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From inequitable to sustainable e-waste processing for reduction of impact on human health and the environment

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Recycling of electric and electronic waste products (e-waste) which amounted to more than 50 million metric tonnes per year worldwide is a massive and global operation. Unfortunately, an estimated 70–80% of this waste has not been properly managed because the waste went from developed to low-income countries to be dumped into landfills or informally recycled. Such recycling has been carried out either directly on landfill sites or in small, often family-run recycling shops without much regulations or oversights. The process traditionally involved manual dismantling, cleaning with hazardous solvents, burning and melting on open fires, etc., which would generate a variety of toxic substances and exposure/hazards to applicators, family members, proximate residents and the environment. The situation clearly calls for global responsibility to reduce the impact on human health and the environment, especially in developing countries where poor residents have been shouldering the hazardous burden. On the other hand, formal e-waste recycling has been mainly conducted in small scales in

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[1] Professor Dr. Lygia Budnik passed away on November 21st, 2020. During the last few years of her life, she had dedicated her effort to lead the COST Action Diagnosis, Monitoring and Prevention of Exposure-Related Noncommunicable Diseases (DiMoPEx) project which was funded by the European Union. This review is one of the key publications from the project and all the co-authors would like to dedicate this review to her memory.

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industrialized countries. Whether the latter process would impose less risk to populations and environment has not been determined yet. Therefore, the main objectives of this review are: 1. to address current trends and emerging threats of not only informal but also formal e-waste management practices, and 2. to propose adequate measures and interventions. A major recommendation is to conduct independent surveillance of compliance with e-waste trading and processing according to the Basel Ban Amendment. The recycling industry needs to be carefully evaluated by joint effort from international agencies, producing industries and other stakeholders to develop better processes. Subsequent transition to more sustainable and equitable e-waste management solutions should result in more effective use of natural resources, and in prevention of adverse effects on health and the environment.

1. Introduction

In modern times, electronic devices are major components of most consumer products in our daily lives and have good recyclable values. This recycling stream is often referred to as Waste Electrical and Electronic Equipment or electronic waste (e-waste) which contains *'various forms of electric and electronic equipment that have ceased to be of value to their users or no longer satisfy their original purpose, including both "white goods" such as refrigerators, washing machines, and microwaves and "brown goods" such as televisions, radios, computers, and cell phones.'* (Encyclopedia Britannica, 2016). Specific examples of these items have been described (Balde et al., 2015) and are also shown in Table 1.

It was estimated that 53.6 million metric tonnes (Mt) of e-waste from consumer products alone were generated in 2019 and it was predicted to exceed 74 Mt by 2030 (Forti et al., 2020). The largest amount of e-waste was generated in Asia (24.9 Mt), followed by the Americas (13.1 Mt) and Europe (12 Mt). In North America, about 20 kg of e-waste was produced per person annually, while Europe was ranked second with an e-waste production of 16.2 kg per capita in 2019 but was with the highest collection and recycling rate of 42.5% (Forti et al., 2020; Hinchliffe et al., 2020). Although this massive amount of e-waste was preferred by consumers to be recycled, an estimated 70–80% of e-waste was shipped from developed to low-income countries and was improperly recycled (Baldé et al., 2017; Pascale et al., 2018; Forti et al., 2020).

The aforementioned amount of e-waste was probably underestimated, as statistics on imports and exports of e-waste were either inadequate or non-existent for many countries. Alternative methods to document e-waste flows need to include GPS trackers or 'person in the port' who checks transported goods personally (Baldé et al., 2017). Nevertheless, the GPS tracking used by the Basel Action Network (BAN) revealed only about 35% overall export rate of e-waste (Lee et al., 2018). A recent study indicates that 64% of the e-waste shipments leaving the EU entered the Africa continent (Laville, 2019), however, another report indicates that "70% of the global e-waste entered a small city, Guiyu, in China". Although the latter data are improbable, it illustrates the poorly characterized e-waste problem which certainly needs to be addressed urgently.

Without proper regulation and investment in e-waste recycling technology, the current process is a low profit, low tech but labour-intensive business. Therefore, such recycling activities have often been performed informally in low- and middle-income countries which have enormous low-tech labour forces, e.g. China, India and African countries. Furthermore, the recycling activities have been performed by home-based recyclers using low-tech methods, such as manual dismantling, cleaning with hazardous solvents, open burning and acid leaching, in order to recover profitable components/materials (Cui et al., 2015; Tansel, 2017). Unfortunately, low-income countries traditionally do not have strong environmental- and worker's-protection laws and practices. Consequently, workers, their family members and the environment have been exposed extensively to toxic substances from the recycling activities.

In this context, health risk and environmental pollution due to e-waste recycling activities are serious local as well as emerging international problems. Furthermore, the e-waste recycling process represents an inequitable activity: typically, the high-income countries generate the waste and the developing nations take the burden. Based on these serious concerns, our review paper provides a critical update of trends, hazards, exposure and prevention in the current situation of e-waste processing with a focus on their impacts on health and environment. In addition, it is expected to stimulate actions for development of sustainable solutions.

Table 1
Typical chemical elements and compounds in e-waste.

Electric(tronic) components	Chemical element and compound
Cables, wires, connectors, metal frames, solder joints, batteries, cathode ray tubes, energy-efficient lamps, mobile phones, etc.)	Aluminium, cadmium, chromium, copper, iron, lead, lithium, mercury, nickel, silver, palladium, platinum, tungsten
Electronic components (capacitors, transformers, transistors, inductors, resistors, diodes, etc)	Mineral oil, polychlorinated biphenyls, epoxide resin and other polymer resins
Printed circuit boards	Polybrominated flame retardants, organophosphorus flame retardants
Coatings, linings, plastic frames, packages	Polyvinyl chloride, polyethylene and other polymers
Casings and plastic components and fabrics	Phthalate plasticizers, polybrominated flame retardants, organophosphorus flame retardants

2. Trading routes and transportation of e-waste

There have been existing rules on proper management and trading of waste but they were not properly utilized. For example, the Basel Convention on the Control of Transboundary Movement of Wastes and their Disposal, and the OECD "Decision C (2001)107/Final" clearly stated the purpose to stop developed countries from exporting their wastes to low income countries (Tansel, 2017; Ruff, 2019). According to these documents, waste should be reduced to the minimum and managed in the countries where they were generated. However, many e-waste export countries which had not ratified the convention continued to export e-waste (Ackah, 2017; Ruff, 2019). In addition, hidden operations and legal loopholes had been used often, e.g. trading e-waste as functional second-hand equipment, i.e. not intended for recycling (Man et al., 2013; Ackah 2017). This practice was estimated to have involved 50% of the electrical and electronic waste transported to Africa, and 40% of the TV waste from Japan to the Philippines (Yoshida and Terazono, 2010; Odeyingbo et al., 2019).

Besides the well-understood environmental pollution and disease burden from e-waste recycling activities around the world (Fig. 1.), a less recognized problem has been on impact related to their transportation via air, land, and sea (Elia 2018; Fiore et al., 2019; Offenhuber 2013). For example, the increasing number of batteries for smart phones, electric scooters or electric automobiles, etc., which could ignite spontaneously, constitutes expanded hazard during transportation and at final destinations. In addition, transportation of electrical and electronic waste in closed spaces, such as in containers, could result in accumulation of harmful chemicals, e.g. from previous fumigation or from released plasticizers and flame retardants, especially if the e-waste had been partially recycled (Pedersen et al., 2014; Budnik et al., 2017).

There is occupational health risk as well. For example, a case of severe PCB exposure of seafarers occurred when two of the transformers shipped from Bangkok, Thailand to Hamburg, Germany for disposal were damaged on the journey and 400 l of transformer oil containing Aroclor 1254 leaked into the cargo hold (Budnik et al., 2014). Such reverse transportation of e-waste from low income to more developed countries could happen more frequently in the future. However, enforcing occupational health and safety regulations can be further complicated in cases of sea transport by merchant ships operating under a third country's flag.

In response to the increasing concern about e-waste activities, several countries have started to reduce the problem. For example, the Chinese government has taken some actions to reduce the importation of e-waste, and Ghana adopted an integrated approach for prohibiting their imports and exports (Chi et al., 2011; Law et al., 2014; Baldé et al., 2017). However, such efforts are still grossly inadequate. Legal management of e-waste has also been improving in some areas, such as in East Asia where the official collection rate has increased to 25%, while it is still almost completely missing in Central and South Asia (Baldé et al., 2017). However, increased legal actions could also force the re-routing of e-waste (Grant et al., 2013; Law et al., 2014). For example, a recent report shows that 9.4% of e-waste in Nigeria were rerouted from China (Odeyingbo et al., 2019) in order to avoid local regulations.

3. Informal e-waste recycling

The majority of e-waste is processed and recycled by informal businesses in Asia: mainly China, India, Pakistan, the Philippines, Sri Lanka, Thailand and Vietnam (Waheed et al., 2019; Seith et al., 2019; Li et al., 2020); in Africa: mainly Ghana, Nigeria and South Africa (Daum et al., 2017; Ohajinwa et al., 2017) and in South America: mainly Brazil, Chile and Uruguay (Yohannessen et al., 2019; Souza et al., 2020). Informal e-waste recycling is carried out either on huge waste dumping sites or in small, often live-in recycling shops. Many operators and their families live at the dumping sites or nearby (Feldt et al., 2014; Awashti et al., 2016). Additionally, many of the processes are performed by children and adolescents (Souza et al., 2020).

Informal e-waste recycling has traditionally involved manual and primitive techniques, and some examples of such recycling are shown in Fig. 2. The recycling processes usually include melting of electronic boards on open fires in order to recover metals and valuable chips, burning cable wires to extract copper, cleaning with hazardous solvents and finally burning off of residual valueless materials. Later on, the extracted metals might be further treated by metallurgy and smelting to purify the metals. This has often been done in settings where metal scraps from different waste streams were treated for separation of material by e.g. density and magnetism. Non-thermal processes usually involve cutting, shredding and acid leaching of electronic components.

Indeed, e-waste operators have frequently been reported to have very high exposure to a variety of toxic substances, such as metals (Gangwar et al., 2019; Ohajinwa et al., 2019; Yang et al., 2020), flame retardants/organic solvents (Ohajinwa et al., 2019; Wang et al., 2019; Zhang et al., 2019a; Kaifie et al., 2020) platicizers (Li et al., 2019), toxicant-laden dust and particulates (Luo et al., 2011; Wittsiepe et al., 2017), combustion products, e.g. polycyclic aromatic hydrocarbons (Yu et al., 2006; Feldt et al., 2014) and dioxins (Wittsiepe et al., 2015). In addition, their family members have often been reported to be directly or indirectly exposed to toxic substances from e-waste processing at their homes (Seith et al., 2019; Waheed et al., 2019; Zhang et al., 2019b; Zeng et al., 2020). A summary of the extensive exposure problem is shown in Table 2.

4. Impact on environment and health

Based on the previous description of the informal recycling process, there is no double that the process has caused widespread pollution in the air, soil and water of the environment and health problems subsequently (Awasthi et al., 2016; Landrigan et al., 2018; Wu et al., 2018; Li and Achal, 2020). Consistent with these observations, exposures to the toxic substances were significantly associated with increase of both cancer and non-cancer risk at all e-waste sites (Platform for Accelerating the Circular Economy, E-waste Coalition, 2019; Zheng et al., 2017; Ohajinwa et al., 2019).

Among non-workers, e.g., children, exposure to lead or to multiple heavy metals were found to be associated with health effects among children and pre-school children (Zeng et al., 2020 and Zhang et al., 2020, respectively). Exposure to e-waste chemicals even affected the unborn after their in-utero exposures. Based on umbilical cord blood lymphocytes and epigenome-wide DNA methylation analyses, a report shows that high heavy metal concentrations were significantly

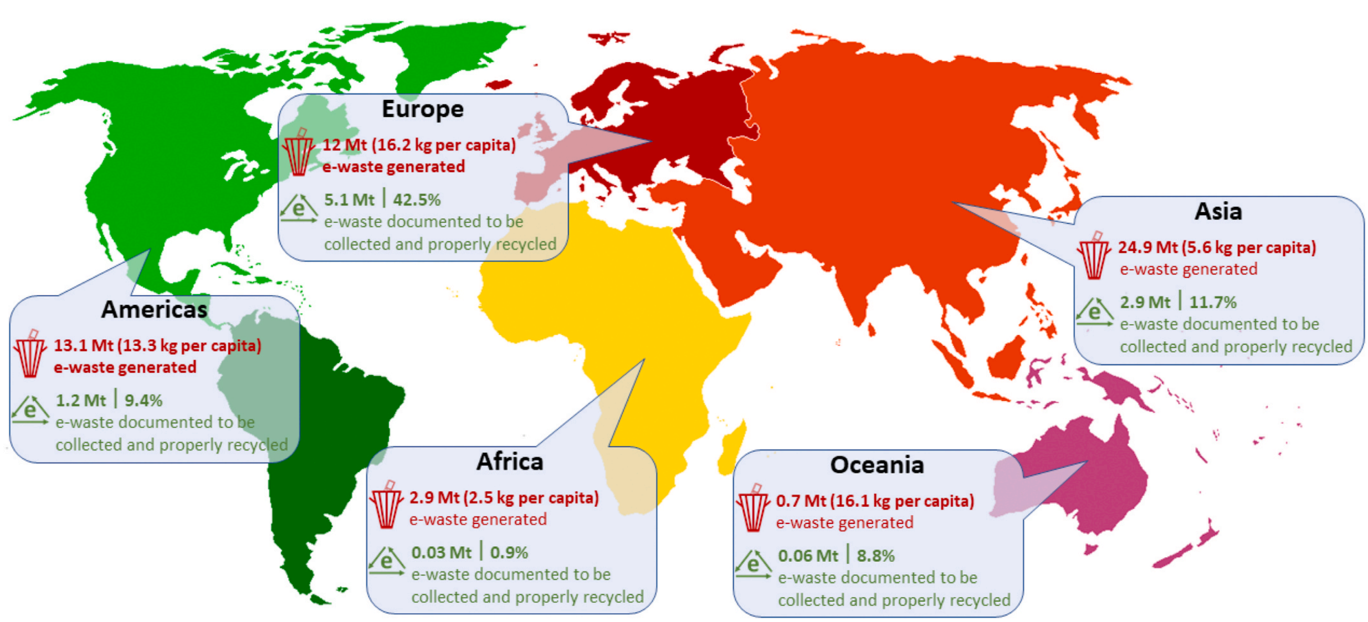

Fig. 1. E-waste production and recycling in the world. (Source of map: Wikimedia Commons, https://commons.wikimedia.org/wiki/File:BlankMap-World-Continents-Coloured.PNG; Source of data: Forti et al., 2020).

Fig. 2. Informal e-waste recycling activities, including circuit board baking (a), wire burning (b), dismantling (c), and acid leaching (d) in Guiyu, China (Source: Xu et al., 2015. Permission to publish the figure was obtained from the Licensed Content Publisher Springer Nature, License Number: 4914780066481 and License date: September 23, 2020).

Table 2
Documented and suspected exposure of workers, proximate residents and the environment by informal and formal e-waste recycling.

	Formal recycling	Informal recycling
Workers/recycling operators	Low risk of exposure suspected; but comprehensive surveys do not exist	Very high exposure to hazardous chemicals of e-waste but also to combustion products; adolescents and children act as operators very often
Proximate residents and relatives	Very low risk of exposure; risk may be higher for (inadequate) joint processing of e-waste and municipal waste	High exposure to hazardous chemicals of e-waste and combustion products (particularly if residence is located on the dumping site or in the recycling facility)
Environment (indirect exposure of the general population)	Low risk of exposure suspected; but comprehensive surveys do not exist	High exposure to hazardous chemicals of e-waste and combustion products

associated with abnormal methylation of 79 genes which are involved in multiple biological processes including calcium ion binding, cell adhesion, embryonic morphogenesis, as well as in signaling pathways which are related to NFkB activation, adherens junction, TGF beta and apoptosis (Zeng et al., 2019). Further analyses of the data suggest that excessive lead exposure could have affected brain neuron development in the developing embryos. Indeed, the same group of investigators reported that excessive lead exposure from eWaste sites were linked to sensory integration difficulties in preschool children (Cai et al., 2019). In another study, increase in maternal urinary metabolites of PAH was significantly associated with decrease of weight, head circumference, BMI and Apgar 1 score among newborns, therefore affecting neonatal development (Huo et al., 2019).

5. Formal e-waste recycling

Although e-waste recycling has been mostly conducted in developing countries, the process has been conducted formally, but in a much smaller scale, in industrialized countries. In the EU, e-waste recycling has been regulated by the Directive on waste electrical and electronic equipment (WEEE Directive; first issued as 2002/96/EC; revised as 2012/19/EU). This Directive was provided for the creation of collection schemes where consumers would return their e-waste free of charge. These schemes aimed to increase the recycling of e-waste and/or their re-use. In December 2008, the European Commission proposed to revise the Directive in order to tackle the rapidly-increasing waste stream. The Directive laid down requirements for the disposal of e-waste. The principle underlying these requirements focused on producers' responsibility. According to this principle, the producers are responsible for the management throughout their product's entire life-cycle. In this framework, the member-states have to ensure:

- that producers of electrical and electronic equipment secure the treatment and recovery of collected and returned e-waste;
- producers guarantee the financing of the environmentally sound disposal when they place new equipment on the market;
- distributors take back e-waste from private households under certain conditions and the recovery targets for collecting, recycling and recovering stipulated in the directive are met.

Additionally, the Directive stated that e-waste must be collected separately from general waste, while consumers must be able to return e-waste free of charge. The corresponding collection systems must be established in line with population density. Member-states must meet a binding target for collection. The directive also laid down the minimum technical requirements for storage and treatment of e-waste.

Unfortunately, the implementation of the mentioned regulations and their adherence are left to be done by the member-states individually in the EU. Thus, the legislation has not been fully realized in all member-states, particularly in the less developed ones and the candidate members. For instance, the Republic of Serbia provides an example of a transitional e-waste recycling situation in Europe. Serbia, an EU candidate country, harmonized and adopted parts of the WEEE Directive 2012/19 requirements, but the e-waste management practise was still underdeveloped, partly due to insufficient collection infrastructure, including equipment and collection points. The generation rate of e-waste was estimated at 11.1 kg/cap/year, which corresponded to 80,000 tons annually (Marinkovic et al., 2017). The majority of e-waste (especially from households), were still mixed with municipal solid waste at landfill sites (Diedler et al., 2018), causing significant environmental and health issues (Petrovic et al., 2018). It is estimated that between 15,000 and 20,000 tons of e-waste were recycled formally every year, which was only 20% of the total e-waste produced (Batinic et al., 2018). During the recycling process, valuable and hazardous components were separated manually and then extracted using mechanical treatment processes. The greatest amounts of the extracted and valuable components were used as secondary raw materials, while some hazardous components were exported to other EU countries for further recycling.

An example for an industrialized country outside of the EU can be taken from Israel which developed its legal processes similar to that of the EU regulation in 2014. Subsequently, two companies received accreditation from 2014 to 2024 to treat electronic waste. During the first five years of accreditation, one of the companies received about five tons of e-waste that stood at about 15% of the imported e-waste. In addition, the law compelled battery vendors to provide containers and, as of 2019, to recycle 35% of their sold products. Since 2020, the burying or landfilling of electronic waste has been prohibited, unless it is a by-product of recycling/recovery effort. By 2021, manufacturers and importers of electric and electronic equipment will be responsible for recycling 50% of the total weight of electronic equipment they sell. Nonetheless, informal e-waste recycling remained active, especially in the Palestinian territories (Grossman, 2016; Davis and Garb, 2015).

For most countries around the world, the proportion of recycled e-waste was always low compared to the total e-waste accrued in the countries. For example, 12.4 kg/cap/year was collected for recycling in Denmark which corresponded to 45% of the e-waste produced, and which, in turn, corresponded to 45% of the marketed electrical and electrical equipment (Eurostat, 2016). According to the Danish Environmental Protection Agency (Danish EPA, 2015), 11 companies in Denmark collected e-waste, among which 6 also sorted e-waste. The e-waste had been collected in several fractions, disassembled manually (e.g. separation of a battery in a laptop) and sorted before further processing. There were no smelters in Denmark and only a few companies provided pre-treatment (shredding) of certain e-waste, such as household appliances. Most companies in Denmark sold the sorted and pre-treated e-waste to international companies for further processing.

In Europe, Switzerland, Norway, and Sweden had the most advanced e-waste management systems and the recycling rate was 49% which was the highest in the world (Baldé et al., 2017). Five years earlier, only 35% (3.3 Mt out of 9.5 Mt) of the e-waste was processed within the EU (Huisman et al., 2015). Consequently, approximately 400,000 tonnes of e-waste left the EU as part of ‘undocumented mixed exports’ (Huisman et al., 2015; Lepawsky, 2018). With adaptation of the EU new circular economy policy (EEA, 2019) and of enhanced recycling of waste, the waste management/recycling sector is expected to grow and to be more formalized.

The current practices in the formal recycling facilities in high-income countries, e.g. USA, Canada and Sweden, require testing, refurbishing and repairing of electronic equipment that are received as ‘waste’. For most other developed countries when there are no clear regulations, however, the recycling process usually adopts a combination of automatic machinery and manual labour protocols. On the other hand, with the tendency towards small (wearable) electronics, the ‘screwdriver’ dismantling would become more challenging and might be replaced by shredding followed by advanced technologies for separation of shredded materials, e.g. gravimetry, static electricity and colour (Xue et al., 2013; Ceballos and Dong, 2016).

As opposed to the informal process, the structure of the formal recycling sector is based on a network of parties who perform specialized processing of certain electronic equipment and deliver their products such as glass, plastics, and metals to other parties downstream. Consequently, the formal process is assumed to impose less exposure for operators and populations and for the environment. To illustrate differences between the formal and informal processes, some examples are provided in Table 2. However, comprehensive surveys are needed to validate the safety of such formal operations.

6. Conclusions and recommendations

The current situation of e-waste recycling is inequitable and hazardous. Consequently, considerable environmental contamination and impact on human health have been reported in developing countries. These are serious issues that are reaching emergency situation in many regions around the world. However, these issues have not generated adequate international effort to regulate and to overcome the problems. One reason is that adverse health outcomes have been considered to be limited only to some local areas, e.g. in China, India, Ghana and Nigeria. However, it is inevitable that pollution’s spreading (via air and water), food chain contamination and migration of individuals would affect the whole world. Indeed, a systematic effort needs to be mounted to better understand environmental and health impacts from exposure to toxic chemicals via the informal as well as formal recycling processes. For example, could workers and family members be identified by their specific body burden for excessive exposure to e-waste products? Could their exposure to unique combinations of toxic chemicals, e.g. organohalogenated compounds plus heavy metals, cause unique health effects?

With the rapid production of new electronic products, e.g. electric automobiles, the e-waste recycling industry will certainly grow exponentially in the future. Therefore, the inequitable distribution of the recycling burden cannot continue further. On the other hand, useful processes for formal collection and recycling have been proposed and some have been initiated, e.g. automation and containment, and use of automatic wire-stripping machine would be helpful (Heacock et al., 2018). A process which involves pyrolysis with or without ultrasound technologies which was capable of recovering about 60 wt % of solid products, e.g. metals, would be useful (Jadhao et al., 2020). In addition, government agencies, producing industries and stake holders can collaboratively develop more reliable procedures, e.g. end-of-life mobile phone circuit board tracing (Anamalai et al., 2020) and better risk assessment (BIimir et al., 2020; Hameed et al., 2020). Indeed, this review has identified a few countries which have been making improvements in the process. There is no doubt that such improved processes would significantly reduce environmental pollution and the subsequent health hazards.

Our review clearly indicates serious risk to the environment and to population health posed by the current e-waste recycling activities. Therefore, systematic efforts need to be initiated with international agencies, producing industries and other stakeholders to develop an improved and sustainable e-waste recycling process which will be universally adapted. The systematic effort to generate a better process may consider the following measures and interventions:

- Ratify the Basel Ban Amendment (BBA) by all countries, which can also reduce inadequate e-waste trading
- Amend the BBA with respect to more specific world and bilateral trade agreements
- Conduct surveillance of e-waste trading and processing practices in and between the counties and verify their compliance with the BBA by independent authorities

- Initiate local programmes to support the transition to socio-economically sustainable small-scale and informal processing of e-waste, to generate sufficient income for those local communities whose livelihoods are currently dependent on informal recycling
- Conduct appropriate and comprehensive surveys on process emissions, individual exposure and health effects during (or by) e-waste processing in order to define specific occupational safety and health standards and protocols as well as to provide hazard identification and assessment of risks
- Emphasize concerted efforts for sustainable products, e.g. fair phones, and processes with regard to protection of resources and prevention of hazardous emissions

It is essential that collaborators need to take concerted actions to convert the informal and hazardous recycling processes into better and more sustainable management as a global priority. Such an effort will minimize inequity, reduce adverse health and environmental impacts, and ensure sustainable prosperity.

Authorship contribution statements

As the leader for the committee, Budnik provided the overall guidance for preparation of the manuscript; Au provided the initial concept for writing the manuscript, prepared the first draft and contributed to completing the manuscript; Adams organized internet-based meetings for the committee members and prepared several revisions; Goen and Scheepers contributed writings for major sections and revisions of the manuscript; the other co-authors provided writings and revisions of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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