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Review article

# Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges

Bouchra Bakhiyi[a], Sabrina Gravel[a,b], Diana Ceballos[c], Michael A. Flynn[d], Joseph Zayed[a,b,*]

[a] Department of Environmental and Occupational Health, School of Public Health, Université de Montréal, Montreal, Quebec, Canada
[b] Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST), Montreal, Quebec, Canada
[c] Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA
[d] National Institute for Occupational Safety and Health, Cincinnati, OH, USA

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ABSTRACT

Despite regulatory efforts and position papers, electrical and electronic waste (e-waste) remains ill-managed as evidenced by the extremely low rates of proper e-waste recycling (e-recycling) worldwide, ongoing illegal shipments to developing countries and constantly reported human health issues and environmental pollution. The objectives of this review are, first, to expose the complexity of e-waste problems, and then to suggest possible upstream and downstream solutions. Exploring e-waste issues is akin to opening a Pandora's box. Thus, a review of prevailing e-waste management practices reveals complex and often intertwined gaps, issues and challenges. These include the absence of any consistent definition of e-waste to date, a prevalent toxic potential still involving already banned or restricted hazardous components such as heavy metals and persistent and bioaccumulative organic compounds, a relentless growth in e-waste volume fueled by planned obsolescence and unsustainable consumption, problematic e-recycling processes, a fragile formal e-recycling sector, sustained and more harmful informal e-recycling practices, and more convoluted and unpredictable patterns of illegal e-waste trade. A close examination of the e-waste legacy contamination reveals critical human health concerns, including significant occupational exposure during both formal and informal e-recycling, and persistent environmental contamination, particularly in some developing countries. However, newly detected e-waste contaminants as well as unexpected sources and environmental fates of contaminants are among the emerging issues that raise concerns. Moreover, scientific knowledge gaps remain regarding the complexity and magnitude of the e-waste legacy contamination, specifically, a comprehensive characterization of e-waste contaminants, information on the scale of legacy contamination in developing countries and on the potential environmental damage in developed countries, and a stronger body of evidence of adverse health effects specifically ascribed to e-waste contaminants. However, the knowledge accumulated to date is sufficient to raise awareness and concern among all stakeholders. Potential solutions to curb e-waste issues should be addressed comprehensively, by focusing on two fronts: upstream and downstream. Potential upstream solutions should focus on more rational and eco-oriented consumer habits in order to decrease e-waste quantities while fostering ethical and sustained commitments from manufacturers, which include a limited usage of hazardous compounds and an optimal increase in e-waste recyclability. At the downstream level, solutions should include suitable and pragmatic actions to progressively reduce the illegal e-waste trade particularly through international cooperation and coordination, better enforcement of domestic laws, and monitoring in both exporting and receiving countries, along with the supervised integration of the informal sector into the recycling system of developing countries and global expansion of formal e-waste collection and recycling activities. Downstream solutions should also introduce stronger reverse logistics, together with upgraded, more affordable, and eco-friendly and worker-friendly e-recycling technologies to ensure that benefits are derived fully and safely from the great economic potential of e-waste.

* Corresponding author at: Department of Environmental and Occupational Health, School of Public Health, Université de Montréal, P.O. Box 6128, Main Station, Montreal, Quebec H3C 3J7, Canada.
*E-mail address:* joseph.zayed@umontreal.ca (J. Zayed).

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## 1. Introduction

Among other terms, electrical and electronic waste (e-waste), or waste electrical and electronic equipment (WEEE), are terms used to cover electrical and electronic equipment discarded as waste without intent of reuse (Step, 2014). E-waste offers particularly high potential for recovery as it contains valuable recyclable components such as gold, platinum and silver. However, e-waste also contains non-negligible amounts of potentially toxic substances (e.g., cadmium and lead) and is thus considered hazardous when improperly managed. These findings highlight the need for the safe and smart management (including proper recycling) and commercial exploitation of e-waste while preserving human health and environmental integrity, given the large volume of e-waste generated worldwide annually (41.8 million - metric tonnes (MMT) estimated in 2014) and its fast growth (Lundgren, 2012; Kiddee et al., 2013; Cucchiella et al., 2016; Step, 2016; Baldé et al., 2015). Canada, which generated an estimated 725,000 tonnes of e-waste in 2014, is well below the 2014 top five e-waste global generators, which were the United States (7.1 MMT), China (6.0 MMT), Japan (2.2 MMT), Germany (1.8 MMT) and India (I.7 MMT). However, with 20.4 kg of e-waste generated annually per inhabitant, Canada remains one of the highest contributors to e-waste volume in relative quantities in the Americas, right between the United States (22.1 kg/in.) and the Bahamas (19.1 kg/in.) (Baldé et al., 2015).

This review aims to expose the complexity of e-waste problems. Its objectives are (a) to provide a brief overview of the historical aspects of e-waste management; (b) to identify gaps, issues and challenges that greatly complicate e-waste management; (c) to gain insight into the current e-waste legacy contamination in terms of critical, emerging or still-unknown human health issues (including occupational health concerns) and environmental contamination, and (d) to propose solutions that could potentially curb e-waste issues both upstream and downstream.

## 2. Background: a bird's-eye view of the history of e-waste management

In the 1970s and 1980s, hazardous waste, including e-waste, was commonly shipped from industrialized countries to less developed nations in Asia, Africa, Central America and Eastern Europe (UNEP, 2010). The hazardous waste trade is rooted in the “Not in My Back Yard” syndrome in developed countries, an expression of the public's vehement stand against poor management of hazardous waste, including e-waste. Since the 1970s, it has led to the adoption of more stringent laws in the developed countries, such as The Resource Conservation and Recovery Act (RCRA) in the United States in 1976 (UNEP, 2010), which led to an escalation in the costs of hazardous waste disposal, while these costs remained low in less developed countries (Massari and Monzini, 2006; Andrews, 2009; UNEP, 2010).

E-waste trading led to heavy environmental contamination in receiving countries, where primitive recycling methods, incineration and landfilling of hazardous waste were widely practiced, supported by inadequate environmental awareness, controls and regulations (UNEP, 2010). To fight what was called the “toxic trade”, the Basel Convention on the Control of the Transboundary Movements of Hazardous Wastes and their Disposal was adopted in 1989 and came into force in 1992. The aim of this international treaty is to regulate the export of hazardous waste from industrialized countries (called “Annex VII countries” and composed of parties to the Basel Convention that are members of the Organization of the Economic Co-operation and Development (OECD) or the European Union (EU), as well as Liechtenstein) to less developed and vulnerable nations (called “non-Annex VII countries” and composed of all other parties to the Basel Convention). The fundamental purpose of the Basel Convention is to promote safe and sound hazardous waste management in order to safeguard human health and the environment. Its main objectives also include the limitation of hazardous waste generation and the restriction of hazardous waste exports unless the receiving country has confirmed the existence of environmentally sound practices for managing the imported waste (Andrews, 2009; Ahmad Khan, 2016).

Amendments to the Basel Convention, known as the Basel Ban or the Ban, were adopted in 1995 and 1997 to completely prohibit the export of hazardous wastes from Annex VII countries to non-Annex VII countries, while Annex VIII was added in 1998 to include e-waste. However, Annex IX, also added in 1998, still allows the export of certain categories of e-waste for strict reuse, for the purpose of giving the receiving parties access to the digital world through second-hand equipment (Basel Convention, 2011; Ahmad Khan, 2016).

A series of regulations and policies have since emerged worldwide at the regional, national and global levels to promote reuse and proper recycling, as well as a reduction in the use of toxic raw materials. For example, in 2003, the European Union adopted significant regulations such as the WEEE Directive, which sought to enhance e-waste collection, reuse and recycling, and the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive, requiring substitutions for or the limitation of certain toxic substances, including heavy metals and flame retardants (European Commission, 2017).

On a global scale, the Nairobi Declaration on the Environmentally Sound Management of Electrical and Electronic Waste was launched in 2006 (Lundgren, 2012). A multi-stakeholder partnership known as the Solving the E-waste Problem (StEP) Initiative, involving United Nations agencies as well as academic and governmental organizations, among others, was instituted in 2007 to achieve more sustainable e-waste management through an international information-sharing platform (Sthiannopkao and Wong, 2013). An entire battery of tools has also been developed and adopted over time in developed and some developing countries to support the safe and optimal handling of the e-waste stream: Extended Producer Responsibility (EPR), Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Multi-Criteria Analysis (MCA) (Kiddee et al., 2013).

Unfortunately, despite regulatory efforts and position papers, e-waste is still ill-managed, with the proper e-waste recycling (e-recycling) rate remaining extremely low worldwide, at roughly 15.5% of the global volume generated in 2014 (Baldé et al., 2015). Even more alarming is the fact that illegal shipments to more vulnerable countries continue to abound, as disclosed by a report of the Interpol Pollution Crime Working Group (Interpol, 2009).

Through a 2014–2016 investigation, a US environmental watchdog group called the Basel Action Network (BAN) unveiled the continuing traffic of e-waste from the US to developing countries (mostly China) and involving computer manufacturers, certified recycling companies and at least one major charity organization. More than 90% of e-waste was actually exported illegally under the guise of second-hand equipment (Hopson and Puckett, 2016). Following the BAN report, the US Environmental Protection Agency (US EPA) strongly condemned such illegal activities and levied a severe fine one of the US electronic recyclers involved (US EPA, 2016a; WDE, 2016).

Given the increasing volume of e-waste being generated worldwide, it is likely that illegal shipments to the developing world have been rising steadily since the Basel Convention, leading to a globalization of e-waste issues. About 50–80% of the e-waste generated in developed countries is considered to be illegally exported to low- and middle-income countries (Ghosh et al., 2016; Someya et al., 2016). China still receives the lion's share of all illegal e-waste, although countries such as the Philippines, India, Nigeria and Ghana remain attractive destinations. It is worth mentioning that most of the receiving countries have nonetheless ratified the Basel Convention and the Basel Ban (Rucevska et al., 2015; Hopson and Puckett, 2016; Terazono et al., 2017). It is estimated that between 1.5 and 2 MMT of e-waste are exported illegally to China from the European Union each year, despite the import ban imposed by China on all e-waste in 2000 (Huisman et al., 2015;