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Strategies for E-Waste Management: A Literature Review

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***Abstract*—**During the last few decades, with the high-speed upgrade of electronic products, electronic waste (e-waste) has become one of the fastest growing wastes of the waste stream. In this context, more efforts and concerns have already been placed on the treatment and management of this waste. To mitigate their negative influences on the environment and society, it is necessary to establish appropriate strategies for e-waste management. Hence, this paper aims to review and analysis some useful strategies which have been applied in several countries to handle e-waste. Future perspectives on e-waste management are also suggested. The key findings found that, to manage e-waste successfully, it is necessary to establish effective reverse supply chains for e-waste, and raise public awareness towards the detrimental impacts of e-waste. The result of the research provides valuable insights to governments, policymakers in establishing e-waste management in a safe and sustainable manner.

***Keywords*—**E-waste, e-waste management, life cycle assessment, recycling regulations.

I. Introduction

IN today's business world with a competitive electronics market, the production of electronic equipment is rapidly growing because customers are likely to own the latest models with more advanced functions and attractive designs. This leads to the amount of e-waste growing speedily, reaching around 41.8 million tonnes in 2014 [1]. The quantity of e-waste produced is approximately three times faster in comparison with other wastes [2]. For example, the average of the lifespan of a new computer in India is reducing from seven years to four years [3].

TABLE I
THE TOTAL AMOUNT OF E-WASTE GENERATED BY DIFFERENT CONTINENTS [4]

Continents	Amount (million tonnes)	Amount (kg/inhabitant)
Africa	1.9	1.7
Americas (north and south)	11.7	12.2
Asia	16.0	3.7
Europe	11.6	15.6
Australia	0.6	15.2

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The total amount of e-waste generated five different continents as shown in Table I. It reveals that although e-waste is a serious issue all over the world, it is more concentrated in continents where economic development is the highest. There is a large difference regarding e-waste generation between developed and developing countries. Developed nations in the world in 2016 produced approximately 15.6 kg per head, while developing nations produced only 0.6 kg per head.

TABLE II
DIFFERENT CATEGORIES AND THE AMOUNT OF E-WASTE [4], [6]

No.	Category	Examples	Amount (million tonnes)
1	Large devices	Washing machines, large printing machines, dishwashing machines.	11.8
2	Small devices	Vacuum equipment, radio, toasters, toys, medical devices, video cameras, electronic tools	12.8
3	Small IT and telecommunications equipment	Telephones, printers, personal computers, pocket calculators	3.0
4	Temperature exchange equipment	Air conditioners, freezers, refrigerators, heat pump	7.0
5	Lamps	LED lamps, fluorescent lamps, high intensity discharge lamps	1.0
6	Screen and monitors	Televisions, monitors	6.3

E-waste has no standard definition but in general, e-waste refers to electronic equipment at the end of the product usefulness [5]. According to [6], e-waste can be divided into six main categories and the amount of these categories generated (as seen in Table II). Each category has different functions, and materials used, which causes various influences on the environment and human health if they are not meticulously managed and treated.

E-waste contains a wide range of valuable substances such as gold, silver, copper, plastic and palladium, which can be recycled to become potential new raw materials [6]. Table III shows the potential value of precious materials contained in e-waste in 2016. However, e-waste also includes a large number of dangerous substances like lead (Pb), hexavalent chromium (Cr6), mercury (Hg), cadmium (Cd) and flame retardants (i.e. polybrominated biphenyls and polybrominated diphenylethers) [7]. These chemicals assorted with solid wastes are posing a great risk for environmental deterioration especially in the developing nations like China and Bangladesh, where the appropriate technology for recycling is limited and non-formal recyclers are handling precious metals through crude ways due to an economic aspect [8]. In most cases, e-waste is exported from developed nations into developing countries due to the lower cost for e-waste handling and management. With the lack of suitable treatment strategies, a large amount of e-waste ends up in landfills, leading to dangerous impacts on the environment and society [9]. Therefore, handling e-waste is really a challenge for the related parties including customers, electronic industries and governments. If e-waste is properly treated and recycled, it could lead to an opportunity for urban mining for recovering precious substances in e-waste with an estimated value of € 48 billion [4].

TABLE III
POTENTIAL VALUE OF MATERIALS CONTAINED IN E-WASTE IN 2016 [6]

Materials	Amount (kilotonnes)	Value (million Euros)
Iron	16,283	3,582
Copper	2,164	9,524
Aluminum	2,472	3,585
Silver	1.6	884
Gold	0.5	18,840
Palladium	0.2	3,369
Plastics	12,230	15,043

E-waste issues will be more intense in the future if proper steps are not taken to mitigate its generation. Hence, this paper aims to review two common tools including Life Cycle Assessment (LCA), Extended Producer Responsibility (EPR) and e-waste recycling policies which have been applied in order to tackle and manage e-waste in some degrees in some nations. The qualitative analysis is used for the research methodology. Several types of documents such as conference papers, journal articles, reports and regulations were collected and analysed in this paper.

II. STRATEGIES FOR E-WASTE MANAGEMENT

A. Life Cycle Assessment (LCA)

LCA is popularly applied to manage e-waste in some countries (as seen in Table IV). LCA aims to measure environmental burdens regarding a product, process, or service by identifying materials consumed and emissions generated to the environment. Further, it can determine alternative ways to improve the environment [10]. This tool can be used during the design phase of new electronic products to design environment-friendly products, and it can also be used to minimize the amount of waste generated at their end-of-life (EoL).

In Europe, many studies have been investigated using LCA to assess the environmental influences of EoL treatment of e-waste [11]. For example, in the United Kingdom, a study conducted by Mayers, France [12] using LCA and costing to examine the possible environmental influences of the waste electrical and electronic equipment (WEEE) directive through a case study of printer recycling. They suggested that the European Union should modify the guideline of WEEE directive to guarantee its life-cycle impacts are handled. Barba-Gutiérrez et al. [13] used LCA to evaluate the ecological impacts of EoL of four different electrical and electronic equipment products in European countries. Their results demonstrated that the distance traveled for collecting e-waste and the location of treatment facilities is important for designing recycling networks and the environmental efficiency.

TABLE IV
APPLICATIONS OF LCA FOR E-WASTE BY DIFFERENT NATIONS

Equipment	Applications	Country	References
Printers	Examining environmental influences	United Kingdom	[12]
Washing machines, refrigerators, TV sets and personal computers	Evaluating environmental perspective	European countries	[13]
TV sets, washing machines, refrigerators and air conditioners	Environmental and financial aspects	Korea	[14]
Personal computers	Investigating the life cycle environmental influences	Korea	[15]
Computers	Evaluating environmental and economic aspects	Taiwan	[16]
TV sets, refrigerators and another home electric device	Investigating alternative life-cycle strategies	Japan	[17]
Desktop personal computer	Investigating environmental performance	China	[18]
Fluorescent lamps	Evaluating environmental influence	Thailand	[19]

LCA has been considered to forecast the influence of e-waste and e-waste management in Asian countries. In Korea, for example, Kim et al. [14] applied LCA to assess recycling activities of waste home appliances in terms of environmental and financial aspects. The results showed that in the environmental aspect, glass and circuit boards accounted for the highest score, followed by iron, copper, aluminum, and plastic, respectively. Regarding financial factor, recycling copper was the highest recycling prospective, followed by iron, glass, circuit board, aluminum, and plastic. In addition, the percentage of a used computer recycled and assessing the environmental influence were conducted by the study of Choi et al. [15]. They considered two options: landfill or recycling for disposal. Their outcomes concluded that recycling is a better choice for disposal compared to sending waste to landfill. In Taiwan, Lu et al. [16] conducted a study about some options (e.g., sending second-hand market, recycling practice, burning, or landfill) for handling EoL computers with the consideration of environmental and economic aspects. They suggested that companies should pay more attention to the improvement of recycling technologies and changes their mind sets in product design rather than focusing on recovery and recycling. In Japan, Nakamura and Kondo [17] applied both the LCA tool and life-cycle cost analysis that compared two options: recycling and landfill for e-waste treatment. They concluded that landfill practice is cheaper compared to recycling but the former leads to higher environmental damage and carbon generated. They suggested that to reduce the cost of recycling, a proper implementation of design for disassembly should be applied.

In China, Duan et al. [18] applied LCA to evaluate the environmental influences of electronic products at a worldwide level. To demonstrate the effectiveness of the proposed LCA procedure, a desktop personal computer system was investigated. The results found that there are two items including the integrated circuits (ICs) and the Liquid Crystal Display (LCD) which contributed the most to the environmental impact. A study was conducted by Apisitpuvakul et al. [19] using LCA to consider various disposal types for used fluorescent lamps.

B. Extended Producer Responsibility (EPR)

There have been a growing number of environmental policies and legislations in many countries in the last two decades, considering on the process of producing a new product with the main goal to mitigate the environmental influences deriving from the product. These policies and regulations are mainly adopted from the fundamentals of EPR.

EPR is considered as an environmental protection policy to mitigate the environmental influences of a product, by giving incentives to the producer of the product responsible for their EoL products, especially take-back programs, recycling operations or disposal. EPR aims to encourage social obligation by motivating manufacturers to handle EoL management during the phase of product design [1]. Some countries in the world like Japan, European Union, Switzerland, Asian nations and some states in the USA have been successfully implemented EPR (as shown in Table V).

In Japan, EPR for e-waste management has established in the late 1990s. Japan manages e-waste by two essential laws. The first law is Promotion of Effective Utilization of Resources (LPUR), which emphasizes improving methods for recycling products and diminishing the amount of waste released. The second law is Recycling of Specified Kinds of Home Appliances (LRHA), which concentrates on duties regarding the recycling of used household products on companies and customers. While LPUR focuses on personal computers and small-sized secondary batteries indicated as recyclable goods, LRHA concentrates on four home applications: television sets, refrigerators, air conditioners and washing machines. The main difference between LPUR and LRHA laws is that the former promotes the willing efforts of manufacturers, whereas the latter emphasizes the required responsibilities on companies [20]. The manufacturer pays for recycling cost and environmentally friendly treatment of end-of-use products in most of the nations, while end-users in Japan are responsible for the recycling cost [11]. The flow of the take-back program of e-waste in Japan is shown in Fig. 1.

Switzerland is the first nation in the world having an official e-waste management system introduced and implemented [7]. 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 organizations (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 organizations and handle the e-waste stream [5]. Khetriwal et al. [21] conducted a study regarding the Swiss experience in e-waste management. They found that only a little amount of e-waste goes as municipal solid waste since all the stakeholders including distributors, users and recyclers have a well-defined and equitable responsibility to work and it is a clear system with very low administrative expenses.

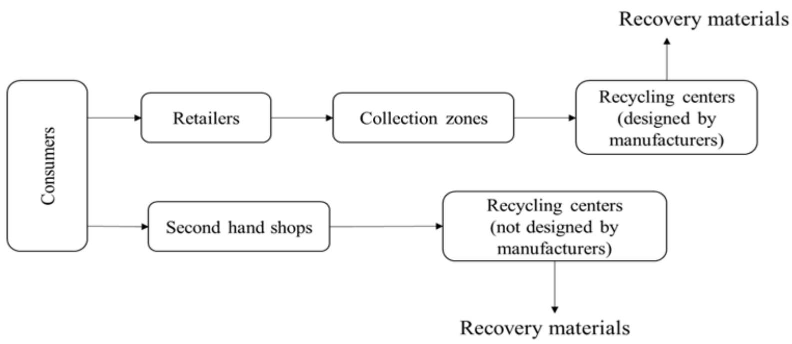

Fig. 1 Take-back program of e-waste in Japan [20]

Some states in the United States (US) and some cities in Canada have been implementing the development of legislative measure including EPR, while some companies started a voluntary activity for take-back programs. Many states in the US have carried out a wide range of measures to ban CRTs, batteries and other disposal waste to landfills. California is considered as the first state in the US implementing Advance Recovery Fee (ARF) for video displays having more than four inches. This fee ranges from six to ten dollars, which is used to collect electronic waste and improve the recycling infrastructure in this state [22]. Moreover, different partners, such as state and local governments, companies, retailers, recyclers and environmental experts in the United States have worked together to find out an optimal method for e-waste management [23].

Some other Asian nations have started to apply the EPR principle to manage e-waste. In Malaysia, EPR is generally integrated into two policies: Solid Waste and Public Cleansing Management Act (SWMA) in 2007 and the Tenth Malaysian Plan (10 MP) in 2010. Several multinational companies like Dell, Nokia, Apple and HP in Malaysia have implemented ERP initiatives with voluntary activities and take-back programs to corporate environmental regulations. Dell's branch in Malaysia, for example, establishes an online recycling website to receive all brands of discarded computers for free recycling, and especially offers incentive fee for consumers who recycle unused Dell products [24]. China introduced legislation on e-waste management in January 2011. Several e-waste recycling companies started to establish their collection network for better development, and some electronic manufacturers began on designing a recycling system in 2012. In Korea, the ERP system was introduced to encourage recycling practices in 2003. The EPR system aims to promote manufacturers responsible for their end-of-life products to implement the improvement in product design, materials used and business operations through economic incentives. Televisions, refrigerators, washing machines, air conditioners and personal computers were chosen as main targets [25]. Two years later, audio equipment and mobile phones were added under the EPR system while facsimiles and printers were included in 2006. In Vietnam, the practices for recovering and disposing of used products were enforced in 2013. A take-back system and laws of the appropriate collection, recycling, processing, and disposal of used products started in 2015 [26].

TABLE V
APPLICATIONS OF EPR FOR E-WASTE MANAGEMENT BY SOME DIFFERENT NATIONS

Nation	Year	Policy	References
Switzerland	1998	Return and take-back programs for the electronic device Disposal ban in a landfill	[5], [21]
Japan	Late 1990s	Take-back programs for four home equipment: televisions, refrigerators, air conditioners and washing machines	[20]
United States	2003	Take-back programs for household equipment in some states Advance Recovery Fee Landfill bans for CRTs and batteries	[22]
Korea	2003	Take-back systems	[27]
Malaysia	2007	Take-back programs Voluntary activities	[24]
China	2012	Take-back programs (tax subsidy by Chinese government)	[28]
Vietnam	2016	Take-back system	[26]

C. E-Waste Recycling Regulations in Some Countries

There are many regulations developed and implemented by different governments and non-government organizations worldwide to prevent the growth and illegal movements of the e-waste between the nations and hence restrict the pollution generated.

In the European Union, there are two typical directives in e-waste handling, namely Waste Electronic and electrical equipment (WEEE) directive and Restriction of Hazardous Substances (RoHS). The recycling rate of e-waste in the European Union is around 35% higher than the e-waste recycling rate in the U.S since the management of e-waste in EU is implemented by these two directives [1]. The purpose of the WEEE directive is to gain the collection percentage for EoL electronic products from 65% by 2012 and to 85% in the year 2016. In addition, RoHS Directive aims to reduce the use of harmful materials in electronics, such as mercury, cadmium, lead, and poly brominated biphenyls (PBB). Moreover, other European countries not part of the European Union have also been successfully handling e-waste. Switzerland, for example, has two different e-waste systems: Swiss Association for Information, Communication and Organization Technology (SWICO) for office, medical and telecommunication equipment and Swiss Foundation for Waste Management (SENS) for home products. The recycling companies related to both systems have recycled approximately 75,000 metric tons of e-waste in 2004, which is 11 kilograms of e-waste per person in comparison with a minimum rate of 4 kilograms per capital guided by WEEE directive in 2002.

In Japan, Home Appliance Recycling Law was passed in 1998 to collect four types of household appliances: televisions, refrigerators, washing machines and air conditioners. A proportion of the recycling and transportation fee is covered by consumers. This fee varies from US$27 to US$65 depending on different types of electronic devices [30]. Consumers are encouraged to send e-waste to the store where they bought the product. Retailers then transfer the used product to established collection centres, and companies are required to recycle e-scrap. The recycling rate of e-waste in Japan is around 75% under this law because consumers have a greater finical responsibility [1]. Until 2004, more than 40 e-waste recycling centres in Japan have been established and they are partially supported funds by the local governments or electronic companies.

Many states in the U.S have made efforts to collect and recycle e-waste from private houses and business sectors. For example, a law in California State has passed to charge consumer fees, namely advanced recycling fees (ARFs), when products are purchased. The ARFs is between US$ 6 to US$ 10 for collecting monitors, televisions and laptops [30]. In 2006, the Electronic Product Recycling Law was introduced by the Washington State. This law aims to require producers of computer and television products to implement recycling system throughout the state with no fee to residential, local businesses, local municipalities, charitable organizations and schools. Moreover, more than 800 local communities have created e-waste collection events, which is an essential role in e-waste management in private houses [29]. Some e-waste collection methods are implemented in the U.S such as curbside, particular drop-off places, persistent drop-off, takeback and purchasing centres [31]. According to Kahhat, Kim [29], the actions of all states and main companies do play a vital role in sustainable development, but they are still limited in e-waste management in the U.S. The government should work together with company approaches to establish a regulatory framework to achieve an efficient solution. As a result, this solution can address collection challenges and create enough recycling centres in each state.

In Australia, the National Television and Computer Recycling Scheme were passed in 2011 in order to improve the rate of e-waste recycling. However, the e-waste management in this country is not properly undertaken, and it lags behind the international best practices [32].

In India, regulations regarding e-waste management were enforced in 2012. The process of e-waste treatment is still quite slow in Southeast Asian nations although many e-waste laws have been introduced and implemented [24]. Thailand, Indonesia, Philippines Malaysia are in the final stage to develop their own e-waste regulations [33].

III. Future Perspectives on E-waste Management

In some developing countries like Vietnam, China, India and etc., they are challenging with the lack of policies and infrastructure to handle and manage e-waste in a sustainable way. Formal recycling of e-waste is a vital step to capture valuable resources like metals, plastics, and so on as well as treat toxic substances in a proper way. Recycling operation involves three key steps such as collection, disassembly, recycling or remanufacturing. However, these developing nations, e-waste recycling operation is normally implemented by informal recycling sectors with improper and unsafe methods. This could result in serious influences on the environment and human health. Hence, transferring appropriate technology from developed countries to developing nations to treat e-waste should be undertaken in the future [26], [34]. In addition, the manufacturers, recyclers, local governments, policymakers and the public should work together to cope with the growing number of e-waste.

Based on the literature review, LCA is currently a common tool used in e-waste management since it can estimate the influence of material consumptions as well as evaluate the environmental and economic aspects. EPR, on the other hand, handles e-waste issues at the national scale and enforces manufacturers to responsible for their end-of-life products. Some developed nations like Japan and Switzerland have implemented EPR principles, which is well supported by electronic companies. Hence, the combination of LCA and EPR may be the optimal model to manage e-waste in the future regardless of the nature of e-waste issues [11].

Electronic firms should be encouraged to invest capital for establishing reverse supply chains to handle their end-of-life products in order to achieve sustainable development. According to De Brito and Dekker [35], reverse supply chains are a set of activities regarding used product acquisition, transportation of used products, sorting, dismantling, remanufacturing, recycling of returned products, and secondary markets for recovered items or products. Financial incentives need to be considered and supported by local government or state for the effective management for e-waste. There are a number of policy such as subsidies, low-interest loans, tax reduction, etc. Further, operating transparency in the e-waste management in firms should be taken into account when incentive schemes are designed and implemented. The transparency can assist the continuous improvement in the reverse supply chain system and thereby facilitate the variation in collection activity and treatment processes. More research in this area would be beneficial to suggest good policies.

To manage e-waste successfully, it is important that the development of eco-design equipment, properly e-waste collection, recycling valuable materials by using appropriate techniques, disposing e-waste accordingly, preventing the illegal trade used electronic devices to developing countries, and raising public awareness towards the detrimental impacts of e-waste should be considered and implemented.

IV. Conclusion

E-waste is a serious issue at local as well as global scales. E-waste consists of a variety of materials, some of which contain hazardous substances which can lead to severe environmental influence and public health risks. Hence, managing e-waste in an environmentally friendly manner is a complicated issue for many countries in the world. This research reviewed some useful tools used in some countries for managing e-waste. Future perspectives on e-waste management are presented as well. This would assist governments, policymakers, firms in designing better e-waste management to mitigate e-waste impacts on the environment.

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