Environment International 95 (2016) 157–166

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

The formal electronic recycling industry: Challenges and opportunities in occupational and environmental health research

Diana Maria Ceballos *, Zhao Dong

Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 17 July 2016
Accepted 20 July 2016
Available online 26 August 2016

Keywords:
E-waste
Occupational health
Environmental health
Formal e-recycling
Electronics recycling
Chemical hazards

ABSTRACT

Background: E-waste includes electrical and electronic equipment discarded as waste without intent of reuse. Informal e-waste recycling, typically done in smaller, unorganized businesses, can expose workers and communities to serious chemical health hazards. It is unclear if formalization into larger, better-controlled electronics recycling (e-recycling) facilities solves environmental and occupational health problems.
Objectives: To systematically review the literature on occupational and environmental health hazards of formal e-recycling facilities and discuss challenges and opportunities to strengthen research in this area.
Methods: We identified 37 publications from 4 electronic databases (PubMed, Web of Science, Environmental Index, NIOSHTIC-2) specific to chemical exposures in formal e-recycling facilities.
Discussion: Environmental and occupational exposures depend on the degree of formalization of the facilities but further reduction is needed. Reported worker exposures to metals were often higher than recommended occupational guidelines. Levels of brominated flame-retardants in worker's inhaled air and biological samples were higher than those from reference groups. Air, dust, and soil concentrations of metals, brominated flame-retardants, dioxins, furans, polycyclic-aromatic hydrocarbons, or polychlorinated biphenyls found inside or near the facilities were generally higher than reference locations, suggesting transport into the environment. Children of a recycler had blood lead levels higher than public health recommended guidelines.
Conclusions: With mounting e-waste, more workers, their family members, and communities could experience unhealthful exposures to metals and other chemicals. We identified research needs to further assess exposures, health, and improve controls. The long-term solution is manufacturing of electronics without harmful substances and easy-to-disassemble components.

1. Introduction

The production, commercialization, use, recycle, and disposal of electronics have increased exponentially in the last decades since the creation of the first computer. The rapid increase of new technologies makes electronics obsolete sometimes even within days of purchase. What is most concerning is the amount of electronics that have accumulated as waste worldwide, often called e-waste. It is estimated that the total amount of e-waste generated worldwide in 2014 was 41.8 million metric tons (United Nations University, 2014). E-waste may include electronics (e.g., keyboards, screens, computers, mobile phones), household appliances (e.g., televisions), office equipment (e.g., printer), lamps, personal items (e.g., cameras), and miscellaneous (e.g., photovoltaic panels). In the US, 4.4 million metric tons of e-waste were recycled in US formal electronic recycling (e-recycling) facilities in 2011 (ISRI, 2016), which constitute only 25% of all e-waste generated (U.S. EPA, 2011).

Part of the world's e-waste is recycled in informal e-waste sites in developing countries, such as Agbogbloshie in Ghana (Kyere et al., 2016). In the last few years, developing countries like Colombia and China have started to establish formal e-recycling facilities, moving e-waste indoors with varying degrees of protection from hazardous materials. China has recently suspended informal recycling operations in Guiyu, aiming to revamp one of the largest e-waste sites in the world into centralized facilities in an industrial park (Standaert, 2015). In developed countries like US, Canada, and Sweden, formal e-recycling facilities are the norm. We will use the term '*informal e-recycling*' when referring to informal recycling operations in e-waste sites, and the term '*formal e-recycling*' when referring to ideally licensed and permitted facilities that process e-waste indoors with some level of industrial hygiene, worker protection, and pollution controls.

Recycling of electronics can be a source of many toxic chemicals including metals and organic compounds. Metals may include cadmium (e.g., batteries and CRTs), lead (e.g., printed circuit boards, CRTs), mercury (e.g., lamps in older LCD screens), nickel (e.g., batteries), among

* Corresponding author at: 401 Park Drive, PO Box 15677, 4th Floor West, Suite 415, Boston, MA 02215, USA.
E-mail address: ceballos@hsph.harvard.edu (D.M. Ceballos).

http://dx.doi.org/10.1016/j.envint.2016.07.010

other metals (Grant et al., 2013; Tsydenova and Bengtsson, 2011). Organic chemical compounds of concern include flame retardants (FRs) (e.g., plastics) and polychlorinated biphenyls (PCBs) (e.g., condensers). If electronics are burned, chemicals such as polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) may be generated (Grant et al., 2013; Matsukami et al., 2015). A systematic review by Grant et al. (2013) identified plausible health outcomes associated with exposure to chemicals from informal recycling in e-waste sites, including thyroid function changes, adverse neonatal outcomes, and impaired lung function.

Formal e-recycling main processes typically start by sorting, testing, refurbishing, and repairing received electronics. Then, electronics that need recycling are dismantled, sometimes shredded, and materials sorted using automatic machinery and manual labor. In some cases, there are specialized processing of certain electronics, e.g., CRTs (Ceballos et al., 2014b; Ceballos et al., 2015; Tsydenova and Bengtsson, 2011), and many formal e-recycling facilities are distributors to other parties downstream for materials recovery of plastics, glass, and metals. Controls to reduce exposures including ventilation and personal protective equipment (PPE) are common. In contrast, informal recycling is generally much more decentralized and involves fewer, if any, automatic procedures and health protective measures, usually relying on natural ventilation and without PPE. Most common processes in informal e-recycling include manual sorting, dismantling, de-soldering of printed circuit boards over coal grills to release valuable chips (Chan and Wong, 2013), open burning of wires to retrieve copper, and disposal of waste in open fields and water (Matsukami et al., 2015; Song and Li, 2014), and the health consequences of these practices disproportionally affect vulnerable populations (Heacock et al., 2016).

The objectives of this paper were 1) to provide a succinct literature review regarding chemical hazards in the formal e-recycling industry and 2) to propose a research framework to strengthen occupational and environmental health of formal e-recycling facilities based on the current literature and discuss challenges and opportunities to advance research in this area.

2. Methods

Four electronic databases were searched for publications related to chemical exposures during formal e-recycling from 1980 to Feb 2016. Key words used were: NIOSHTIC-2: 'recycling' and other databases: 'electronic,' 'recycling,' 'electronics recycling,' 'waste,' 'e waste,' 'ewaste,' 'e scrap,' 'escrap,' or 'WEEE'. Web of Science search was refined within domain 'science technology' and research areas 'environmental sciences ecology,' 'public environmental occupational health,' or 'toxicology.' Two outside studies were identified through references. Results were combined and duplicates removed to create a database of 1827 articles (Fig. 1).

We included studies in journal articles or government reports in English about formal e-recycling facilities principally engaged in the dismantling and mechanical processing of electronics for the recovery of raw materials. We excluded articles on downstream recycling facilities (i.e., plastic recycler, metallurgical processes), articles on informal or unspecified e-waste sites, cities, areas, or regions (e.g., Guiyu, China; Agbogbloshie, Ghana), and articles on management, life cycle assessment or material flows, economic analysis, new equipment, and other hazards beyond chemicals. We reviewed articles by title and abstract before final inclusion of 37 studies that met the predetermined criteria.

3. Results

3.1. Current literature on occupational health in the formal e-recycling industry (occupational health studies in Table 1)

In the US, several formal e-recycling facilities have been found with deficiencies in handling metal dust contamination (Ceballos et al., 2014a; Page et al., 2015). Inhalable worker overexposures (i.e., air samples above occupational exposure limits or OELs) have been documented during CRT processing for lead or cadmium (Ceballos et al., 2014a), cleaning operations (Almaguer et al., 2008; Page and Sylvain, 2009), and shredding (Ceballos et al., 2014a). Two workers processing CRTs

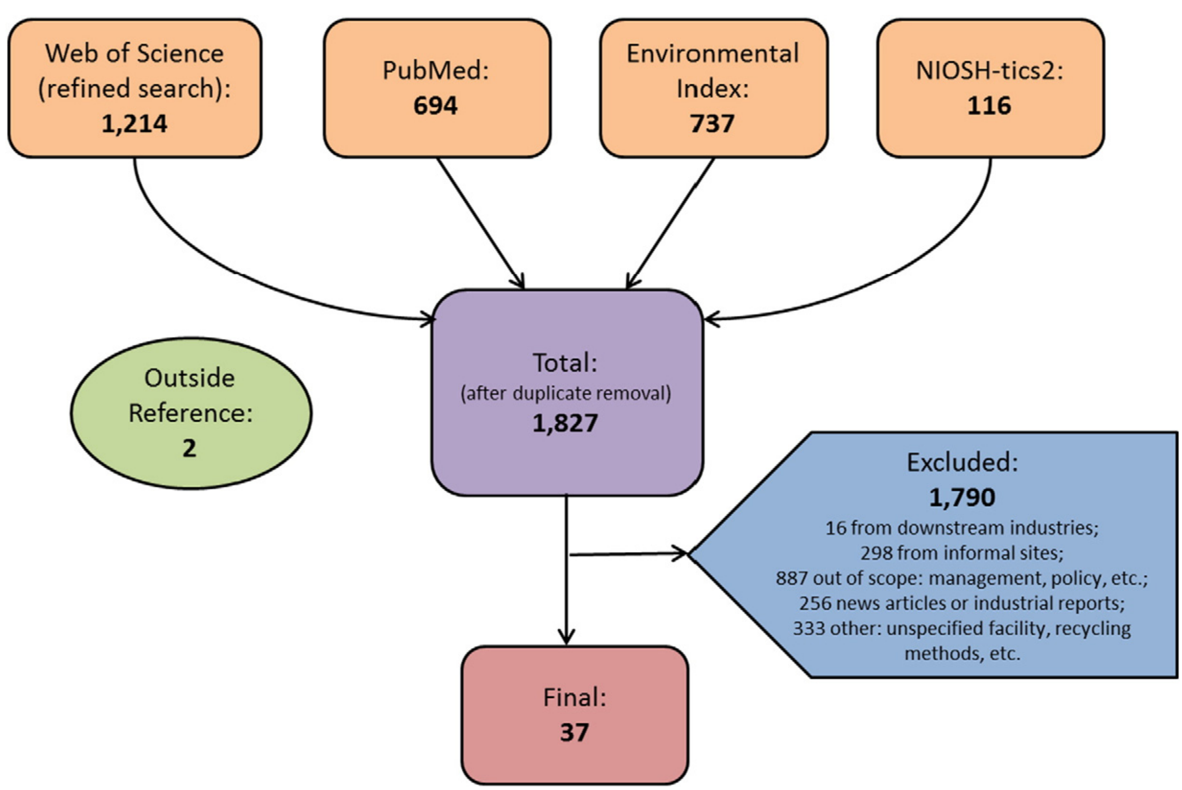

Fig. 1. Flowchart of a systematic literature review on occupational and environmental health in the formal e-recycling industry.