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Review

Electronic waste management approaches: An overview

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ABSTRACT

Electronic waste (e-waste) is one of the fastest-growing pollution problems worldwide given the presence if a variety of toxic substances which can contaminate the environment and threaten human health, if disposal protocols are not meticulously managed. This paper presents an overview of toxic substances present in e-waste, their potential environmental and human health impacts together with management strategies currently being used in certain countries. Several tools including Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Multi Criteria Analysis (MCA) and Extended Producer Responsibility (EPR) have been developed to manage e-wastes especially in developed countries. The key to success in terms of e-waste management is to develop eco-design devices, properly collect e-waste, recover and recycle material by safe methods, dispose of e-waste by suitable techniques, forbid the transfer of used electronic devices to developing countries, and raise awareness of the impact of e-waste. No single tool is adequate but together they can complement each other to solve this issue. A national scheme such as EPR is a good policy in solving the growing e-waste problems.

1. Introduction

Managing electronic waste (or e-waste) is one of the most rapidly growing pollution problems worldwide. New technologies are rapidly superseding millions of analogue appliances leading to their disposal in prescribed landfills despite potentially their adverse impacts on the environment. The consistent advent of new designs, "smart" functions and technology during the last 20 years is causing the rapid obsolescence of many electronic items. The lifespan of many electronic goods has been substantially shortened due to advancements in electronics, attractive consumer designs and marketing and compatibility issues. For example, the average lifespan of a new computer has decreased from 4.5 years in 1992 to an estimated 2 years in 2005 and is further decreasing (Widmer et al., 2005) resulting in much greater volumes of computers for either disposal or export to developing countries. While difficult to quantify the volume of e-waste generated globally, Bushehri (2010) presented an overview of the volume of e-waste generated in a range of categories in China, Japan and US based on available information for the period 1997–2010 (Table 1). This report estimates that over 130 million computers, monitors and televisions become obsolete annually and that the annual number is growing in the United States (Bushehri, 2010). Around 500 million computers became obsolete between 1997 and 2007 in the United States alone and 610 million computers had been discarded in Japan by the end of December 2010. In China 5 million new computers and 10 million new televisions have been purchased every year since 2003 (Hicks et al., 2005), and around 1.11 million tonnes of e-waste is generated every year, mainly from electrical and electronic manufacturing and production processes, end-of-life of household appliances and information technology products, along with imports from other countries. It is reasonable to assume that a similar generation of e-waste occurs in other countries.

E-waste generation in some developing countries is not such a cause for concern at this stage because of the smaller number and longer half-life of electronic goods in those countries due to financial constraints, on both local community and national scales. The major e-waste problem in developing countries arises from the importation of e-waste and electronic goods from developed countries because it is the older, less ecologically friendly equipment that is discarded from these Western countries 80% of all e-waste in developed countries is being exported (Hicks et al., 2005). Limited safeguards, legislation, policies and enforcement of the safe disposal of imported e-waste and electronic goods have led to serious human and environmental problems in these countries. For instance, e-waste disposal impacts on human health has become a serious issue that has already been noted in case studies from China (Chan et al., 2007; Huo et al., 2007; Qu et al., 2007; Wang et al., 2009b; Xing et al., 2009; Zhao et al., 2008; Zheng et al., 2008).

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Table 1
The quantity of e-waste annually generated in the United States of America, Japan and China.

Countries	Products	Quantity (million)	Classification	Years	References
United States	Computers	500	E-waste	1997–2007	Bushehri (2010)
Japan	Computers	610	E-waste	2010	Bushehri (2010)
China	Computers	5	New products	Every year	Hicks et al. (2005)
	Televisions	10	New products	Since 2003	

Concern arises not just from the large volume of e-waste imported into developing countries but also with the large range of toxic chemicals associated with this e-waste. Numerous researchers have demonstrated that toxic metals and polyhalogenated organics including polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) can be released from e-waste, posing serious risks of harm to humans and the environment (Czuczwa and Hites, 1984; Robinson, 2009; Williams et al., 2008). A review of published reports on e-waste problems in developing countries, and countries in transition, showed that China, Cambodia, India, Indonesia, Pakistan, and Thailand, and African countries such as Nigeria, receive e-waste from developed countries although specific e-waste problems differ considerably between countries. For instance, African countries mainly reuse disposed electronic products whereas Asian countries dismantle those often using unsafe procedures (US Government Accountability Office, 2008; Wong et al., 2007a). Social and human health problems have been recognised in some developing countries and it is worth noting that China, India, and some other Asian countries have recently amended their laws to address the management and disposal of e-waste imports (Widmer et al., 2005). Moreover, some manufacturers of electronic goods have attempted to safely dispose of e-waste with advanced technologies in both developed and developing countries (US Government Accountability Office, 2008; Widmer et al., 2005). Problems associated with e-waste have been challenged by authorities in a number of countries and steps were taken to alleviate them with the introduction of management tools and laws at the national and universal levels. Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Multi Criteria Analysis (MCA) are tools to manage e-waste problems and Extended Producer Responsibility (EPR) is the regulation for e-waste management at the national scale.

This review provides an overview of the risk that e-wastes poses to human and environmental health from recycling and landfill disposals together with tools for the management of such wastes. Human toxicity of hazardous substances in e-waste is based on published case studies from e-waste recycling in China, India and Ghana.

2. Human toxicity of hazardous substances in e-waste

E-waste consists of a large variety of materials (Zhang and Forssberg, 1997), some of which contain a range of toxic substances that can contaminate the environment and threaten human health if not appropriately managed. E-waste disposal methods include landfill and incineration, both of which pose considerable contamination risks. Landfill leachates can potentially transport toxic substances into groundwater whilst combustion in an incinerator can emit toxic gases into the atmosphere. Recycling of e-waste can also distribute hazardous substances into the environment and may affect human health. While there are more than 1000 toxic substances (Puckett and Smith, 2002) associated with e-waste, the more commonly reported substances include: toxic metals (such as barium (Ba), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), lithium (Li), lanthanum (La), mercury (Hg), manganese (Mn), molybdenum (Mo), nickel (Ni), silver (Ag), hexavalent chromium (Cr(VI)) and persistent organic pollutants (POPs) such as dioxin, brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs), Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and polyvinyl chloride (PVC) (Table 2).

E-waste disposals impact human health in two ways which include: (a) food chain issues: contamination by toxic substances from disposal and primitive recycling processes that result in byproducts entering the food chain and thus transferring to humans; and (b) direct impact on workers who labour in primitive recycling areas from their occupational exposure to toxic substances. Along with this, numerous researchers have demonstrated a direct impact of backyard recycling on workers. The danger of e-waste toxicity to human health, both in terms of chronic and acute conditions, has become a serious societal problem and has been well demonstrated by case studies in China (Chan et al., 2007; Huo et al., 2007; Qu et al., 2007; Wang et al., 2009b; Xing et al., 2009; Zhao et al., 2008; Zheng et al., 2008), India (Eguchi et al., 2012; Ha et al., 2009) and Ghana (Asante et al., 2012). For instance, blood, serum, hair, scalp hair, human milk and urine from people who lived in the areas where e-wastes are being recycled showed the presence of significant concentrations of toxic substances. Qu et al. (2007) studied PBDEs exposure of workers in e-waste recycling areas in China and found high levels of PBDEs with the highest concentration of BDE-209 at 3436 ng/g lipid weight in the serum of the sample groups. This is the highest concentration of BDE-209 in humans so far recorded. High levels of Pb (Huo et al., 2007; Zheng et al., 2008) and Cd (Zheng et al., 2008) were found in the blood of children around e-waste recycling regions. Zhao et al. (2008) detected PBBs, PBDEs and PCBs in hair samples at 57.77, 29.64 and 181.99 ng/g dry weight, respectively which were higher than those from reference sites. Wang et al. (2009b) found Cu (39.8 μg/g) and Pb (49.5 μg/g) in scalp hair samples. PCDD/Fs (Chan et al., 2007) and PCBs (Xing et al., 2009) were detected in human milk samples at 21.02 pg/g and 9.50 ng/g, respectively. In India concentrations of Cu, Sb and Bi in the hair of e-waste recycling workers was higher than at the reference site (Ha et al., 2009) and levels of tri to tetra-chlorinated PCBs, tri to tetra-chlorinated OH-PCBs, PBDEs, octa-brominated OH-PBDEs, and tetra-BPhs in the serum of workers from e-waste recycling areas were higher than those in serum taken from people living near the coastal area (Eguchi et al., 2012). Moreover, in Ghana significant concentrations of Fe, Sb and Pb in the urine of workers from primitive recycling sites were found at 130, 0.89 and 6.06 μg/l, respectively. These were higher than at reference sites (Asante et al., 2012). These findings confirm that human exposure to heavy metals and POPs released from e-waste treatment processes pose significant health risk to workers and local inhabitants especially women and children. Also these studies demonstrate the effect of long-term exposure to human. Similar studies need to be extended to other developing countries or countries in transition where back yard e-waste recycling is being conducted. Although, the Stockholm Convention (UNEP, 2012) takes action to reduce and prevent global contamination from POPs, there has been significant delay with the implementation of guidance and legislation in some countries. For

Table 2
Common toxic substances associated with e-waste and their health impacts. *Sources*: Five Winds International (2001), Puckett and Smith (2002), Ecroignard (2006) and Herat (2008).

Substance	Applied in e-waste	Health impact
Antimony (Sb)	a melting agent in CRT glass, plastic computer housings and a solder alloy in cabling	Antimony has been classified as a carcinogen. It can cause stomach pain, vomiting, diarrhoea and stomach ulcers through inhalation of high antimony levels over a long time period
Arsenic (As)	Gallium arsenide is used in light emitting diodes	It has chronic effects that cause skin disease and lung cancer and impaired nerve signalling
Barium (Ba)	Sparkplugs, fluorescent lamps and CRT gutters in vacuum tubes	Causes brain swelling, muscle weakness, damage to the heart, liver and spleen though short-term exposure
Beryllium (Be)	Power supply boxes, motherboards, relays and finger clips	Exposure to beryllium can lead to beryllicosis, lung cancer and skin disease. Beryllium is a carcinogen
Brominated flame retardants (BFRs): (polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol (TBBPA))	BFRs are used to reduce flammability in printed circuit boards and plastic housings, keyboards and cable insulation	During combustion printed circuit boards and plastic housings emit toxic vapours known to cause hormonal disorders
Cadmium (Cd)	Rechargeable NiCd batteries, semiconductor chips, infrared detectors, printer inks and toners	Cadmium compounds pose a risk of irreversible impacts on human health, particularly the kidneys
Chlorofluorocarbons (CFCs)	Cooling units and insulation foam	These substances impact on the ozone layer which can lead to greater incidence of skin cancer.
Hexavalent chromium/chromium VI (Cr VI)	Plastic computer housing, cabling, hard discs and as a colourant in pigments	Is extremely toxic in the environment, causing DNA damage and permanent eye impairment
Lead (Pb)	Solder, lead-acid batteries, cathode ray tubes, cabling, printed circuit boards and fluorescent tubes	Can damage the brain, nervous system, kidney and reproductive system and cause blood disorders. Low concentrations of lead can damage the brain and nervous system in foetuses and young children. The accumulation of lead in the environment results in both acute and chronic effects on human health
Mercury (Hg)	Batteries, backlight bulbs or lamps, flat panel displays, switches and thermostats	Mercury can damage the brain, kidneys and foetuses
Nickel (Ni)	Batteries, computer housing, cathode ray tube and printed circuit boards	Can cause allergic reaction, bronchitis and reduced lung function and lung cancers
Polychlorinated biphenyls (PCBs)	Condensers, transformers and heat transfer fluids.	PCBs cause cancer in animals and can lead to liver damage in humans
Polyvinyl chloride (PVC)	Monitors, keyboards, cabling and plastic computer housing	PVC has the potential for hazardous substances and toxic air contaminants. The incomplete combustion of PVC release huge amounts of hydrogen chloride gas which form hydrochloric acid after combination with moisture. Hydrochloric acid can cause respiratory problems
Selenium (Se)	Older photocopy machines	High concentrations cause selenosis

instance, while the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and their Disposal was launched on March 22, 1989 and enforced on May 5, 1992, the USA is one of the world's largest e-waste producers, has not ratified this Convention or the Basel Ban Amendment. Communities are still debating the legal loophole, which permits the export of whole products to other countries provided it is not for recycling.

3. Environmental impacts of e-waste during treatment processes

The presence of toxic substances in e-waste was recognised only within the last 20 years. There is inadequate legislation worldwide for effective management of such waste. The rapid growth of e-waste and the ineffectiveness of legislation has led to inappropriate management strategies in both developed and developing countries, leading to profound impacts on the environment. Management of e-waste by recycling and by disposal to landfills has been shown to pose significant risks to the environment (Puckett and Smith, 2002; Robinson, 2009; Wong et al., 2007a). The impact of e-waste from recycling and disposal processes is summarised below.

3.1. Recycling

Vast quantities of e-waste are now being moved around the world for recycling in developing countries using manual processes in backyards of residential properties, resulting in significant contamination of soil, water and air in these countries. Such practices have also resulted in the poisoning of many local people engaged with the recycling process. For example, Guiyu and Taizhou in China, Gauteng in South Africa, New Delhi in India, Accra in Ghana and Karachi in Pakistan are the large e-waste recycling sites and this is where extensive pollution is emitted from the e-waste recycling processes (Asante et al., 2012; Brigden et al., 2005; Puckett and Smith, 2002; Tsydenova and Bengtsson, 2011; Widmer and Lombard, 2005; Widmer et al., 2005). The investigations from Guiyu, China showed POPs and heavy metals in air, dust, soil, sediment, and freshwater around the e-waste recycling site (Chen et al., 2009; Deng et al., 2007; Leung et al., 2010; Wang et al., 2009a). The major heavy metals released included Pb, Cd, Ni, Cr, Hg and As. Organic pollutants emitted included PAHs, PCBs, brominated flame retardants (BFRs) such as PBDEs, and polychlorinated dibenzo-p-dioxin/furans (PCDD/Fs), which can be formed during crude thermal processes of e-waste recycling. Polybrominated dibenzo-p-dioxin/furans (PBDD/Fs) may occur as impurities in PBDEs, byproducts of PBDE degradation during production, weathering, and recycling of flame-retardant plastics. It is apparent from these studies that the entire ecosystem including soil, sediment, water and air is being contaminated by these toxic substances (Table 3). A wide range in the concentrations of total PBDEs, PAHs, PCDD/Fs and PCBs have been reported in surface soils from e-waste recycling sites. For instance PBDE ranged from 0.26 to 4250 ng/g (dry weight) (Cai and Jiang, 2006; Leung et al., 2007; Wang et al., 2005, 2011), PAHs from 44.8 to 20,000 ng/g (dry weigh) (Leung et al., 2006; Shen et al., 2009; Tang et al., 2010; Yu et al., 2006), PCDD/Fs from 0.21 to 89.80 ng/g (Leung et al., 2007; Shen et al.,

Table 3
Selected toxic substances associated with recycling e-waste and their presence in the surrounding environment.

Environment	Toxic substances	Country/region	References
Soil	PBDEs	Guiyu, China	Wang et al. (2005), Leung et al. (2007) and Wang et al. (2011)
		Taizhou, China	Cai and Jiang (2006)
	PAHs	Guiyu, China	Leung et al. (2006) and Yu et al. (2006)
		Taizhou, China	Shen et al. (2009) and Tang et al. (2010)
	PCDD/Fs	Guiyu, China	Leung et al. (2007)
		Taizhou, China	Shen et al. (2009)
	PCBs	Taizhou, China	Shen et al. (2009) and Tang et al. (2010)
	As, Cu, Cr, Cd, Hg, Pb and Zn	Taizhou, China	Tang et al. (2010)
	Ag, Bi, Cd, Co, Cr, Cu, In, Hg, Mn, Mo, Pb, Sb, Sn, Tl, V and Zn	Bangalore, India	Ha et al. (2009)
Water	As, Cd, Cr, Cu, F, Fe, Hg, Mn, Ni, Pb, Zn	Guiyu, China	Wang and Guo (2006)
	Ag, Al, As, Be, Ca, Cd, Co, Cr, Cu, Fe, Li, Mg, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, V and Zn		Wong et al. (2007b)
Air	PBDEs	Guiyu, Guangzhou, Hong Kong, China	Deng et al. (2007)
		Guiyu and Chendian, China	Chen et al. (2009)
		Thailand	Muenhor et al. (2010)
	PAHs	Guiyu, China	Deng et al. (2006)
	PCDD/Fs	Guiyu and Chendian, China	Li et al. (2007)
	polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs)	Guiyu and Chendian, China	Li et al. (2007)
	As, Cd, Cr, Cu, Mn, Ni, Pb, Zn,,	Guiyu, China	Deng et al. (2006)
	Ag, Bi, Cd, Co, Cr, Cu, In, Hg, Mn, Mo, Pb, Sb, Sn, Tl, V and Zn	Bangalore, India	Ha et al. (2009)

2009) and PCBs from 11 to 5789.5 ng/g (Shen et al., 2009; Tang et al., 2010), in Guiyu and Taizhou, China. In Bangalore, India high concentrations of Ag, Bi, Cd, Cu, In, Hg, Pb, Sn and Zn were found in soil near recycling areas (Ha et al., 2009). On the impact of e-waste on water, Wang and Guo (2006) found appreciable concentrations of Pb in surface water downstream of the recycling industry in Guiyu. The concentration of Pb was as high as 0.4 mg/l which is eight times higher than the drinking water standard in China ($\leqslant$0.05 mg/l). Wong et al. (2007b) reported the presence of elevated levels of toxic metals in Liangjian and Nanya Rivers compared to that in the reservoir outside of Guiyu. They found that the rivers inside Guiyu had higher dissolved metal concentrations than those sampled outside. Therefore, recycling activities in Guiyu can be shown to adversely impact water quality surrounding this area (Wang and Guo, 2006). On air quality, given that most e-waste disposal and recycling has been in China and other developing countries, most of the studies are from these regions with reports demonstrating major impacts of backyard e-waste disposal and recycling. Results from these studies demonstrate severe contamination of the ambient air from chlorinated and brominated compounds and heavy metals around e-waste recycling sites in China. High concentrations of heavy metals including Cr, Zn and Cu were detected at 1161, 1038 and 483 ng/m^3, respectively which were 4–33 times higher than those in other Asian countries and PAHs contained in TSP and PM$_{2.5}$ were found at 40–347 and 22.7–263 ng/m^3, respectively (Deng et al., 2006). PBDEs associated with TSP and PM$_{2.5}$ were detected at 124 and 62.1 μg/m^3, respectively while the high pollution levels of PBDEs in Guiyu were 58–691 times higher than at other urban sites (Deng et al., 2007). The concentrations of PBDD/Fs were found to be at 8.12–61 pg/m^3. Moreover, PCDD/Fs in Guiyu were detected at 64.9–2365 pg/m^3 and these are the highest concentrations in ambient air worldwide (Li et al., 2007). Early reports implied that the air pollution in Guiyu has also been traced to e-waste recycling plants. In Bangalore, India high levels of Bi, Co, Cr, Cu, In, Mn, Pb, Sb, Sn and Tl were found in air around recycling areas which were higher than the levels around reference sites (Ha et al., 2009). In addition, in Thailand the level of $\sum$PBDEs (BDE-17, 28, 47, 49, 66, 85, 99, 100, 153 and 154) in the indoor air of an e-waste storage facility were found at 46–350 pg/m^3 whereas in outdoor locations, air pollutants were found at 8–150 pg/m^3 which were lower than the levels of PBDEs in China (Muenhor et al., 2010).

These findings confirm that significant levels of potentially toxic substances released during the recycling processes are building up in the environment. The potential hazards of persistent inorganic and organic contaminants (such as toxic PCBs, PBDEs, and metals) to the ecosystem and human health are expected to persist for many years to come. Moreover, weathering of organic contaminants is likely to result in the formation of metabolites that could potentially be more toxic than parent compounds. One such example being the debromination of DecaBDEs by photolytic (Söderström et al., 2004) and anaerobic degradation reactions (Gerecke et al., 2005) which gives rise to highly toxic congeners. It is apparent from published studies that much effort during the past decade has been directed towards surveys conducted to determine the nature of toxic substances associated with e-wastes and the presence of these in the environment with a limited number of studies focussing on human health. There is limited information, however, on the impact of e-wastes on environmental health especially their impact on terrestrial and aquatic ecosystem.

3.2. Landfill disposal

Irrespective of the current global move towards zero wastes, the number of landfills has been increasing in both developed and developing countries. While the owners of modern landfills argue that recently constructed landfills are capable of safely isolating from the environment the pollutants found in electronics (SWANA, 2004), the presence of thousands of old landfills with no barrier and containing a mixture of putrescibles and e-wastes is of much concern. There is sufficient evidence now to demonstrate that landfills accepting electronic devices or old landfills containing e-wastes will cause groundwater contamination (Schmidt, 2002; Yang, 1993). Pollutants have the potential to migrate through soils and groundwater within and around landfill sites (Kasassi et al., 2008). Organic and putrescible material in landfills decomposes and percolates through soil as landfill leachate. Leachates can contain high concentrations of dissolved and suspended organic substances, inorganic compounds and heavy metals. However, the concentrations of toxic substances from leachate depend on the waste characteristics and stages of waste decomposition in a particular landfill (Qasim and Chiang, 1994).

One measure designed to assess the potential toxicity of leachates from e-waste disposal is Toxicity Characteristic Leaching Pro-

Table 4
Leachate from electronic devices under laboratory-based TCLP conditions.

Devices	Unit	Ag	As	Ba	Cd	Cr	Hg	Pb	Se
Cellular phones[a]	mg/l	0–0.010	0.056–0.067	1.46–2.88	0.0006–0.006	0.04–0.13	0–0.010	38.2–147.0	0.073–0.12
CRTs – TVs[b]	mg/l	na	na	na	na	na	na	16.5	na
CRTs – computers[b]	mg/l	na	na	na	na	na	na	19.3	na
CPUs[c]	mg/l	na	na	na	na	na	na	0.7	na
Laptops[c]	mg/l	na	na	na	na	na	na	37.0	na
Cellular phones[c]	mg/l	na	na	na	na	na	na	20	na
Keyboards[c]	mg/l	na	na	na	na	na	na	2.4	na
Computer mice[c]	mg/l	na	na	na	na	na	na	19.8	na
Remote controls[c]	mg/l	na	na	na	na	na	na	17.0	na
Smoke detectors[c]	mg/l	na	na	na	na	na	na	23.0	na

na: Not available.
Sources:
[a] Lincoln et al. (2007).
[b] Musson et al. (2000).
[c] Townsend et al. (2004).

cedure (TCLP) which simulates landfill leaching in terms of a worst case eventuality. A number of electronic devices were subjected to tests by laboratory based TCLP (Table 4). TCLP test helps to determine if a solid waste processes physical and chemical properties that make it a toxicity characteristic (TC) hazardous waste. Electronic devices are considered to be TC hazardous waste under provision of the Resource Conservation and Recovery Act (RCRA) if the devices contain specific elements higher than TC regulated concentrations, which are 5 mg/l of As, 100 mg/l of Ba, 1 mg/l of Cd, 5 mg/l of Cr, 5 mg/l of Pb, 0.2 mg/l of Hg, 1 mg/l of Se and 5 mg/l of Ag (Townsend et al., 2005).

There have been a number of studies to investigate the leachability of components that comprise e-waste. Lead from cathode ray tubes (CRTs) in televisions and computer monitors is one of a number of toxic substances that can leach to the wider ecosystem (Musson et al., 2000). Jang and Townsend (2003) compared leachates from eleven Florida landfills to determine Pb leachability from computers' printed circuit boards and cathode ray tubes from computers and televisions using the TCLP test. They found that the concentration of Pb in TCLP extracts ranged from 0.53 to 5.0 mg/l in printed circuit boards and 1.7 to 6.0 mg/l in cathode ray tubes whereas Pb in landfill leachates were detected from <0.04 to 0.07 mg/l. This is not surprising given that TCLP acts by assessing the total bioavailable fraction (quantity factor) while landfill leachates only provide an estimate of immediately available Pb and also because the TCLP test uses "worst case scenario" to generate measurements. Townsend et al. (2004) studied leachability of Pb, Fe, Cu and Zn from twelve types of electronic appliances: CPUs, computer monitors, laptops, printers, colour TV, VCRs, cellular phones, keyboards, mice, remote controls, smoke detectors and flat panel television displays to examine the concentration of heavy metals. They found that Pb concentrations leached exceeded 5 mg/l in many types of electronic devices including laptops, cellular phones, mice, remote controls and smoke detectors. Li et al. (2006) examined the TCLP from printed wire boards including motherboards, various expansion cards, disk drives and power supply units to test the concentration of eight elements, which were As, Ba, Cd, Cr, Pb, Hg, Se and Ag. They found that Pb is predominant element which was 150–500 mg/l in printed wire boards. Spalvins et al. (2008) studied the impact of e-waste disposal on Pb leachability from electronic equipment including computers, keyboards, mouse devices, smoke detectors, monitors, cell phones, and cell phone batteries in simulated landfills. They found Pb concentrations of 7–66 μg/l in the simulated landfill column containing e-waste while the concentration of Pb in the simulated landfill column without e-waste ranged from <2 to 54 μg/l. The Pb concentrations in the simulated landfill columns containing e-waste were greater than those in the columns without e-waste. Li et al. (2009) investigated eighteen heavy metals in the leachate of personal computers and CRTs in the simulated landfills. They analysed the leachate from the simulators that showed that Pb and the other heavy metals were not detected while they analysed the solid samples in simulated landfill columns and found a significant amount of Pb in the range 1590–2930 mg/kg.

Moreover, the leachability of PBDEs from e-waste in landfills was investigated in many countries including Japan (Osako et al., 2004), Canada (Danon-Schaffer et al., 2006), South Africa (Odusanya et al., 2009) and Australia (Hearn et al., 2011). The concentration ranges of PBDEs from landfill leachates and e-waste leachates are shown in Table 5. PBDEs (all congeners) concentrations in e-waste leachates were generally higher than landfills leachates. Japanese landfills (Osako et al., 2004) had lower concentration of PBDEs than Canadian (Danon-Schaffer et al., 2006), South African (Odusanya et al., 2009) or Australian landfills (Hearn et al., 2011). This may be attributed to the requirement in Japan for the incineration of wastes prior to the disposal of ash into landfills. Incineration is likely to destroy organic flammable components of the waste (Osako et al., 2004) thus reducing the concentration of PBDEs.

4. Strategies to manage e-wastes

There is currently extensive research into e-waste management in order to mitigate problems at both the national and international levels. Several tools have been developed and applied to e-waste management including: LCA, MFA, MCA and EPR (see Table 6). The management of e-waste in developed countries has taken a further step forward with the release of a waste electric and electronic equipment (WEEE) directive (Directive 2002/96/EC) that is expected to reduce the disposal of such waste and improve the environmental quality (EU, 2002). Research includes the separation of components that could be recycled and the recovery of rare and precious metals. This section summarises the range of approaches that has been adopted, and points to future developments.

4.1. Life Cycle Assessment (LCA)

Life Cycle Assessment is a tool used to design environmentally friendly electronic devices and to minimise e-waste problems. Since the 1990s considerable research has been conducted on the LCA of electronic devices in terms of eco-design, product development and environmental impacts (Table 7). The published reviews show the necessity of having more consideration in the design of electronic devices to take account of environmental and economic

Table 5
Concentration ranges of PBDEs in landfill leachate and e-waste leachate reported by different researchers (ng/l).

PBDEs Congener	Danon-Schaffer et al. (2006)	Osako et al. (2004)	Danon-Schaffer et al. (2006)	Odusanya et al. (2009)	Hearn et al. (2011)
	E-waste	Landfills			
		Japan	Canada	South Africa	Queensland, Australia
MonoBDEs	nd–52.2	<0.008–0.5	0.119–0.317		
BDE-3					
DiBDEs	0.04–119	<0.008–0.5	0.0272–0.639		
BDE-7					
BDE-15					
TriBDEs	0.80–253	0.014–0.97	0.037–6.490		
BDE-17					
BDE-28		<0.008–0.97		0.1–3.333	
TetraBDEs	1.29–1110	<0.008–3.20	0.332–355		
BDE-47		<0.008–2.2		1.469–9.793	7–40.5
BDE-49					
BDE-66		<0.008–0.5		nd–4.020	
BDE-71				1.667–9.459	
BDE-75				0.743–7.426	
BDE-77				nd–4.257	
PentaBDEs	2.69–36,100	<0.008–1.8	0.343–743		
BDE-85				nd–1.240	
BDE-99		<0.008–1.8		nd–5.191	5.5–90.5
BDE-100		<0.008–0.5		nd–2.162	
BDE-119				nd–5.392	
BDE-126					
HexaBDEs	1.71–1,530,000	<0.008–1.2	nd–257		
BDE-138					
BDE-153		<0.008–0.5		nd–0.875	nd–11.5
BDE-154		<0.008–1.2		nd–2.176	nd–13
BDE-156					
HeptaBDEs	5.04–2,050,000	<0.01–11	0.907–20.4		
BDE-183				nd–0.263	nd–5.5
BDE-184					nd–3.5
BDE-191					
OctaBDEs	3.21–5,190,000	<0.04–2	0.548–17.8		
BDE-196					
NonaBDEs	nd–1,910,000	<0.08–5	nd–11.5		
BDE-206					nd–9.5
BDE-207					nd–47.0
DecaBDEs	nd–1,670,000		nd–56.7		
BDE-209		<0.8–50			nd–113

nd: Not detected.

impacts. An environmentally friendly design is a better alternative product and it may in turn appeal to consumers. LCA is a powerful tool for identifying potential environmental impacts to develop eco-design products such as printers (Pollock and Coulon, 1996), desktop personal computers (Kim et al., 2001), heating and air conditioner devices (Prek, 2004), washing machines (Park et al., 2006), and toys (Muñoz et al., 2009). It is also a systematic tool to define many environment impact categories such as carcinogens, climate change, ozone layer, ecotoxicity, acidification, eutrophication and land use, to improve the environmental performance of products (Belboom et al., 2011; Duan et al., 2009; Environment Canada, 2000; Faist Emmenegger et al., 2006; Hischier and Baudin, 2010; Schischke and Spielmann, 2001; Socolof et al., 2005; Syafa Bakri et al., 2008; Yanagitani and Kawahara, 2000).

LCA is widely used for e-waste management (Table 6). In Europe, much research has been conducted using LCA to evaluate the environmental impacts of end of life (EoL) treatment of e-waste. For example, in Switzerland, Hischier et al. (2005) studied the environmental impacts of the Swiss take-back and recycling systems for e-waste. The results showed that the e-waste recycling system and take-back were clearly advantageous from an environmental perspective, compared to incineration. Wäger et al. (2011) followed up Hitcher's research (Hischier et al., 2005) and compared the results. Their work showed that the environment impacts of e-waste in 2009 were much lower than previously determined due to the recycling of plastic waste instead of incineration. In addition, Scharnhorst et al. (2005) studied environmentally preferable EoL treatment alternatives for mobile phone devices. The study carried out six EoL treatment scenarios. They found that recycling material leads to a twofold reduction of environmental impacts of mobile phones. In United Kingdom, Mayers et al. (2005) studied four alternative disposal methods for printers. They found that landfill without material recovery is not the worst case to compare with recycling and recovery alternatives. In Germany, Barba-Gutiérrez et al. (2008) found recycling to be the best option for EoL treatment of e-waste. Their results showed that disposal is not good for the environment. Environmental impacts from collection processes had impacts due to the use of fossil fuels or respiratory inorganics (winter smog).

In Asia LCA has been applied to estimate the impact of e-waste and e-waste management. In Korea, Kim et al. (2004) used LCA to evaluate recycling potentials in terms of environmental and economic factors. The recycling potential in terms of the environmental score showing the highest value was for glass and circuit boards, followed by iron, copper, aluminium and plastic, respectively. In terms of economic score the results showed the highest

Table 6
Tools for e-waste management approaches being used or proposed.

Tools	Application	Aspects	Country/ region	References
LCA	Recycling potential	Environment and economic	Korea	Kim et al. (2004)
LCA	Six EoL treatment scenarios: case study of mobile phones	Environment	Switzerland	Scharnhorst et al. (2005)
LCA	Recycling of end-of-life of personal computers	Environment	Korea	Choi et al. (2006)
LCA	Recycling systems: case study of notebook computers	Environment and economic	Taiwan	Lu et al. (2006)
LCA	Recycling of end-of-life	Economic	Japan	Nakamura and Kondo (2006)
LCA	Decision makers for managing computer waste	Environment and economic	India	Ahluwalia and Nema (2007)
LCA	Compare different disposal methods (recycle and non-recycle): case study of fluorescent lamps	Environment	Thailand	Apisitpuvakul et al. (2008)
LCA	Compare different waste scenarios	Environment	Germany	Barba-Gutiérrez et al. (2008)
LCA and EPR	Four EoL treatment scenarios: case study of printers	Environment and economic	United Kingdom	Mayers et al. (2005)
LCA and MFA	The supply of computers to schools	Environment, economic and social	Colombia	Streicher-Porte et al. (2009)
LCA and MFA	Recycling systems	Environment	Switzerland	Hischier et al. (2005)
LCA and MFA	Collection and recovery systems	Environmental impacts	Switzerland	Wäger et al. (2011)
MFA	The flow of e-waste	Generation	China	Liu et al. (2006a)
MFA	E-waste trade value chain	Life span and market supply	India	Jain and Sareen (2006)
MFA	The flow of personal computers and the pathways of recycling	Economic value	India	Streicher-Porte et al. (2007)
MFA	The flow of mobile phones	Environmentally sound and eco-efficient management	Nigeria	Osibanjo and Nnorom (2008)
MFA	The flow of e-waste and e-waste trade	Law and environmental pollution	Asia	Shinkuma and Nguyen Thi Minh (2009)
MFA	The flow of used personal computers	Compare the results from before and after the introduction of personal computers recycling system	Japan	Yoshida et al. (2009)
MFA	E-waste quantities	Generation	Chile	Steubing et al. (2010)
MCA	Decision making for optimisation of product disassembly	Environment and economic	United State	Hula et al. (2003)
MCA	Decision making for e-waste management	Environment, economic and social	Cyprus	Rousis et al. (2008)
MCA	Decision making for the location of e-waste recycling plants	Economic, infrastructural and legal	Spain	Queiruga et al. (2008)

value was copper, followed by aluminium, iron, plastic, glass and circuit boards. Choi et al. (2006) studied the practical recycling rate of an EoL personal computer and assessed the environmental impact. Disposal included two scenarios: landfill or recycling. Their results showed that recycling is the most efficient option for disposal. In Taiwan, Lu et al. (2006) studied the alternatives for notebook computer disposal considering selling to the secondhand market, recycling, incineration and landfill, in terms of environmental and economic aspects. They found that recycling is not a good option due to impacts on the environment from hazardous materials. They emphasised reuse through second hand sales. In Japan, Nakamura and Kondo (2006) used the LCA tool in terms of life cycle cost analysis that compared two scenarios: recycling and landfill for e-waste disposal. They found that landfill disposal saved cost compared to recycling but landfill disposal resulted in higher environmental load and carbon emissions. In India, Ahluwalia and Nema (2007) used LCA as a decision making tool for computer waste management. LCA was used to evaluate economic aspects, perceived risk and environmental impacts. The results showed the optimal life cycle of a computer desktop was observed to be shorter by 25% than the optimised cost and the optimised value of computer waste impacts to either the environment or any perceived risk to the public. In Thailand, Apisitpuvakul et al. (2008) studied the environmental impact of fluorescent lamp disposal in several proportions of recycling. They found that increasing recycling rates reduced environmental impacts.

In South America, LCA was also used to evaluate the environmental impact for e-waste management. Streicher-Porte et al. (2009) studied the sustainability of computer supply scenarios from local or overseas refurbishment and new low-cost computers donated to Colombian schools. The results showed that the local second hand computers are good options in terms of technical standards but had disadvantages related to maintenance of appliances, and environmental aspects.

Studies conducted using LCA in a number of countries suggest that recycling is the most appropriate strategy for managing e-waste as compared to landfilling or incineration (Apisitpuvakul et al., 2008; Choi et al., 2006; Hischier et al., 2005; Kim et al., 2004; Scharnhorst et al., 2005; Wäger et al., 2011). However, this is not always the case as some researchers concluded recycling is not a good option where the recycling processes impacts on the environment (Barba-Gutiérrez et al., 2008; Lu et al., 2006).

4.2. Material Flow Analysis (MFA)

Before the Basel Convention came into force large volumes of e-waste from developed countries were exported for reuse or recycling in developing countries especially China, India and South Africa. MFA is a tool used to study the route of material (e-waste) flowing into recycling sites, or disposal areas and stocks of materials, in space and time. It links sources, pathways, and the intermediate and final destinations of the material. Material Flow Analysis is a decision support tool for environmental and waste management (Brunner and Rechberger, 2004). This tool can be applied to develop appropriate e-waste management (Table 6). This includes a consideration of the flow of e-waste and its assessment it in terms of environmental, economic and social values. Shinkuma and Nguyen Thi Minh (2009) used MFA to investigate the flow of e-waste in Asia. They found that secondhand electronic devices from Japan are reused in Southeast Asia (e.g., Vietnam and Cambo-

Table 7
Applications of LCA for electronic devices.

Category	Products	Application	References
Large household appliances	Air conditioners	Environmental impacts	Yanagitani and Kawahara (2000)
	Heating and air conditioning equipment	Eco-design	Prek (2004)
	Refrigerators	Environmental and economic impacts (focus on energy consumption)	Horie (2004)
		Environmental impacts	Belboom et al. (2011)
	Washing machines	Eco-design	Park et al. (2006)
IT and telecommunications equipment	Printers	Product development	Pollock and Coulon (1996)
	CD-ROM drives	Environmental impacts (focus on carbon emissions)	Satake and Oishi (1998)
	Electronic components (semiconductor devices, passive components, transducers, CRTs, connecting components, printed circuit boards, liquid crystal display devices)	Environmental impacts (focus on energy consumption and emission)	Ueno et al. (1999)
	Electronic components (semiconductor devices)	Environmental impacts	Schischke and Spielmann (2001)
	Desktop personal computer	Eco-design and Economic impacts	van Mier et al. (1996)
		Product design stage	Kim et al. (2001)
		Environmental impacts	Duan et al. (2009) and Socolof et al. (2005)
	Telephones	Environmental impacts	Environment Canada (2000)
		Environmental impacts (focus on greenhouse gas emissions)	Andræ et al. (2005)
	Mobile phones	Environmental impacts	Faist Emmenegger et al. (2006) and Scharnhorst (2006)
Consumer equipment	Televisions	Environmental impacts	Hischier and Baudin (2010)
Lighting equipment	Fluorescent lamps	Environmental impacts	Syafa Bakri et al. (2008)
Toys, leisure and sports equipment	Toys	Eco-design	Muñoz et al. (2009)

dia) while most of the e-waste is recycled in Gangdong Province, China, where improper recycling methods were being used. In addition, Yoshida et al. (2009) found that the proportion of personal computers sent for domestic disposal and recycling decreased to 37% in fiscal year 2004, while the proportion of domestic reuse and exports increased to 37% and 26%, respectively in Japan. Liu et al. (2006a), Jain and Sareen (2006), Osibanjo and Nnorom (2008) and Steubing et al. (2010) investigated e-waste generation using MFA. Many different methods are being used to estimate possible quantities of e-waste. Liu et al. (2006a) and Jain and Sareen (2006) used market supply method which provided data for production and sales in regions, and time for estimation. Steubing et al. (2010) also used the market supply and survey method to estimate e-waste generation. Osibanjo and Nnorom (2008) used surveys to estimate quantities of e-waste. They found that e-waste generation will increase in China, India, Nigeria and Chile. For instance, based on MFA, it was reported that the quantiy of e-waste would double from 2005 to 2010 and increase by 70% for obsolete devices by 2020 in China (Liu et al., 2006b), while it will increase four to five times during 2010–2019 in Chile (Steubing et al., 2010). Streicher-Porte (2007) used MFA and evaluation of economic values as a tool for system analysis of the Au and Cu that flows from personal computer recycling in India. They found that the concentration of Au and Cu and the high value of these metals resulted in profits for recyclers. It is apparent from the study conducted by Streicher-Porte (2007) that coupling of MFA and economic evaluation can be a useful tool when limited data is available and where there is rapid economic growth.

4.3. Multi Criteria Analysis (MCA)

MCA is a decision-making tool developed for considering strategic decisions and solving complex multi-criteria problems that include qualitative/quantitative aspects of the problem (Garfì et al., 2009). MCA models have been applied to environmental problems, including those of e-waste management, to provide optional e-waste management strategies (Table 6). For example, Hula et al. (2003) used MCA decision-making methodologies to determine the trade-offs between the environmental benefits and economic profit of the EoL processing of coffee makers. They analysed a six-step methodology: definition of EoL scenarios, defined product models, development of an EoL evaluation model, formulation of a multi objective problem, solutions for the Pareto set, and construction of EoL strategy graphs for the Pareto set of optimal EoL strategies that minimises environmental impacts and economic cost. Queiruga et al. (2008) used MCA to select the best location for e-waste recycling plants in Spain. Their study was based on quantitative criteria, specifically the economics of warehouse locations. Rousis et al. (2008) used MCA methodology to examine alternative systems for managing e-wastes in Cyprus. There were 12 alternative management systems which were compared and ranked according to their performance and efficiency. The best option was partial disassembly and forwarding of recyclable materials to the local prevailing market with the remainder deposed at landfill sites.

Although, MCA is not widely used for e-waste management, it is commonly used for solid waste (Cheng et al., 2003; Herva and Roca, 2013; Vego et al., 2008) and hazardous waste management (Hatami-Marbini et al., 2013; Koo et al., 1991; Sharifi et al., 2009). MCA has been recommended for social response to e-waste management (Williams, 2005) and to this end it is a useful tool in combination with other tools being used for E-waste management.

4.4. Extended Producer Responsibility (EPR)

EPR is an environment policy approach that attributes responsibility to manufacturers in taking back products after use, and is based on polluter-pays principles (OECD, 2001; Widmer et al., 2005). EPR approaches to e-waste management at a national scale are summarised in Table 8. Leaders of EPR programs for e-waste management are the advanced nations, including the European Union (EU), Switzerland, Japan and some states or provinces of the United States and Canada. The Organisation for Economic Co-operation and Development (OECD) has supported an environmentally friendly program and published a guidance manual for governments (OECD, 2001).

In 1991 the EU designated e-waste as a priority waste stream and in 2004 the regulation on WEEE was introduced to take back products for treatment and recycling processes. Directive 2002/96/EC of the European Union on the WEEE Directive developed regulations based on EPR. Legislation establishes the responsibility of producers for downstream e-waste management and leads to end-of-life environmentally sound reuse, recycling and recovery of e-waste (EU, 2002). The target recycling rate is between 50% and 75% by weight (Mayers et al., 2005; Nnorom and Osibanjo, 2008; Roller and Furhr, 2008; Widmer et al., 2005). In 2011, the EU adopted Directive 2011/65/EU of the European Parliament and of the Council of 8 June, 2011, on restrictions of the use of certain hazardous substances in electrical and electronic equipment and this was enforced from 22 July, 2011. All 27 member states must bring it into effect by 2 January 2013 (EU, 2011).

Switzerland has been a forerunner in regulation of e-waste management. In 1998 the Swiss Federal Office for the Environment (FOEN) announced the Ordinance ‘‘The Return, the Taking Back and the Disposal of Electrical and Electronic Equipment (ORDEE). Switzerland has four producer responsibility organisations (PROs), namely SWICO (The Swiss Association for Information, Communication and Organizational Technology) Recycling Guarantee, SENS (Swiss Foundation for Waste Management), SLRS (Swiss Light Recycling Foundation) and INOBAT (Stakeholder Organisation for Battery Disposal), most of them are as non-profit organisations and handle the e-waste stream (Khetriwal et al., 2009; Nnorom and Osibanjo, 2008; Widmer et al., 2005). Khetriwal et al. (2009) studied the Swiss experience in e-waste management. They found that the Swiss system was successful in high level of compliance, including stakeholders, distributors, users and recyclers.

Japan provided environmental policy on the responsibility for e-waste management in the late 1990s. Japan regulates e-waste by two main laws: the Specified Home Appliances Recycling (SHAR) Law and the Electric Household Appliance Recycling Law, which was promulgated in 1998 and came into force in 2001. SHAR was established to take back e-waste including large household appliances: TV sets, refrigerators, air conditioners and washing machines (Chung and Murakami-Suzuki, 2008; Lease, 2002; Nnorom and Osibanjo, 2008; Tojo, 2001). Another law is the Promotion of Effective Utilization of Resources (LPUR) which deals with personal computers and used batteries (Chung and Murakami-Suzuki, 2008; Ogushi and Kandlikar, 2007). The difference between SHAR and LPUR is that the former relies on manufacturers' voluntary efforts whereas the latter enforces compulsory commitments on manufacturers (Chung and Murakami-Suzuki, 2008). In 2003 LPUR was revised so that new computer purchasers pay the recycling costs in the product cost as an advanced recycling fee (Chung and Murakami-Suzuki, 2008; Nnorom and Osibanjo, 2008). SHAR accepts the principle of EPR, which extends the manufactures' obligation in the entire life cycle of the products (Chung and Murakami-Suzuki, 2008). Home appliances were taken back by retailers or second hand shops according to the flow in Fig. 1.

A Japanese take back system needed to be paid for by end users who then took their e-waste to retail or second hand shops. After that, the e-waste was transferred to recycling facilities to dismantle and recover materials. The mandated requirement for the recycling rate is 50–60% by weight. The funds for recycling are supported both local government and manufacturers who are aware of and responsible for the environmentally sound management (Nnorom and Osibanjo, 2008; Tojo, 2001). Moreover, EPR is supported by manufactures in the form of product Design for Environment (DfE). The electronic manufacturers have developed lead-free solders and bromine-free printed circuit boards, and have designed new devices for ease of disassembly and reuse (Lease, 2002; Nnorom and Osibanjo, 2008; Tojo, 2001).

Unlike the EU countries, the US Federal Government cannot require each state to accept EPR programs and cannot implement a product take back policy at a national scale. In the mid-1990s, there was much debate on EPR policy with the question being ‘‘who is the polluter?'' under the auspices of the Clinton Administration's President's Council on Sustainable Development (PCSD). The manufacturers strongly resisted responsibility as ‘‘polluters'' with respect to disposal of products. The PCSD accepted ‘‘Extended Product Responsibility'' to share the responsibility (Sachs, 2006). The first state, Maine, adopted e-waste legislation based on the EPR model in 2004. The scope of Maine's EPR program is limited to televisions and computer monitors. This program shares the responsibility for e-waste management with three groups i.e. the stakeholders, the generators and the municipality (Wagner, 2009).

Table 8
E-waste management approaches to EPR.

Country	Policy	Target	References
The Netherlands	– Take back (large household appliances and IT equipment)	Recycling rate 45–75% by weight	Tojo (2001)
United Kingdom	– Take back (electronic appliances)	Recycle and recovery 50–80%	Gottberg et al. (2006) and Mayers et al. (2005)
Germany	– Take back (electronic appliances)	–	Roller and Furhr (2008)
Switzerland	– Take back (electronic appliances) – Disposal ban in landfill – Advance recycling fees	–	Khetriwal et al. (2009), Nnorom and Osibanjo (2008), and Widmer et al. (2005)
Japan	– Take back (four large household appliances: TV sets, refrigerators, air conditioners and washing machines) – Product re-design (lead free solders and bromine free printed circuit boards)	Recycling rate 50–60% by weight	Nnorom and Osibanjo (2008) and Tojo (2001)
United States	– Take back household appliances in some states, such as Maine (take back only televisions and computer monitors)	–	Sachs (2006) and Wagner (2009)
Canada	– Take back household appliance in some provinces, including Alberta and Ontario – Develop advanced EPR program	–	McKerlie et al. (2006)
India	– Feasibility study	–	Manomaivibool (2009)
Thailand	– Developing legal framework	Collection and recycling	Manomaivibool and Vassanadumrongdee (2011)

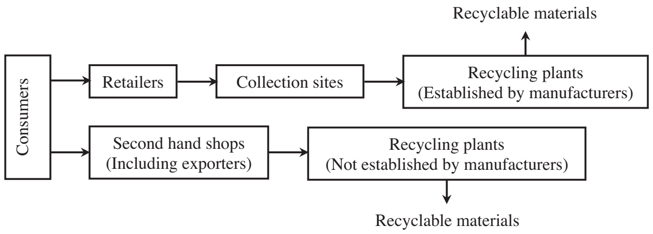

Fig. 1. Flow of the take back system in Japan. *Source*: from (Chung and Murakami-Suzuki, 2008)

Canada has approached EPR quite differently from Europe and has developed a progressive EPR that focused on product stewardship and pollution prevention. Currently Canada does not have a national EPR system for e-waste management. In 2003, the Federation of Canadian Municipalities provided a national municipal survey for the disposal of e-waste, whereas some municipalities considered that the manufacturers should be responsible for the cost of collection, recovery, recycling and disposal of e-waste. Some provinces enacted a procedure to manage e-waste problems. Alberta was the first province to develop an e-waste management program (2004) which was only to take back computers and televisions. Ontario offered an e-waste regulation that is more flexible and takes back e-waste from more than 200 items. The other provinces understand the lesson of EPR from Europe and Asia's lead to confirm the effective of e-waste regulation in Canada (McKerlie et al., 2006). Moreover, six Canadian provinces, Alberta, British Columbia, Nova Scotia, Ontario, Prince Edward Island and Saskatchewan are promulgated to take back seven e-waste items. These are computers (laptop and/or desktop), monitors, printers, peripherals (e.g., keyboard, mouse), televisions, DVD players and CD players by the end of 2010 (Lepawsky, 2012).

OECD countries have supported the principle of e-waste programs whereas many non-OECD countries are proposing EPR programs for e-waste. India is a non-OECD country and has an enormous "backyard" e-waste recycling sector (Ha et al., 2009; Manomaivibool, 2009). The draft guidelines for Environmentally Sound Management of e-waste were provided by the Indian government, through the Central Pollution Control Board in 2007. Manomaivibool (2009) studied the relation of such problems in a non-OECD country context with EPR. He found that e-waste management in India was possibly driven by the EPR principal policy. However, this program has two major barriers due to illegal imports of e-waste and the huge grey (or black) markets of electronic devices. In 2010, the Government of India Ministry of Environment and Forests (MoEF) was moving forward to propose a draft of e-waste producer responsibility for which Greenpeace India had been campaigning for the preceding 4 years. The draft was the first responsible for the whole life cycle of the product from design to waste, and included a provision for the reduction of certain hazardous substances in electronic devices and forced a prohibition on the import of all second hand electronic devices for charity purposes (Waste management world, 2010).

Thailand is one other non-OECD countries to follow EPR lessons learnt from OECD countries and is striving to develop a policy. Manomaivibool and Vassanadumrongdee (2011) provide the context of the EPR program for the Thai e-waste policy proposal. They found that EPR is one of the aims in the national integrated strategy for e-waste management. The Thai e-waste strategy of the Pollution Control Department, Ministry of Natural Resources and Environment in 2007 had five objectives: "(1) to manage domestic post-consumer e-waste in a scientific and systematic manner, (2) to establish an efficient and sustainable e-waste management system with cooperation from every sector of society, (3) to reduce hazardous wastes from electronic equipment at the origin and to encourage environmentally friendly design and production, (4) to enhance the competitiveness and negotiation power of the country in international trade and (5) to have nationwide efficient and effective integrated e-waste management by 2017". Thailand uses a product fee system to buy back e-waste. Financial inducement is provided to encourage the end-consumers for e-waste collection to pass material onto the recycling sector. On the other hand, EPR has become a costly arrangement of policy tools while the institutional design of the government fund is rigid.

4.5. The distinctive features of each tool for e-waste management

The key to success in terms of e-waste management is to develop eco-designed devices, to properly collect e-waste, recover and recycle material by safe methods, dispose of e-waste by suitable techniques, forbid the transfer of used electronic devices to developing countries, and to raise awareness of the impact of e-waste pollution of both users and manufacturers. This approach is currently used routinely in most developed countries, although developing countries and countries in transition are yet to convince local community to implement such management strategies. In these countries, education of young generation may be one way forward with the management of e-wastes.

While there are many tools available for the management of e-waste problems, we focussed on LCA, MFA, MCA and EPR given its popularity in some countries. Each tool has distinctive features when applied to e-waste management and these are summarised in Table 9. LCA presents various advantages to support e-waste management. LCA estimates the effects of materials consumption that impacts on eco-design products (Muñoz et al., 2009; Park et al., 2006; Prek, 2004; van Mier et al., 1996) and product development (Kim et al., 2001; Pollock and Coulon, 1996) and allocates the impacts of the examined product or process of environmental interest (Andræ et al., 2005; Belboom et al., 2011; Faist Emmenegger et al., 2006; Hischier and Baudin, 2010; Horie, 2004; Satake and Oishi, 1998; Scharnhorst, 2006; Schischke and Spielmann, 2001; Socolof et al., 2005; Syafa Bakri et al., 2008; Ueno et al., 1999; Yanagitani and Kawahara, 2000). It also evaluates the environmental and economic aspects related to the end of life disposal of electronic devices and enables better decision making for e-waste disposals (Ahluwalia and Nema, 2007; Apisitpuvakul et al., 2008; Barba-Gutiérrez et al., 2008; Choi et al., 2006; Hischier et al., 2005; Kim et al., 2004; Lu et al., 2006; Mayers et al., 2005; Nakamura and Kondo, 2006; Scharnhorst et al., 2005; Streicher-Porte et al., 2009; Wäger et al., 2011). Based on published literature, LCA is a popular tool currently being used for e-waste management including design and product development and environmental decision making in many countries including Columbia, Germany, Japan, Korea, India, Switzerland, Taiwan, Thailand, and United Kingdom. MFA has several distinctive points for e-waste management. As discussed above this tool is used to investigate the flow of e-waste (Osibanjo and Nnorom, 2008; Shinkuma and Nguyen Thi Minh, 2009; Streicher-Porte et al., 2007; Yoshida et al., 2009), estimates e-waste generation (Liu et al., 2006a; Steubing et al., 2010) and its use for environmental decision making (Brunner and Rechberger, 2004). MFA is largely used in the countries that have large recycling plants such as in China, India and Nigeria to investigate destinations to where e-waste is being exported. MCA is used for decision making in terms of the environmental benefits and economic profit (Hula et al., 2003), the best location of e-waste recycling plants (Queiruga et al., 2008) and the greatest option for e-waste disposal (Rousis et al., 2008). Although MCA is a useful tool for environmental decision making, it is not widely used for e-waste management. EPR is a tool entirely focussed on policy that ascribes the responsibility to producers to take back products

Table 9
The distinctive features of LCA, MFA, MCA and EPR for e-waste management.

Tools	Benefits	Country/region	References
LCA	– Estimates the effects of materials consumption. Conducts assessment of eco-design and product development – Allocates the impacts of the examined product or process of environmental interest – Evaluate the environmental and economic aspects related to the end of life disposal of electronic devices – Takes better decisions regarding e-waste disposal	Columbia	Streicher-Porte et al. (2009)
		Germany	Barba-Gutiérrez et al. (2008)
		Japan	Nakamura and Kondo (2006)
		Korea	Choi et al. (2006) and Kim et al. (2004)
		India	Ahluwalia and Nema (2007)
		Switzerland	Hischier et al. (2005), Scharnhorst et al. (2005), and Wäger et al. (2011)
		Taiwan	Lu et al. (2006)
		Thailand	Apisitpuvakul et al. (2008)
		United Kingdom	Mayers et al. (2005)
MFA	– Investigates the flow of e-waste – Estimates e-waste generation – Used for environmental decision making	Asia	Shinkuma and Nguyen Thi Minh (2009)
		Chile	Steubing et al. (2010)
		China	Liu et al. (2006a)
		Columbia	Streicher-Porte et al. (2009)
		India	Jain and Sareen (2006) and Streicher-Porte et al. (2007)
		Japan	Yoshida et al. (2009)
		Nigeria	Osibanjo and Nnorom (2008)
		Switzerland	Hischier et al. (2005) and Wäger et al. (2011)
MCA	– Used for environmental decision making	Cyprus	Rousis et al. (2008)
		Spain	Queiruga et al. (2008)
		United State	Hula et al. (2003)
EPR	– Solves e-waste problems in national scale – Enforce producers based on polluter-pays principal	Canada	McKerlie et al. (2006)
		Germany	Roller and Furhr (2008)
		Japan	Nnorom and Osibanjo (2008) and Tojo (2001)
		India	Manomaivibool (2009)
		Switzerland	Khetriwal et al. (2009), Nnorom and Osibanjo (2008) and Widmer et al. (2005)
		Thailand	Manomaivibool and Vassanadumrongdee (2011)
		The Netherlands	Tojo (2001)
		United Kingdom	Gottberg et al. (2006) and Mayers et al. (2005)
		United States	Sachs (2006) and Wagner (2009)

and manage the treatment process and this is based on a polluter-pays principal (OECD, 2001; Widmer et al., 2005). EPR is currently available in a number of developed and developing countries including Germany, Japan, India, Switzerland, Thailand, The Netherlands, United Kingdom and some states of Canada and United States. However, adherence to EPR policy varies amongst countries with many developing countries finding it difficult to get the end users to implement this approach to managing e-wastes. Developed countries such as Japan and Switzerland have progressed with the application of EPR and this is well accepted by industries associated with electronic goods.

In general, all the tools summarised in Table 9 are useful for e-waste management. Each environment management tool has a specific information category when applied to e-waste management some of which overlap. The findings indicated that LCA, MFA and MCA overlap with regards to environmental decision making while each tool has a distinctive feature that separates them with EPR which is being used at national scale especially in terms of national policy (see Fig. 2) on polluter pays principal. Thus a combination of either LCA, MFA or MCA with EPR may be the optimal model to promote for the management of e-wastes irrespective of the nature of e-waste problem. Indeed, EPR may be most appropriate for all countries in order to minimise generation of e-waste given that the responsibility for e-waste generated post Basel Convention is passed back to the producers.

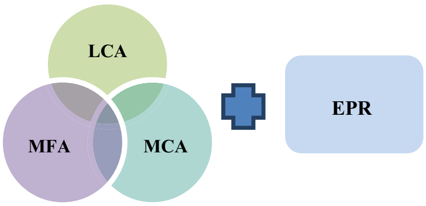

Fig. 2. Optimum e-waste management requires a combination of LCA and MFA and MCA and EPR.

5. Conclusion

E-waste is a serious problem at both local and global scales. E-waste problems appeared initially in developed countries and now extend widely to other countries around the world. The volume of e-waste is growing fast because consumer technology is rapidly changing and the innovation of technology results in rapid obsolescence, thus generating massive amounts of e-waste. E-waste consists of many different materials, some of which contain a variety of toxic substances that can contaminate the environment and threaten human health, if the end-of-life management is not meticulously managed. Many case study from e-waste recycling plants confirmed that the toxic chemicals such as heavy metals and POPs have and continue to contaminate the surrounding environment. This results in considerable accumulation of hazardous substances into the ecosystem and which can adversely impact human health. Both laboratory simulation studies and landfill leachates from disposal sites demonstrate the release of toxic substances from e-wastes with the concentration varying significantly between field and laboratory based studies.

In order to mitigate e-waste problems, there are investigations in term of the volume, nature and potential environmental and human health impacts of e-waste and extensive research into e-waste management. Several tools including LCA, MFA, MCA and EPR approach for e-waste management could ultimately ameliorate most e-waste problems. Any one tool may be imperfect but in concert they can complement each other to solve this issue. Moreover, a national scheme such as EPR is a good policy tool to solve the growing e-waste problem. Interaction of four tools can drive to success for e-waste management that is to develop eco-designed devices, to properly collect e-waste, recover and recycle material by safe methods, dispose of e-waste by suitable techniques, forbid the transfer of used electronic devices to developing countries, to raise awareness of the impact of e-waste pollution of both users and manufacturers. Over and above all of these, no matter how well the policies are introduced and implemented benefits will only arise provided end users are prepared to accept introduced policies and adhere to them.

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