult to overcome at the present, only dismantling and sorting activities should be focused. Potential hazardous materials from e-waste processing (e.g., transformer oils, lubricants, coolants, acid solutions, toxic gases) should be managed and treated in appropriate ways. Critical activities such as uncontrolled pyrolysis, open burning, dumping, and storage of e-waste must be minimized. Recyclable plastic parts should be sold

Table 4 An overview of recommendations on the e-waste management practices in Vietnam

Sector	Issue	Recommendations and improvements
Legislation and government managers	Completion of e-waste legislation	The following issues should be clarified and/or implemented in the regulation system: specific standards and guidance for collection, storage, transportation, and treatment activities of e-waste; roles and responsibilities of each level of government established for e-waste management; strong sanctions against violators; environmental and exposure guidelines for e-waste-related pollutants
	Public awareness	The knowledge and awareness of general population, especially groups directly involved in e-waste processing, about socio-economic benefits and potential adverse effects of e-waste should be improved under different activities such as parading, investigating, and propagating on mass media and social networks
	Collecting system	A synchronized collecting system of e-waste should be established, probably at homes (with clear distinction to normal domestic waste) or at designated stations
	Environmental quality management	The environmental quality and human exposure to e-waste-related pollutants, especially in the e-waste processing facilities, should be considered and managed by the competent authorities such as local government and provincial agencies of environment, industry and trade, science and technology, and health
	E-waste recycling fee	An e-waste recycling fee should be imposed by the government on new purchases of electronic products, which has been applied in European Union, California (US), and Ontario (Canada)
Electrical and electronic industries	Production and management practices	The following aspects should be considered: clean production for avoidance of use and generation of hazardous materials, design for environment including decarbonization measures, information disclosure of used materials and parts (e.g., chemical compositions and manufacturing information on their dismantling and separation), and promotion of the use of recycled products
Consumers	Storage and disposal	Storage of obsolete EEE, especially old-type items such as CRT TVs, at homes is not recommended. E-waste should be donated to producers, retailers, or other formal collectors rather than peddlers or second-hand dealers
Formal e-waste processing facilities	Processing	Hazardous liquid from e-waste (e.g., transformer oils, lubricants, coolants) should be separated and treated in appropriate ways. Precious metals other than copper, plastics, and other recyclable materials should also be recovered
	Waste management	Waste streams from e-waste processing such as acid solutions and toxic gases from hydrometallurgy, and solid waste and air emission from incinerators should be managed and treated in appropriate ways

Table 4 (continued)

Sector	Issue	Recommendations and improvements
	Labor protection	Workers should be equipped with protective equipment such as work clothing, facemask, helmet, goggles, and gloves. Periodic health examination is required
Informal e-waste recycling sites	Storage	E-waste should be stored inside the facilities other than outdoors
	Dismantling	Effective and safe dismantling and sorting of e-waste should be improved. Copper wires should be mechanically separated from coating materials rather than by pyrogenic methods
	Open burning	Open burning activities, including metal recovery and final disposal of less valuable parts, should be prohibited. Final disposal should be operated by suitable environmental services
	Plastic recycling	It is relatively difficult to manage and treat the waste streams from plastic recycling in the informal e-waste sites by appropriate ways. Recyclable plastic parts should be sold to formal industrial facilities for further treatment rather than recycled by primitive technologies
	Labor protection	Workers should be equipped with protective equipment such as work clothing, facemask, helmet, goggles, and gloves. Periodic health examination is required
	Normal residents	Living activities of normal residents, especially children, should not take place near or in working areas of the e-waste households to avoid unintentional exposure to hazardous substances

to formal industrial facilities for further treatment rather than recycled by primitive technologies. The best available techniques/best environmental practices (BAT/BEP) approach should be applied to recycling processes in the informal e-waste recycling sites (Suzuki et al., 2016; Tran & Salhofer, 2018b). Labor protection and periodic health examination schemes should be provided for e-waste recycling workers.

The current review has some knowledge gaps: (1) information about e-waste management of some sectors such as producers, importers, sale agents, private intermediate collectors and service shops, and illegal importers and exporters is still lacked; and (2) little is known about informal e-waste recycling activities in central and southern Vietnam. Besides, similar challenges are also expected for other modern waste types such as end-of-life vehicles (ELVs), solar panels, various kinds of batteries, etc., which contain recyclable materials, metals (including precious elements), and (possibly) hazardous chemicals. In addition to e-waste, these modern wastes have been reported with increasing demand, disposal amounts, and possible negative impacts on human and environmental health during their recycling activities in Asian countries including Vietnam (Anh et al., 2019, 2020; Fujimori et al., 2016; Noguchi et al., 2014; Takahashi et al., 2017). Establishment of BAT/BEP on e-waste recycling should be applicable for future challenges on comprehensive management on various kinds of modern wastes to develop sound material-cycle societies in local, regional, and global basis.

Conclusions

A portion of e-waste has been produced and handled under poorly controlled conditions in Vietnam due to improper management systems and limited awareness of the majority of people. The available monitoring data indicate significant environmental levels and human exposures to toxic elements, flame retardants, and unintentionally produced contaminants (e.g., DRCs and PAHs) in some informal e-waste recycling areas in northern Vietnam. For example, concentrations of PBDEs in workplace dust (130–250,000 ng/g) and sediment (100–3800 ng/g) samples collected from Bui Dau e-waste recycling areas were markedly higher than those measured in non-e-waste sites. Breast milk samples donated by recyclers in Bui Dau were contaminated with relatively high dioxin-like activities with specific accumulation of brominated dioxins. In order to effectively exploit benefits from e-waste and minimize their adverse impacts on environmental and human health, the completion of e-waste legislation, human awakening, and development of management best practices for e-waste in all stakeholder categories, especially in formal and informal e-waste processing facilities, are in urgent need. To improve the current situation of e-waste management and processing, the integrated effort of policy makers, government managers, scientists, entrepreneurs, workers, and Vietnamese people, is required. The collaboration and experience from other countries in the region and developed countries in the world are also very important and necessary. Despite the overlapping difficulties in the present, we believe in a bright future for an effective and environment-friendly management and practice system of e-waste in Vietnam and other countries.

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Declarations

Competing interests The authors declare that they have no competing interests.

Consent to participate Not applicable.

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Ethics approval Not applicable.

Human and animals rights In this review paper, analytical data from human participants and animals were retrieved from previous original researches published in peer-reviewed journals. No experiments involving humans and animals were conducted in the present study.

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