Achieving sustainability in solving the electronic waste (e-waste) problem

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Abstract

Waste from used electrical and electronic equipment, commonly known as e-waste, is growing at a higher rate than the regular municipal waste streams. Global generation of e-waste in 2019 was 53.6 million tonnes. Rising demand for high technology products and their early obsolescence coupled with lack of proper end-of-life management options have all led to unsustainable management of e-waste in many countries. Recycling, design for environment, extended producer responsibility and public-private partnerships (PPPs) are some of the practices attempted by many countries to achieve sustainability in solving the e-waste problem. This paper provides an overview of the practices mentioned above.

Key Words: Design for environment, E-waste, Extended producer responsibility, Health impacts, Public-private-partnerships, Sustainability

Introduction

The waste from electrical and electronic equipment (EEE), commonly referred to as e-waste or WEEE, is growing fast in the world with a generation of 53.6 million tonnes in 2019 and projected to grow to 74.7 million tonnes by 2030 (Forti et al., 2020). The modern world heavily depends on EEE to drive the high technology sector, critical for many countries' economic development. The benefits of the high technology sector are well known. However, the environmental and health impacts of poor management of end-of-life EEE are relatively unknown. The issue is compounded by the fact that the average life span of many EEEs is reducing by the day due to the availability of products with increased memory, processing power, and attractive design features. This has led to the early obsolescence of many EEEs, causing a significant increase in e-waste generation. Many countries are grappling with the options to manage this challenging waste stream, which consists of several toxic compounds and valuable ones. This paper aims to provide an overview of some initiatives attempted by many countries to move towards proper management of e-waste.

Electronic and electrical industry and generation of e-waste

E-waste comprises many EEE and its accessories used EEE with an electronic circuit or EEE which utilises electrical power or battery power. Table 1 describes some of the commonly used items. The determination of correct data related to e-waste generation in a particular country is a difficult task. This is because some of the used EEEs do not enter the end-of-life management processes as they are stored by the households. Therefore, most estimates are based on manufacturing or sales data or by estimating the products' lifespan. One of the most recent and comprehensive analyses and estimation of e-waste generated around the world was conducted by Forti et al. (2020). According to this study, the global total e-waste generation in 2019 was 53.6 million metric tonnes (Mt). The Asian region generated the most substantial quantity of e-waste (24.9 Mt), followed by the American region (13.1 Mt), Europe region (12 Mt), Africa (2.9 Mt), and Oceania (0.7 Mt). Furthermore, Forti et al. (2020) has estimated that within the Asian region, China generated the largest amount of e-waste (10.1 Mt), followed by India (3.2 Mt) and Japan (2.5 Mt). Table 2 summaries the e-waste generated in selected countries around the world. In general, EEE comprises different metals and chemical compounds, many of which are toxic to human health and the environment.

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Table 1. Classification of e-waste

| Category                  | Items                                                                 |
|---------------------------|----------------------------------------------------------------------|
| Thermal products          | Refrigerators, air conditioners, freezers                            |
| Monitors and Screens      | Televisions, laptops, notebooks, monitors, tablets                   |
| Lamps                     | Light bulbs, fluorescent bulbs,                                      |
| Heavy items               | Washing machines, dryers, dishwashing machines, PV panels, photocopiers, electric stoves |
| Small items               | Microwaves, electric kettles, video cameras, calculators, toys, electrical tools, small medical devices, toasters, shavers, hairdryers, scales, many small electrical and electronic items used in the kitchen |
| Small high technology equipment | Mobile phones, personal computers, printers, telephones, routers |

Table 2. E-waste in selected countries

| Country        | E-waste (tonnes/year) | E-waste (kg/person) |
|----------------|-----------------------|---------------------|
| Argentina      | 465,000               | 10.3                |
| Australia      | 554,000               | 21.7                |
| Brazil         | 2,143,000             | 10.2                |
| Canada         | 757,000               | 20.2                |
| China          | 10,129,000            | 7.2                 |
| Hong Kong      | 153,000               | 20.2                |
| France         | 1,362,000             | 21.0                |
| Germany        | 1,607,000             | 19.4                |
| India          | 3,230,000             | 2.4                 |
| Indonesia      | 1,618,000             | 6.1                 |
| Japan          | 2,569,000             | 20.4                |
| Nigeria        | 461,000               | 2.3                 |
| Republic of Korea | 818,000            | 15.8                |
| Russian Federation | 1,631,000         | 11.3                |
| Saudi Arabia   | 595,000               | 17.6                |
| Singapore      | 113,000               | 19.9                |
| United Kingdom | 1,598,000             | 23.9                |
| United States of America | 6,918,000     | 21.0                |

When these toxic materials are intact with the EEE, they do not cause harm to humans or the environment. However, when EEE is dismantled during their end-of-life processes such as recycling, these compounds become exposed to the environment. Poor recycling practices adopted by many countries result in severe human health and environmental impacts. Generally, EEE contains toxic metals such as (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), which are also knowns as flame retardants.

Although in 2003, the European Union banned the manufacturing of EEE containing these toxic mental and compound through their Restrictions of Hazardous Substances (RoHS) Directive, there is a considerable backlog of used and old EEE in homes and offices awaiting disposal. The environmental sound management (ESM) of e-waste has also become a significant challenge to many countries due to the widespread transboundary movement of used EEE in the name of recycling or final disposal. A significant amount of e-waste and used EEE are transferred from industrialised countries to...
developing countries for end-of-life processes. Unfortunately, most e-waste processing facilities in developing countries do not have the technical skills to operate in an environmentally sound manner due to the heavy involvement of the informal waste recycling sector. Poor extraction of metals, open burning, and other rudimentary practices are causing significant impacts on human health and the environment.

**Human health and environmental impacts of e-waste recycling**

The human health and environmental impacts of e-waste recycling have been well studied by researchers around the world, in particular, in countries where e-waste recycling is predominantly undertaken by the informal sector. This section describes some of these studies conducted to highlight the human impacts and environmental effects caused by informal e-waste recycling. Ackah et al. (2019) studied the effects of trace elements in e-waste on the topsoil and subsoil of e-waste recycling sites in Accra, Ghana. They found metal concentrations in Agbogbloshie site (one of the largest informal e-waste recycling sites in the world) exceeded the Dutch Soil Intervention values by 72% (Cu), 57% (Zn), 57% (Pb), 38% (Ba), 16% (Cd) and 2% (As) meaning significant metal contamination in the site. They also found substantial Pb contamination in open burning and dismantling areas of the site, causing significant carcinogenic risks to people living nearby. A similar study conducted at a major e-wasteumpsite in Lagos, Nigeria (Alabi et al., 2020) found an increase in Pb blood levels of teenage scavenging the site with a range from 2.84 to 189.44 µg/L compared to the control group range 0.01 to 4.21 µg/L. A study conducted by Alam et al. (2019) to assess the genotoxicity of e-waste leachates an e-waste dumpsite in Metro Manila, Philippines showed the heavy presence of Cd, Cu, Ni, Pb and Zn in the soil samples of the e-waste recycling sites and the hair of the informal recyclers. Cai et al. (2019) investigated the effect of lead exposure on child sensory integration by correlating the blood levels of children with sensory processing measures living close to e-waste recycling town in China (Guiyu). They concluded that Pb exposure in e-waste recycling areas might impact the serum cortisol levels and an increase in the difficulty of child sensory integrations, further confirming the impacts on humans, especially young children. Tables 3, 4, and 5 summarises selected studies conducted on the effects of e-waste recycling on human health and the environment.

**Table 3. Selected studies on impacts on sediments around recycling sites**

| Contaminants and study area | Reference |
|----------------------------|-----------|
| Investigation of polycyclic aromatic hydrocarbons (PAHs) in soil near an informal e-waste facility in China | Gu et al., 2019 |
| Study into soil pollution caused by metals from e-waste recycling activities Pearl River Delta | He et al., 2017 |
| Contamination of soils by PAHs near informal e-waste recycling area in Vietnam | Hoa et al., 2020 |
| Distribution of heavy metals in the soils near an informal e-waste recycling facility in Nigeria | Isimekhai et al., 2017 |
| Contamination of soil by heavy metals generated from a Nigerian e-waste site | Jiang et al., 2019 |
| Changes in the microbe structure in sediments from rivers near e-waste recycling facilities in China | Liu et al., 2018 |
| Determination of PBDEs in soils and river sediments near an e-waste recycling facility in Vietnam | Matsukami et al., 2017 |
| Study into impact from PAHs, PBDEs, and PCBs on the sediments near e-waste recycling site in Ghana | Moeckel et al., 2020 |
| Impact of chlorobenzenes and PCBs in soils from an e-waste recycling area in Vietnam | Nishimura et al., 2018 |
| Investigation of chlorinated and brominated PAHs in soils resulting from open burning of e-waste | Nishimura et al., 2017 |
Table 4. Selected studies on human health impacts

| Human health impacts and the study area                                                                 | Reference                      |
|-------------------------------------------------------------------------------------------------------|--------------------------------|
| Impact of health on people living near e-waste recycling activities at Agbogbloshie dumpsite, Ghana    | Adusi et al., 2020             |
| Health impacts due to organic compounds from e-waste recycling in developing countries                | Awere et al., 2020             |
| Exposure through inhalation of particulate matter due to open burning of e-waste in Thailand          | Bungadaeng et al., 2019        |
| Human health and injuries among e-waste recycling workers in Ghana                                    | Burns et al., 2019             |
| Generation of dioxin-like compounds in e-waste recycling areas                                       | Dai et al., 2020               |
| Study into the association between open burning of e-waste and childhood lymphoma in the West Bank, Palestine | Davis and Garb, 2019          |
| Determination of mercury levels in the urine of workers in e-waste shops in Thailand                  | Decharat, 2018                 |
| Generation and exposure of PBDEs in a modern e-waste dismantling facility in China                   | Die et al., 2019               |
| Study into human health impacts from air pollution resulting from open burning of e-waste in India    | Gangwar et al., 2019           |
| Disruption of thyroid hormone-regulated proteins in residents living near an e-waste recycling site from PAHs, and PBDEs | Guo et al., 2019               |
| The correlation of maternal urinary metabolites of PAHs and adverse birth outcomes of people living near an e-waste recycling area | Huo et al., 2019               |
| Concentration of heavy metals in pregnant women and new born children resulting from informal e-waste recycling in China | Kim et al., 2019               |
| Impacts of birth outcomes connected with maternal exposure of heavy metals from informal e-waste recycling in China | Kim et al., 2020               |

Table 5. Studies on impacts on biota.

| Impacts on biota and the study area                                                                 | Reference                      |
|----------------------------------------------------------------------------------------------------|--------------------------------|
| Study in polychlorinated biphenyls in settled dust from informal e-waste recycling in India         | Chakraborty et al., 2016       |
| Concentration of flame retardants and organophosphate esters in the environment near e-waste recycling facilities | Gravel et al., 2019           |
| Determination of chlorinated paraffins in aquatic organisms near an e-waste site                    | Guan et al., 2020              |
| Environmental impacts and human exposure to flame retardants from e-waste recycling in Pakistan   | Iqbal et al., 2017             |
| Determination of PCBs near an e-waste recycling facility in North-Rhine Westphalia                  | Klees et al., 2017             |

Formal e-waste recycling

Recycling is widely recognised as one of the most popular options for end-of-life management of e-waste. Many countries are starting to realise that although e-waste contains many toxic metals and chemical compounds, they also provide valuable metals that have value in the secondary resource market. This has resulted in many industrialised countries investing funds to develop formal e-waste recycling facilities adopting advanced technologies. Unfortunately, even with such formal facilities, many industrialised countries have achieved a low recycling rate for many reasons. The challenge for e-waste recycling enterprises is to gain access to e-waste for processing. Many households tend to store their used EEE at home, hoping that they will increase value in the future. Due to this fact, many used EEEs are not entering formal e-waste recycling paths. Another issue is most of the e-waste collected by recycling companies in developed countries finally end up in recycling facilities in developing countries. In comparison to industrialised countries, e-waste recycling in developing and emerging economies is predominantly undertaken by the informal sector. However, lately, there has been some movement of
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formal e-waste recycling facilities in these regions. The formal e-waste recycling facilities in developing and emerging economies encounter stiff competition for e-waste from the well-established informal e-waste processors.

**Formal e-waste recycling - Example 1**
E-Parisaraa Pvt. Ltd ([http://ewasteindia.com/](http://ewasteindia.com/))
The company aims to reduce the e-waste being disposed of in landfills or partly recycled by the informal sector that has poor operational processes. E-Parisaraa has the objective of converting e-waste into beneficial resources using environmentally friendly, locally appropriate technologies. These processes are capable of dismantling toner cartridges, recovery of gold from printed circuit boards, recovery of silver from silver-coated components, and shredding printed circuit boards for further processing in Umicore precious metal refining company in Belgium.

**Formal e-waste recycling – Example 2**
Terrapro ([http://terrapro.in/](http://terrapro.in/))
Terrapro was set up as the first PRO to provide services for the manufacturers of EEE to take responsibility for their end-of-life products. According to the E-waste Management Rules 2016 in India, the manufacturers must fulfill several obligations under the EPR scheme. Terrapro provides a total solution to the manufactures by assisting them with plans to achieve specific goals required under the regulations and the preparation of EPR reporting paperwork.

**Formal e-waste recycling - Example 3**
Attero Recycling ([http://www.attero.in/](http://www.attero.in/))
Attero is a metal extraction and e-waste refurbishing facility in India with establishments in several cities. E-waste to the company mainly comes from the informal waste recycling sector and major manufacturers. The company takes away the printed circuit boards from the informal waste collectors by providing a higher price, thereby avoiding the potential environmental and health benefits. The company has developed a comprehensive e-commerce platform to facilitate the sale of refurbished electronics to customers.

**Design for Environment (DfE)**
Design for Environment (DfE), commonly referred to as Eco-design, investigates the entire life cycle of a project (from raw material extraction to final disposal) to determine the environmental impacts at each stage and propose changes to product design to minimise those impacts. Such a process involves designing products for practices such as design for energy efficiency, design for re-use, re-manufacture, disassembly and recycling, and design for resource conservation. The rationale behind adopting DfE is due to the fact that environmental impacts from products are continually rising, and 60-80% of its environmental impacts are determined during the design phase. Given the challenges of environmentally sound recycling of e-waste, it is crucial to adopt DfE practices to move away from end-of-pipe considerations. Towards this, the substitution of toxic raw materials with non-toxic materials, designing EEE for easy disassembly and repair, and designing EEE for energy efficiency to reduce the power consumption could contribute significantly to reduce the environmental footprint of the high technology industry. For example, the industry is now required by many countries to remove Pb metal from the manufacturing process. Pb was highly utilised in the soldering process of electronic circuits. The industry has now moved to lead-free soldering.

**DfE – Example**
Dell is a multinational company that manufactures computers and related products. Their DfE program is one of the most compressive among computer manufactures. Dell's system incorporates DfE at four different stages: Design and Build, Shipping, Use, and Re-use/recycling. During the design and build stage, Dell ensures that the substances they use for their products do not cause any harm to the environment and human health. For example, Dell has phased out medium chained chlorinated paraffins, certain phthalates, and polycyclic aromatic hydrocarbons in addition to the substances banned under the European Union's Restriction of Hazardous Substances Directive (RoHS). During the shipping stage, Dell ensures the use of sustainable packaging materials, smaller transportation footprints, and the use of recyclable materials.
Extended Producer Responsibility (EPR)
The Extended Producer Responsibility (EPR) involves making the producer or importer of a product physically and financially responsible for collection and processing of their products after use. The rationale behind EPR is shifting the administrative, logistical, and financial responsibility from government authorities to the manufacturers or importers of the products. Through this process, it is also expected that manufacturers will take into account the environmental considerations (design for the environment) in their manufacturing process to minimise the end-of-life processing costs. EPR has been implemented in many industrialised countries with great success in dealing with the e-waste problem. The reason for this success is the ability of these countries to keep clear records of original manufacturers or importers. Identifying the manufacturer or importer is a crucial element of a successful EPR system. However, the same cannot be said when it comes to emerging and developing nations. Some of these countries already have EPR systems to deal with the e-waste problem; however, successful implementation has become a major challenge for various reasons. The European Union implemented an EPR system in 2003 to deal with the e-waste problem through its Waste Electrical and Electrical Directive (WEEE Directive). Since then, many countries adopted various forms of EPR, including product take-back schemes, advanced recycling fees, container deposit schemes, etc. Most of these schemes are managed by Producer Responsibility Organisations (PROs), typically appointed by the government to administer the system on their behalf. The manufacturers or importers of EEE pay an annual fee to the PRO-based on their market input. The fee is utilised by the PRO towards the logistics and proper recycling of e-waste through licensed recyclers.

EPR – Example 1
Samsung Takeback and Recycling
(https://www.samsung.com/us/aboutsamsung/sustainability/environment/responsible-recycling/)
The Samsung takeback and recycling program (STAR) provides free drop-off of Samsung branded products in several locations in Indian cities. They provide fixed drop-off locations for smaller products, such as mobile phones and cameras. For larger items such as televisions, washing machines, and refrigerators, Samsung offers free pick-up service from the customers. The STAR initiative also includes a program to raise awareness among the consumers about the proper recycling of used EEEs.

EPR – Example 2
Xiaomi (India) (https://karosambhav.com/)
Xiaomi, one of the largest selling mobile phones and smart television brands in India, has developed a nationwide campaign to manage e-waste responsibly. The company has an extensive home pick-up service to collect their used products from Indian homes. To expand their services, Xiaomi has partnered with Karo Sambhav, a leading PRO appointed by the Indian government. The customers can also utilise the collection points provided by Karo Sambhav to deposit their used Xiaomi brand products.

Public-private partnerships (PPPs) to manage e-waste
The public-private partnerships, commonly known as PPPs, form a crucial link in the e-waste management system. While the national governments set the agenda or targets to achieve in solving the e-waste problem, the operational responsibility of the system heavily depends upon the financial and human resource potential of the provincial or the municipal sector. These alone are unable to achieve sound e-waste management systems, thus requiring input from the private sector to build the necessary infrastructure and bring in the technology. The PPPs also benefit the businesses and the community as they can effectively utilise the services provided by the private sector. The private sector can also benefit from expanding its marketing potential and enhancing their productivity.

PPP - Example 1
Clean e-India Initiative
(http://www.cleaneindia.org/)
The Clean e-India initiative was launched by Attero, which is one of the largest e-waste recycling companies in India. The initiative was implemented to ensure responsible and sustainable collection and recycling of e-waste across the nation. The program
utilises a services of e-captains who come and visit the households to collect their e-waste from the doorstep. The e-captain transfers the products to the Attero e-waste processing center for responsible recycling.

**PPP – Example 2**

**E-waste: From Toxic to Green**

As in many developing countries, informal e-waste recycling sector is very active in India. Although the collection and recycling rate is high, these groups are not aware of the environmental and human health impacts of their operation. To address this issue, the Toxic to Green initiative was launched to train the waste pickers for safe disposal and recycling of e-waste. Chintan, an Indian non-governmental organisation, has cooperated with the government sector to develop a partnership with a registered association of waste pickers, to train their members on how to collect and handle e-waste in a safe manner.

**Conclusion**

E-waste has become a hidden dilemma as it is growing at a faster rate than many other waste streams but with low visibility. The paper highlighted the lack of proper formal infrastructure to process end-of-life EEE, inability to deal with e-waste processing conducted by the informal e-waste sector, weak regulatory framework to deal with this emerging waste stream, underdeveloped/poor waste management systems, illegal import of e-waste for recycling, accessing funds towards developing proper e-waste recycling facilities, awareness-raising among the consumers, and effective implementation of EPR systems as key driving challenges for moving towards a sustainable e-waste management system. The paper also found that the private sector can bring in the technology and investment to assist the public sector in dealing with the e-waste problem. However, it would be difficult to attract the private sector towards e-waste management unless the policymakers have created the enabling conditions to ensure they receive economic and business benefits from the processing of e-waste.

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