

E-waste: Current Research and Future Perspective on Developing Countries

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ABSTRACT

The increase of population and purchasing power, supported by the development of technology, give consequence to the generation of “Waste of Electronic and Electrical Equipment (WEEE)” or e-waste. The increasing rate of WEEE production and its hazardous contents raise the concern regarding e-waste. This paper describes the research development on e-waste and proposes the perspective of future research. The study based on the literature survey in open access articles using ‘e-waste’ as the keyword. Article selection was done by considering the reputability of the source and cited frequency. From the articles reviewed, China contributed to most of the researches. Some of the most studied topics, namely management of e-waste, environmental and human health effects, and current status of e-waste treatment in a specific region. A brief explanation of each topic and insight on future research are also provided. Some of the research opportunities to improve e-waste management in Indonesia are the assessment of e-waste path, economic analysis considering the cost, closed-loop management system, and application of the cyber-physical systems to promote industrial symbiosis.

Keywords: E-Waste, WEEE, Research Review, Developing Countries.

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1. INTRODUCTION

Fast-growing technology and the increase in consumer purchasing power affect the increasing number of electronic product use. The increase in consumption brings consequences to the environment, whether from raw material extraction or waste generated after product usage. The electronic waste, called “e-waste” or “Waste of Electronic and Electrical Equipment (WEEE)”, is “all components, sub-assemblies, and consumables, which are part of the product at the time of discarding” (EU WEEE Directive 2012/19/EU Article 3e, 2012). There are several definitions given by different references (Mmerekki et al., 2016), but highlight that e-waste was the electrical-powered appliance, which can come in any size and function and no longer desired by the consumer. The term ‘no longer desired’ be meant that e-waste can be generated not only because the product has lost its

service function or reached its lifespan, but also because of the behavior of the consumer or obsolete technology which decreases the lifespan of EEEs.

Based on the definition, e-waste may consist of various products with different sizes and components. Directive 2012/19/EU Annex II (2012) has signified a detail list of electronic and electrical equipment. Vats and Singh (2014) give the classification and its percentage as in Figure 1.

The awareness of e-waste has emerged since 2002 in the Basel Convention and “European Union Waste of Electronic and Electrical Equipment Directive”. The concern of e-waste related to the growth of its volume every year caused by the increase of consumption and short lifespan. E-waste is considered the most rapidly growing waste in the past decade (3-4% per year), while only 15% of them are recycled (Sahajwalla and Gaikward, 2018). The concern of e-waste is proportionally growing with the amount of e-waste

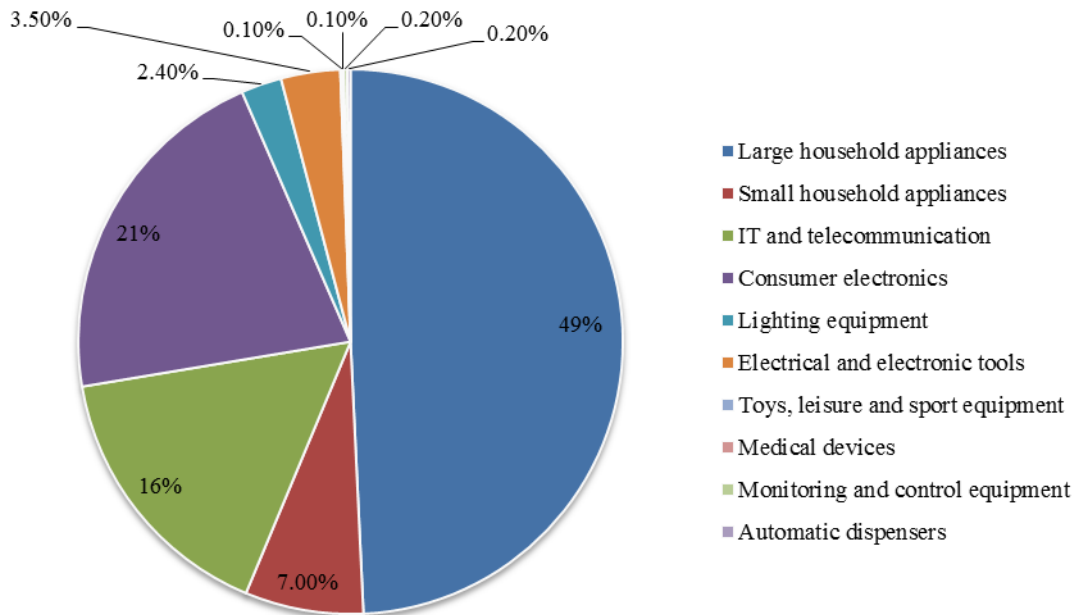


Figure 1. Classification of WEEE

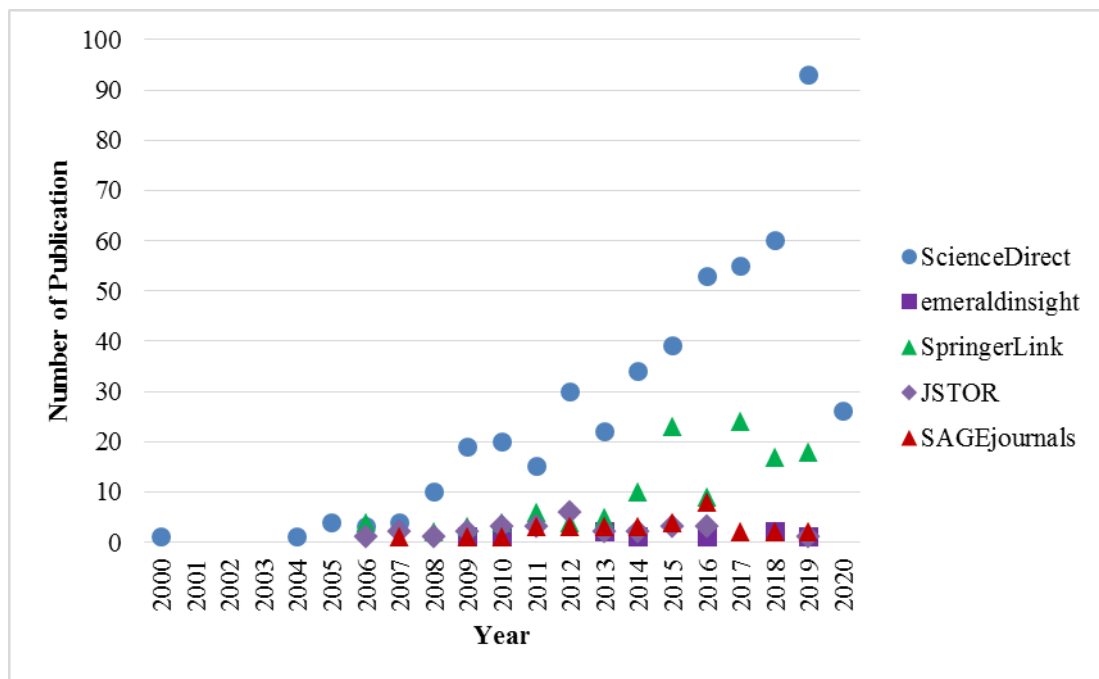


Figure 2. The Number of Researches Related to E-Waste Published in Several Academic Publishers

generated since it contains toxic compounds that could influence health and environmental aspects. The growing concern is proved by the increasing number of researches by years in some reputable academic publishers (Elsevier, 2020; Emerald, 2020; Springer Nature, 2020; ITHAKA, 2020; SAGE Publications, 2020) since 2004 (Figure 2). The researches of e-waste are distributed among different countries and different topics, such as management, recovery of the valuable materials of e-waste, the effect on human health, etc.

This paper aims to describe the research development on e-waste since 2004-2020 in various countries and

state the perspective of future research. The study based on a literature survey in open access articles using ‘e-waste’ as the keyword in several academic publishers. The article selection will be discussed in Section 2, while a brief discussion of each topic will be presented in Section 3. Section 4 will present the future challenges of e-waste researches.

2. ARTICLE SELECTION

The articles reviewed were searched in reputable

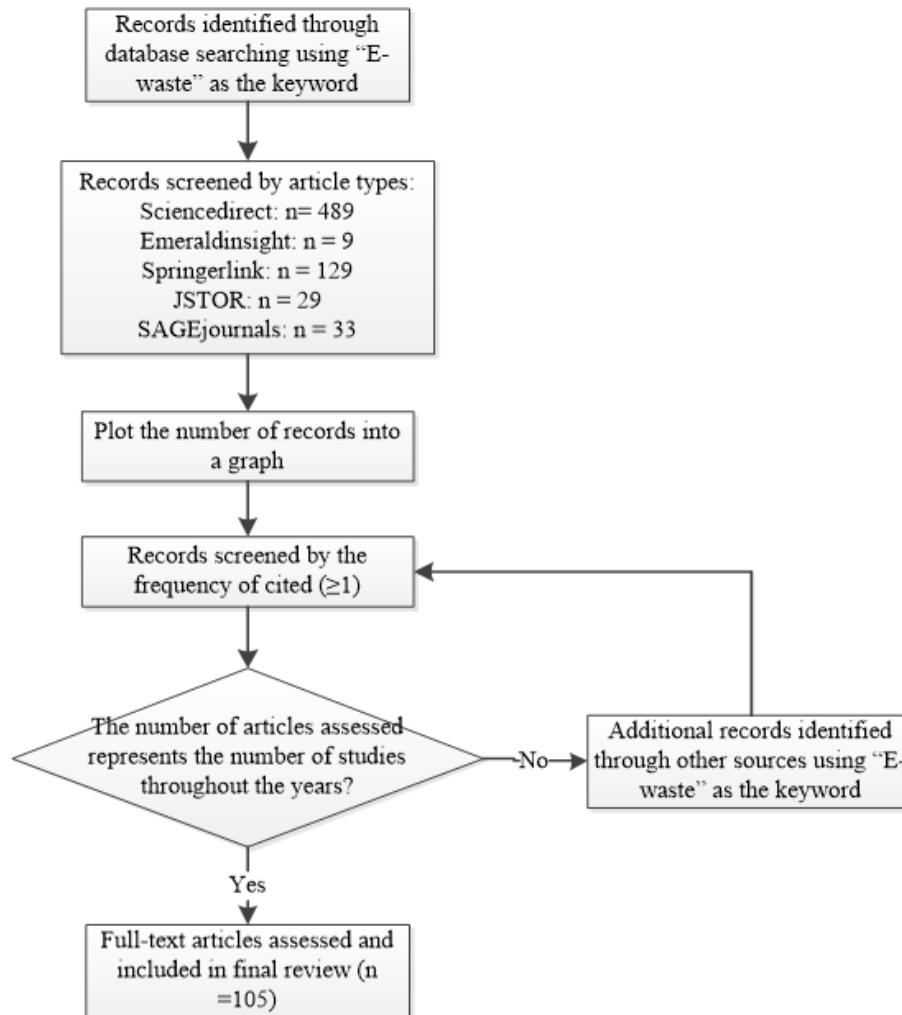


Figure 3. Flowchart of Articles Selection

academic publishers using 'e-waste' as the keyword from the year 2004 to 2020. Only open access articles were selected. The articles were reviewed based on the compatibility with the discussion topics and the number of citations. The articles between 2004 and 2018 must have been cited at least one time, while articles published in 2019 and 2020 may not have been cited, considering the time of publication. Based on the criteria, 105 articles were selected and reviewed. Figure 3 shows the flowchart of articles selection, while the distribution of citation frequency of those articles is shown in Figure 4.

The highest citation number was 450 times, where the article reviewed the toxic substances in e-waste and the environmental effect. Several tools and their application to manage e-waste were also described, i.e. Extended Producer Responsibility (EPR), Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and Multi-Criteria Analysis (MCA). The articles also gave some suggestions to improve the management system using these tools for designing devices, e-waste collection, recycle, and raising awareness (Kiddee, et al., 2013).

Figure 4 shows that the most citation frequency lays in the range of 1-50 times (76 articles). Five articles have not been cited yet since they are published in 2020 or late 2019. From those articles, we can analyze the research distribution based on its geographical object and topic related.

2.1. Online Review Aggregator

Geographical distribution is based on the object countries of the researches. Some of the researches focus on lab study so the countries of research are the countries where the study conducted or the samples taken. Other researches review or compare the practices of management in several countries. Therefore, the total number of all countries discussed may exceed the number of articles reviewed since an article may review several countries. Some articles do not mention or review specific countries so the origin countries of the writers are taken to identify the geographical aspect. The distribution of researches countries is shown in Figure 5.

During 2004-2020, most of the researches discussed or conducted in the Asia region (64.2%) and mainly focused on China (22.4%) and India (11.9%). It is

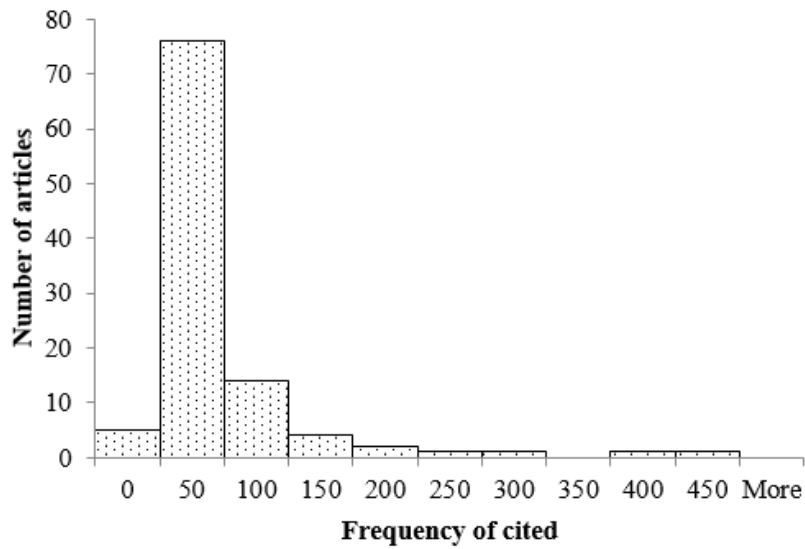


Figure 4. Citation Frequency of Articles Reviewed

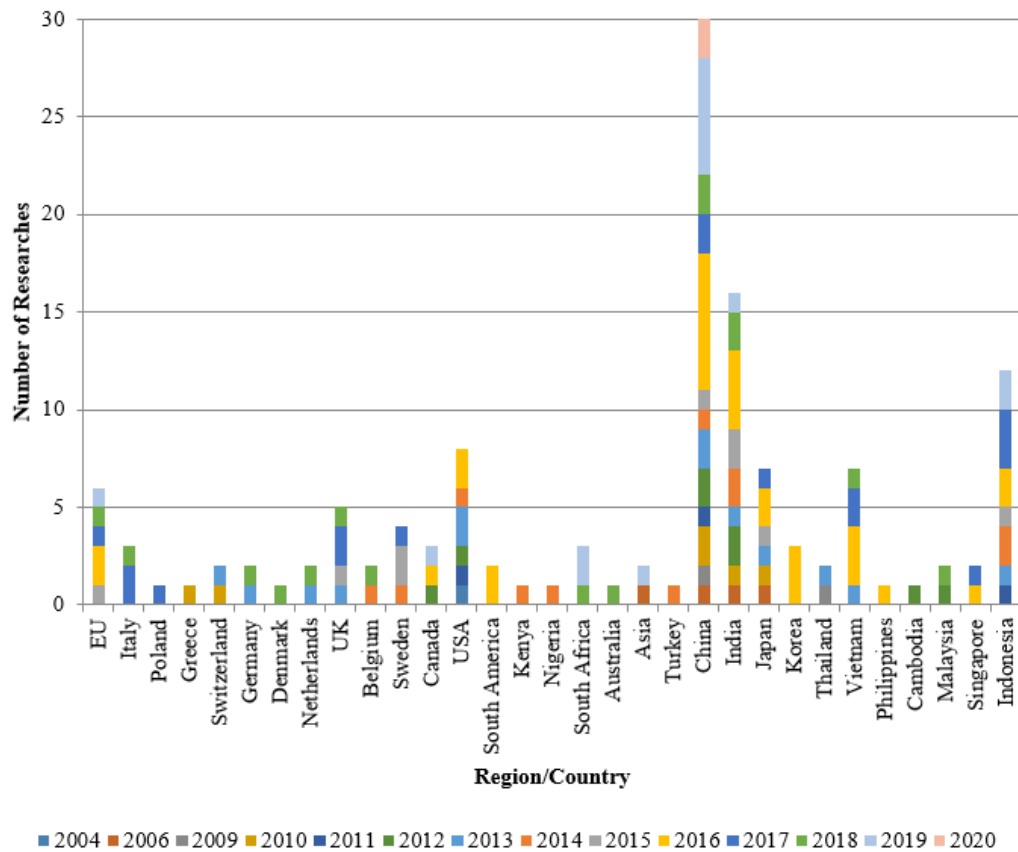


Figure 5. Distribution of E-waste Researches Based on Region and Year

associated with the fact that China is the major contributor because of the import of e-waste and rapid economics and industrial development (Hossain et al., 2012). Figure 5 also shows that the e-waste researches in China and India are consistent each year.

The e-waste research in Europe is quite popular, which 21.6% of articles reviewed or conducted in

various countries across Europe. As developed countries, European Union (EU) that contributes 26.7% of global e-waste reflects its concern on e-waste not only by researches on emerging technologies but also by the detailed regulation, such as Directive 2002/95/EC which disallows the use of toxic and hazardous substances and Directive 2002/96/EC regarding WEEE and EPR.

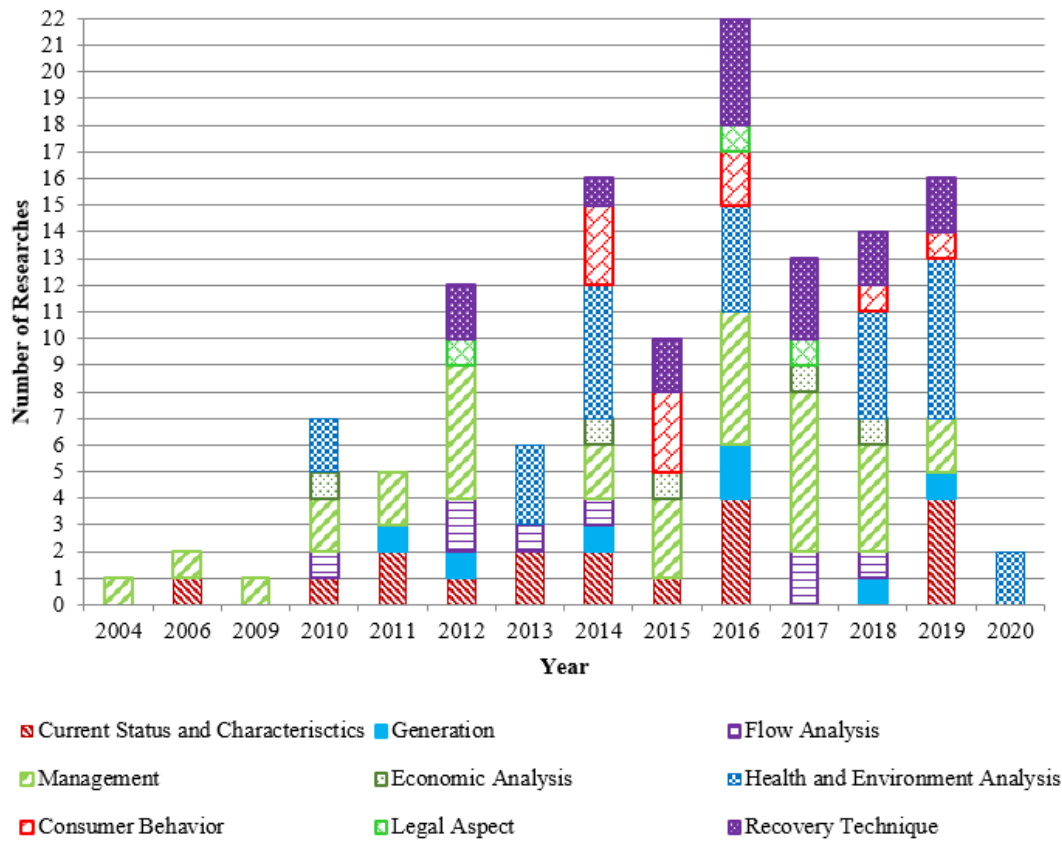


Figure 6. The Number of E-Waste Researches Based on Topics and Years

Meanwhile, there is less information on e-waste researches in America, Africa, and Australia.

2.2. Topic Distribution

The researches on e-waste are classified into nine major topics, which are current status and characteristics, generation of e-waste, flow analysis from EEE reaching its End of Life (EOL), e-waste management strategies, economic analysis, health and environment assessment, consumer behaviour, legal aspect, and recovery technique. The number of researches discussing each topic per year is shown in Figure 6.

The most popular topics on e-waste researches are management, environmental and health impact and current treatment in a specific country. From year to year, e-waste management is constantly researched, although the discussion becomes more detailed and adjusts technology development. For example, from 2004 to 2006, researches on management focus on investigate current management strategy and offer some global solutions to improve the existing system, from building recycling plant, price internalization, promote reduce and reuse (Realff et al., 2004; Terazono et al., 2006). The topics then grew to comparative studies among developed and developing countries (Galdajis et al., 2010; Awasthi et al., 2016; Yoshida et al., 2016), design of a mobile plant, implement autonomous robots in recycling plants, or using the cyber-physical system to manage e-waste. (Zeng et al., 2015; Alvarez-de-los-

Mozos and Renteria, 2017; Marconi et al., 2017).

The researches on e-waste's environmental and health impact emerged since 2010 and shifted from the literature survey to laboratory research since 2014. Most of the researches were conducted in China. Meanwhile, the researches on the recovery technique of e-waste were recorded since 2012 and thrived using a different kind of approaches. Quantitative researches such as calculate e-waste generated, analyze the flow, and estimate the economic benefit was not explored widely.

3. REVIEW ON E-WASTE TOPIC RESEARCH

3.1. E-waste Characteristic

E-waste can be classified based on a physical and chemical constituent. The classification of its characteristics in references is presented in Table 1. The differences in physical and chemical composition may come from different years of the data. Due to technological change, the chemical constituent in e-waste might be changed. A study conducted to assess the chemical composition of dynamic RAM (DRAM) between 1991 to 2008 projected that DRAM would have a stable level of gold and silver, 80% reduction in palladium content, increase in copper content with 75% from 2008 to 2020. Although the number of DRAM modules decreases due to the change of technology and modular design which will affect the physical composition of global e-waste, the number of precious

Table 1. Composition of E-Waste

Constituents	Vats and Singh (2014)	Realf <i>et. al.</i> (2004)	Kong <i>et. al.</i> (2012)	Hossain <i>et. al.</i> (2015)
Metals	60.20%	49%	13%	39.50%
- Copper			7%	20.10%
- Iron				8.10%
- Tin				4%
- Nickel				2%
- Lead				2%
- Aluminium				2%
- Zinc				1%
- Silver				0.20%
- Gold				0.10%
- Palladium				0.01%
Plastics	15.20%	33%	21%	30.30%
Metal-plastic mixture	5%			
Cables	2%			
Screens (CRT and LCD)	11.90%	12%		
PCB	1.70%			
Others	1.40%	1%		
Pollutants	2.70%			
Wood		5%		
Refractory Oxides				30.20%

metals in ICT may remain stable (Charles et al., 2017). Hence, the physical composition of global e-waste may change due to technology but its total of chemical constituents is predicted to be stable.

3.2. Generation and Flow

The exact number of e-waste generated from several countries will not be discussed since most references give different projections for different years. This section will discuss the methods to predict the e-waste produced since the weakness of developing countries in managing e-waste is the insufficient data. Therefore, these methods can be useful to predict the benefit and harm of e-waste in developing countries.

The most basic way is by forecasting using the EEE production data and estimate the portion of EOL discarded and recycled to get the volume of EOL (Bhutta et al., 2011). Another study use questionnaire adapted from the United Nations Environment Program (UNEP) to analyze the potential generation and flow of e-waste (Rimantho and Nasution, 2016). Nevertheless, the data accuracy depends on the role of respondents in the EEE or WEEE life cycle, which means an error in choosing the respondent will mislead the interpretation of e-waste flow.

Some common models for estimating e-waste generations are Material Flow Analysis and Population Balance Model (Andarani and Goto, 2014; Santoso et al., 2019). Scenarios created based on the variation of usage time and transfer coefficient among the stakeholders. However, some assumptions must be made since not all of the data needed were available, for example, the frequency of reuse from the secondhand market to end-users and the stock available on the market.

Another study using system dynamics modelling showed that the increasing number of EOL EEE affected by population growth, economic development, and change in consumption patterns. (Alamerew and Brissaud, 2018). The simulation results showed that the EOL WEEE products increased during the past decade and so did the recovery rate if it could be pushed by the legislation. By knowing the critical factors of e-waste generation and recovery, policymakers may improve the decision and e-waste management program involving the main stakeholders.

There are four to six main stakeholders of reverse e-waste supply chain network in developing countries, i.e. end-users (households, institutions or corporates), collectors (scavengers and service centres), secondhand markets, sub-dealers or recyclers, refurbishment, and dealers who export e-waste which cannot be recycled (Veenstra et al., 2010; Hanafi et al., 2011; Dwivedy and Mittal, 2012). The flow in the country studied will affect the number of stakeholders involved. To study the e-waste flow, some researches adopted the Markov chain model, Life Cycle Assessment (LCA), or mixed-integer multi-objective linear programming. The qualitative researches and literature surveys found that up to 90% of e-waste in developing countries end in informal waste sectors. If the government wants to apply the Extended Producer Responsibility (EPR) system, special attention must be taken to informal waste sectors to improve their roles in the collection to recovery processes.

3.3. Environmental and Health Effect

Environmental conditions have a strong connection to human health since e-waste impact on health may come in two ways, which are the contamination from food chains and the direct exposure in recycling areas. Most of the researches on health and environment are

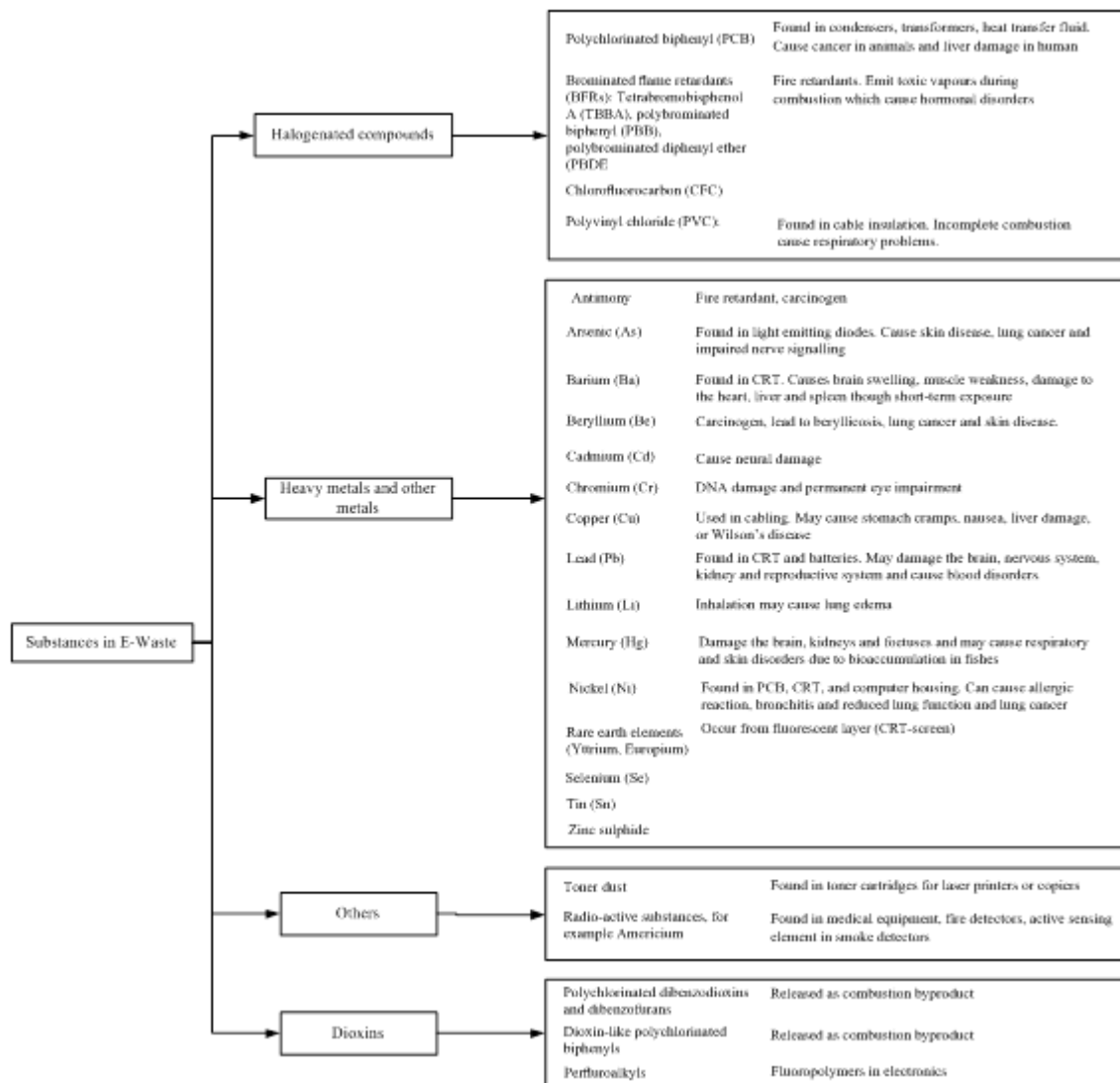


Figure 7. List of Substances in E-Waste and Its Health Impact

conducted in developing countries, especially in Asian, for example in China, India, and Vietnam. The economic view of e-waste, inadequate knowledge, and limited resources for e-waste treatment technologies become the major factor backyards treatment emerged. Inappropriate e-waste treatment will lead to air, soil, and water contamination of chemical constituents which affects human health.

The substances in e-waste and the impact on health are listed in Figure 7 (Gaidajis et al., 2010; Monika and Kishore, 2010; Kiddee et al., 2013; Grant et al., 2013; Garlapati, 2016). These substances can be classified into three types of contaminants. Primary contaminants are the hazardous constituent of e-waste, such as heavy metals and halogenated compounds. Secondary contaminants are by-products or residues produced due to improper recycling process, including dioxins, polyaromatic hydrocarbons (PAHs), poly-halogenated aromatic hydrocarbons (PHAHs). Tertiary emissions or contaminants are compounds used for recycling that must handle properly to avoid environmental and health

issues, for example, aqua regia, the residue of nitric acid, hydrochloric acid, cyanide, thiourea, and bromide in leaching process of metal recycling. (Khanna et al., 2014).

3.3.1. Soil Contamination

A study in Vietnam confirmed the pollution of dioxin compounds on the soil in the e-waste processing sites. The concentration detected was higher than the maximum acceptable concentration based on WHO regulation which mainly due to the open burning and open storage practice (Suzuki et al., 2016). Improper recycling activities, for example, open burning and manual dismantling, pollute the soil and river in Vietnam, proved by the presence of fire retardants in soils and river sediments (Someya et al., 2016).

A study conducted in China investigated the soil samples from rice paddy sites, open burning sites, e-waste processing sites, and sediment samples from a river near the village. Seven metals, i.e. calcium, copper, molybdenum, lead, nickel, tin, and zinc, were detected

in soil and sediment samples in high concentration. Multivariate analysis confirmed that a high concentration of those elements strongly correlated to e-waste processing. Meanwhile, analysis of soil from open-burning sites showed Cu accumulation which signified the influence of open burning activities (Uchida et al., 2018). Hence, implementation of the proper treatment process and wastewater treatment at e-waste recycling sites is needed to reduce contamination of chemical constituents to the soil.

3.3.2. Air Contamination

E-waste burning, besides contaminates the soil, also increases the concentration of air pollutants, particularly the particulate matter. An investigation in India observed the heavy metal concentration (Cu, Pb, Zn, Cr, and Ni) and particulate matter level (PM₁₀) in air samples in e-waste open burning site and two residential areas. It was found that levels of heavy metal and PM₁₀ and in e-waste burning sites have a significant highest mean concentration among the studied areas. It was also found the residents of e-waste burning sites have the highest level of exposure based on the blood analyses. This study showed that open burning by the informal waste sector contributed to a high level of air contamination which affected the high level of heavy metal exposure to the residents. (Gangwar et al., 2019). In line with the study in India, a study in two informal e-waste recycling sites Vietnam in the urban area found that level of PCBs and BFRs in indoor dust were higher than non-e-waste houses (Tue et al., 2013). Human exposure was estimated and the result was dust ingestion contributed to most BFRs intake, while air inhalation to PCBs intake.

3.3.3. Water Contamination

Illegal dismantling of e-waste along with open-air burning was the major cause of high contamination of cadmium in groundwater in four districts in India, namely Rampur, Shahjehanpur, Moradabad, and Bareilly (Idrees et al., 2018). The level of cadmium contamination was higher than the regulatory threshold, indicated serious toxicity problems at the groundwater system.

The presence of a contaminant in surface water will affect the living water organisms and lead to bio-magnification. A study in China examined plasticizers, organophosphorus flame retardants (PFRs), and PFR metabolites of water snake samples in a polluted pond. Bio-magnification did not happen, shown by bio-magnification factors (BMFs) which were less than 1, suggesting a bio-dilution driven by metabolism (Liu et al., 2019).

3.3.4. Assessment of Human Health

Several studies concerning the exposure identification of heavy metals and other chemicals from e-waste have been conducted. Study in South America analyzed manual gathering of metals by low-income children in South America and its correlation to

increased blood lead levels (BLLs) due to lead exposure during the process. It was found that the children and adolescents have higher BLL than the BLLs suggested (Pascale et al., 2016).

In addition to the blood test, hair and urine testing are the common bio-indicator to assess human exposure to e-waste contaminants. Two studies used different indicators to observed exposure in e-waste sites. Zhang et al. (2019) investigated the exposure of phthalic acid esters (PAEs) which are abundant in e-waste recycling areas by taking urine samples of the residents. These samples were compared to residents in the non-e-waste site as the reference area. The result showed that the concentration of \sum mPAEs in the urine of the residents living in the e-waste site was significantly higher than those living in the reference area. About 22% of the residents in e-waste sites have hazard index (HI) values more than 1, indicated exposure beyond tolerable levels and might cause potential adverse effects (Zhang et al., 2019). The most important finding is 68% of them were 0-18 years old.

Identification of PAH using hair and urine as bio-indicators was also done for workers and residents near the e-waste recycling area. There was no significant difference in exposure level between residents and e-waste dismantling workers. Another finding was one of the carcinogenic metabolites was detected in the internal hair of the respondents (Lin et al., 2020).

Heavy metals exposure causes acute and chronic effects; respiratory reproductive problems, irritation, cardiovascular and urinary disease (Awasthi et al., 2018). Further, human exposure to e-waste contaminants may affect human DNA. A study conducted to assess potential genomic damages in workers recycling e-waste showed a strong correlation between DNA damage and the duration of processing e-waste (Wang et al., 2018). This result is supported by a review of residents' health in informal e-waste recycling sites. Exposure to e-waste also leads to stillbirths, spontaneous abortions, premature births, and reduced birth length and birth weights (Grant et al., 2013).

Some WEEEs contain radio-active substances but its total composition in global e-waste (Table 1) is less than 1%. An assessment of radiation exposure at three municipal waste dumpsites and the e-waste dumpsite in Southwest Nigeria did not find immediate radiological risk to the residents or workers near the dumpsites (Jibiri et al., 2014). The composition of e-waste in the dumpsites may contribute to this result since not all of the e-waste has radio-active substances.

Not all the studies conducted by direct sampling of human bio-indicator and lab analysis. Estimation of the exposure using Monte Carlo analysis has been done to investigate the daily intakes of photo initiator (PI) for e-waste dismantling workers in China. It was found that the e-waste workers have higher daily intakes of PI than the urban residents (Li et al., 2020).

Although previous studies in China emphasized the hazard caused by improper treatment, the same level of hazard is found in the formal recycling plant. A study in

Sweden examined the workers in three recycling plants, consisted of direct recycling workers and office workers. Exposure bio-indicators (blood, urine, and plasma) and personal air exposure were monitored. Air sampling results showed higher airborne exposure (10 to 30 times) in recycling workers than those in office workers. The biomarkers showed significant levels of cobalt, chromium, indium, mercury, and lead in the urine, blood, or plasma of recycling workers than those in office workers. It is recommended to use an automated process to improve the protection for workers and the environment (Julander et al., 2014).

3.4. Economic Assessment

There are not many kinds of research done to predict the potential value of e-waste. A study in 2015 analyzed the potential recovery value of 14 products using e-waste volume at that year and the prediction of e-waste volume in 2020. The highest potential revenue in 2015 was 528 M€, given by CRT monitors. As the years change, the number of individual products change, depending on technology development. Therefore, in 2020, the highest potential revenue was contributed by smartphones at value 746M€ (Cucchiella et al., 2015). Another study projected that cell phones would contribute the most revenue in 2020 (15,777 M€) while smartphones came in second place with a total value of 2,306 M€ (Charles et al., 2017). These researches show that the precious metals in e-waste can give economic benefit when treated properly. However, the assessment limited to the potential revenue without considering the cost of recovery processes.

3.5. Management Practises

3.5.1. Current Condition in Developing Countries

E-waste management in developing countries has similar constraints. Import of e-waste from developed countries is usually found in developing countries since e-waste is considered as a kind of livelihood by the residents. Lack or absence of formal recycling facilities makes the informal waste treatment thrived near residential areas. The backyard processes in informal treatment facilities were done manually and without adequate resources and knowledge on the hazard which affects the environment and human health. Some developing countries, for example, Cambodia and Indonesia have not specified the law for e-waste management. (Rode, 2012; Sothun, 2012). Lack of data such as the material flow of e-waste and lack of awareness becomes other constraints in e-waste management. (Chibunna et al., 2012, Panambunan-Ferse and Breiter, 2013).

By connecting the local or national regulations to EPR schemes, improvement in management in developing countries can be achieved. Combining the regulation with the incentives system will increase the success of the new regulation implementation (Zeng et al., 2016; Shevchenko et al., 2019). The effectiveness of legislation has been proved by a study using system dynamics modelling. The major factor that affects the

amount of collected e-waste for product recovery is the enforcement of legislation. (Alamerew and Brissaud, 2018).

On the other hand, the government as one of the stakeholders must provide infrastructure for formal e-waste treatment plants and encourage the EEE producer to focus on Extended Producer Responsibility (EPR) and (Wei and Liu, 2012; Ilankoonet.al, 2018). The collaboration between formal and informal waste sectors (IWS) may also reduce the negative impacts caused by improper treatment in IWS (Li and Tee, 2012). Existing formal recycling plant must be supported by technical support (e.g., providing technical guidelines) and financial support (e.g., subsidies for investment) to improve the treatment processes (Yoshida et al., 2016).

The best example of how the e-waste treatment scenario changed from primitive, artisanal practices into a developed system (pyro-metallurgical or hydrometallurgical) is China. Although both of the methods have weaknesses; where pyro-metallurgical releases hazardous substances (dioxins and furans) while hydrometallurgical generates more acid waste streams, the improvement of each system would reduce the negative impacts (Ilankoonet et al., 2018).

3.5.2. Extended Producer Responsibility (EPR)

EPR means that the manufacturers and importers have the responsibility to collect and recycle the EOL EEE. The concept of EPR has been known well in developed countries, yet the implementation in developing countries has two major challenges. The first challenge is related to producer identification cause by smuggling, production of imitation product or small shop-assembled products. This will result in hidden material flows on EPR implementation. Another challenge is the possibility of the accuracy of the number of collected e-waste which will affect the subsidies from the incentive system (Kojima et al., 2009). In developing countries which not supported by an infrastructure for treatment, legislation, and awareness of stakeholders (private, public and government), the implementation of EPR will find many gaps (Nguyen et al., 2017). EPR system in developed countries, such as the Republic of Korea, has been integrated with recycling law, supported by several recycling centers and recycling promotion (Rhee, 2016).

3.5.3. Reuse, Remanufacturing, and Refurbishing

Reuse is the first tier in the waste hierarchy which gives higher environmental advantages than a basic collection of e-waste. A study analyzed two EOL computer treatment chains in Belgium using a comparative Life Cycle Assessment (LCA). The first chain focuses on take-back obligations in the name of manufacturers. Meanwhile, the second chain prioritizes reuse and manual dismantling of e-waste before mechanical treatment. The latter chain was found to have more environmental benefits due to the high recovery rate and reuse (Gonda and Degrez, 2018).

For products that are expensive or infrequently used, reuse scenario is more appropriate. A study stated that the reuse scenario is economically viable, while the main limiting factor is collection methods. Sorting, testing, and repair tasks contribute to major costs (Angouria-Tsorochidou, 2018). There are several ways to promote reuse on a larger scale by resolving the key issues on logistics, process operation (such as testing, repairing, cleaning, and refurbishment), quality, and consumer acceptance. Developing quality labels or standards for reused items will tackle the issues of public confidence (Cole et al., 2017). Appropriate differentiation of reusable and non-reusable e-waste will also encourage reuse scenario (Terazono et al., 2006). In this scenario, loss of reuse potential during waste collection caused by the flow to waste system and the handling damages is the main concern (Cole et al., 2018).

Other forms of reuse are remanufacturing and refurbishing. These practices were studied in Japan, Singapore, and Indonesia by interviewing 2 companies (OEM or IR) in each country to study the current situation of remanufacturing and refurbishing of photocopiers. Photocopier OEMs in Japan have been conducting remanufacturing for more than a decade, by taking back 80%, which 10-15% of them was remanufactured. By remanufacturing, total CO₂ emission can be reduced by 20% while maintaining the same functional level. Remanufactured products are often bundled to new products for large-lot purchasing. In Indonesia, the refurbished product has a 60-70% market share. Used B/W photocopiers are imported and sold 20% of the new price. However, the company did not take the used products back (Kamigaki et al., 2017).

3.5.4. Role of Automation and Cyber-physical System (CPS)

Automation in e-waste dismantling can give more protection to workers' health and environment. However, various types of e-waste create difficulties in classifying and dismantling process which implementation of full automation process hard. A collaborative robot, which shares the process between human operators and robots, is considered as the best solution (Alvarez-de-los-Mozos and Renteria, 2017). By combining manual and robotized operations, the operator can teach a robot on cutting, separating, and other low skilled operations. This will solve the problems in the identification, classification, and disassembling of e-waste.

Another treatment using a cyber-physical system (CPS) was proposed to decrease the e-waste sorting cost in Japan (Torihara et al., 2015). Roughly crushed particles of e-waste delivered on a conveyor and a sorting device separate the metal-rich particles. By modifying the sorting device, it can be remotely controlled from locations where labor cost is cheaper or via the internet as a game.

The Cyber-physical system (CPS) can also improve the e-waste refurbishment business for several main

processes such as sorting, dismantling and repair, cost, and routing. Implementation of CPS increases the traceability where RFID tags on the cores allow control, monitoring and decision making for appropriate processes. The system saves operational time up to 664 hours and reduces the process inefficiencies. (Sharpe et al., 2018).

Another study proposed a collaborative web-based platform that connects producer, end-user, service, and dismantlers, recyclers, or remanufacturers to recycle electronic EOL. The decision-making algorithm will evaluate the economic and environmental of reuse scenarios (Marconi et al., 2017). The web platform will also support the industrial symbiosis among companies in the same or different sectors (Marconi et al., 2018). It can be concluded that automation and cyber-physical systems improve e-waste management by data sharing which permits collaboration in the refurbishment system and/or industrial symbiosis, process sharing to promote efficiency and human health, and remote process to reduce cost.

3.6. Consumer Behaviour on E-waste

Customer behavior influences the willingness to participate in e-waste management. Behavior is also identified as one of the prominent factors, along with attitudes and knowledge, which affect the favor to pay more for e-waste management funding (Pandebesie, et al., 2019). A study conducted in Indonesia found that 77% of respondents knew about e-waste, while 58% and 12% of the respondents may be and willing to be involved in recycling e-waste (Hanafi et al., 2011). Without awareness of disposal practices of e-waste and willingness to participate, the e-waste management system will find difficulty in implementation since customers mix the e-waste up with solid waste and fail to dispose of it in an environmentally friendly way (Bhat and Patil, 2014).

3.7. Recovery and Recycling

The main limitation in recycling e-waste is the broad range of material value. E-waste has precious and rare metals which can be valuable resources of raw material (e.g. copper, aluminium and gold), but 30% of e-waste comprises plastics with low material value (Realff et al, 2004; Kong et al., 2012). The technologies for recycling metals and plastic are evolving; so do the researches to reduce the weaknesses of the methods which will be discussed in this section.

3.7.1. Metal Recovery and Recycling

Methods for metal recycling such as incineration, manual dismantling, strong acid leaching, or hydraulic shaking bed separation have low recovery efficiency and contribute to environmental damage. Incineration will lead to severe contamination of Volatile Organic Compounds (VOCs). Total VOCs generated from the incinerator is about 40, 139, 180, and 190 times higher than those treated by the electric heating furnace, blower, soldering iron, and mechanical cutting.

Excessive exposure to VOCs will increase cancer risk to the workers (An et al., 2014).

There are several technologies on metal recycling, some of them have a high recovery rate for almost all metals but also have some limitations in the economic aspect due to reagent or investment cost, for example, mild extracting technology and pyro-metallurgical. Supercritical technology may result in high recovery of almost all metals, yet it generates waste oil and gas. Bio-metallurgical (bioleaching and bio-sorption) and vacuum metallurgical are considered as environment-friendly technology, still need improvement in selectivity and industrialization (Zhang and Xu, 2016).

Improvement in the metal recycling process can be done by improving the operation parameter of the technologies or integrated different technologies or methods in the recycling process. Torihara et al. (2015) combined magnetic separation and electrostatic separation to improve the sorting process. Pulverization plus physical separation for printed circuit board (PCB) origin particles were continued by separation of metal-rich particles using a sorting device.

The combination of bio-metallurgical and hydrometallurgical was proposed to recover the precious metals (gold - Au, and silver - Ag). The hydrometallurgical uses chemicals, i.e. cyanide, for leaching gold/silver from WEEE. This process followed by the bio-sorption using *Eichhornia* root biomass and bio-sorbent, i.e. waste-tea powder (Bath et al., 2012).

Several types of research were done to improve existing technologies. For example, a study to improve the pyrolysis of a printed circuit board (PCB). High-temperature treatment was used to process PCBs to remove lead and recover precious metals. The temperature used is 1150-1350°C where PCBs were heated up to 20 minutes using Argon gas. PCB pyrolysis enhanced the separation of metals and ceramics where ceramic impurities were precipitated out (Khanna et al., 2014; Evangelopoulos et al., 2017). Khatri et al. (2018) experimented with finding the type of chemicals to get the best result of metal leachate. It was found that the mixture of ferric sulphate and ferrous sulphate (70:30) was best for copper leaching after 4 days of reaction time. Meanwhile, ferric sulphate will give the best dissolution for zinc and nickel after 4 days and 7 days of reaction time.

A new method to recover the gold from e-waste was studied using polyaniline. E-waste was crushed and treated by acidic solutions without extensive reagents or external energy, by utilizing the redox properties of polyaniline (Wu et al., 2017). Cyganowski et al. (2017) proposed a novel resin to adsorb gold in metal recycling. The processes consist of enrichment, leaching, and adsorption using core-shell anion exchange resins. The resins have great selectivity towards gold; the removal rate from leachate is up to 86% and the gold-containing polymers then could be recovered 100%.

Microbial remediation of metals or bio-metallurgical is catching high attention in recent researches since it is considered as an environment-friendly approach. The acidophilic group of bacteria is the most common

bacteria used in bioleaching. Most microorganisms studied in bioleaching are *Pseudomonas putida*, *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, *Leptospirillum ferrooxidans*, *Aspergillus niger*, *Penicillium simplicissimum*, and *Bacillus megaterium*. Those bacteria have a high recovery rate of Cu (65%-100%) and other metals, i.e. Li, Ni, Al, and Zn. The temperature range in the bioleaching process is 25 to 30°C and pH of 1.5-9.2. For gold recovery, *Chromobacterium violaceum* has been reported for its leaching efficiency of gold over 70% (Liu et al., 2016). *Pseudomonas aeruginosa* and *Pseudomonas fluorescens* can also reinforce the cyanide generation in the leaching process and improve gold-leaching efficiency.

3.7.2. Plastic Recycling

The recycling of plastic in WEEE is complicated since there are more than 15 different types of polymer that composed the plastics fraction of WEEE. The presence of brominated flame retardants (BFRs), such as polybrominated diphenyl ether (PBDE) and polybrominated biphenyls (PBB), complicate the recycling process (Kong et al., 2012).

Current technologies of plastic recycling are classified into four types. Primary recycling means that plastic wastes are processed mechanically to produce a product that has similar properties as the first product. Meanwhile, secondary recycling will convert the polymer into a product with properties lower than the original product. Tertiary recycling is used to recover chemical components from plastic waste. Converting plastic waste to energy is classified as quaternary recycling. CreaSolv (tertiary recycling) and KDV (quaternary recycling) are examples of notable technologies that can process e-waste plastics. New technology, known as micro-factory, is considered as 5th category since it can transform plastics containing BFR into value-added products such as Grenew briquettes for steelmaking, super-capacitor, silicon carbide, polymer composite, and 3D printing filaments. (Sahajwalla and Gaikwad, 2018).

3.7.3. Glass Recycling

Recycling methods from e-waste can be divided into glass-to-lead recycling and glass-to-glass recycling. The first process recovered glass using lead smelter. The lead, contained in CRT glass is in the range of 0.5-5 kg of lead which used as the screen protector from X-ray exposure. The benefit of this process is high throughput, yet it may reduce the value of high-quality glass (Kong et al., 2012). The latter method used the collected glass as raw material to produce new cathode ray tubes. It reduces cost and improves the efficiency of the furnace in the recycling process. However, there is a risk due to the difficulty to determine the exact composition of the recycled glass.

4. CONCLUSION AND PERSPECTIVE ON FURTHER E-WASTE RESEARCH

Review on e-waste studies found that the trend of research topic was shifted to using cyber-physical system (CPS) to promote symbiosis among the stakeholders (Torihara et al., 2015; Marconi et al., 2017; Sharpe et al., 2018; Marconi et al., 2018). Another emerged topic is finding environment-friendly recovery technique which can promote e-waste as resources for production (Bath et al., 2012; Kong et al., 2012; Liu et al., 2016; Wu et al., 2017; Cyganowski et al., 2017; Sahajwalla and Gaikwad, 2018). However, the implementation of the aforementioned research becomes future goals in developing countries due to less research and limited topic regarding e-waste and lag of technology development.

There are some perspectives regarding each topic studied for developing countries. Lack of data on EEE traceability complicates the study on e-waste generation and flow. Although some researches have modeled e-waste generation quantitatively, the scenario of EEE reuse across the diverse economic area in a country must be considered. Markov model or semi-Markov model is suggested to model the current situation and predict the lifetime of EEE usage in consequence of several tiers of product reuse (Veenstra et al., 2010; Dwivedy and Mittal, 2012; Andarani and Goto, 2014).

Analyzing the flow of EEE products sold in developing countries is still a challenge due to smuggling, unrecorded local production, and product traceability (Kojima, et al., 2009; Panambunan-Ferse and Breiter, 2013; Nguyen, et al., 2017). How to assess the product life cycle of electronic products from material extraction to the disposal or return remains unclear. However, life cycle analysis will provide a quantitative review on product path and can be applied to choose the management strategy, which gives the lowest negative impact on the environment.

According to the writer's knowledge, economic analysis on e-waste potential recovery while concerning the cost has not been conducted. Even further, the economic analysis of the potential revenue of e-waste recovery has not been studied in developing countries. This study will also help to decide on the incentive system to promote e-waste closed-loop management system (Kojima, et al., 2009; Gnoni, et al., 2017; Shevchenko, et al., 2019). Based on previous studies, the incentive system will promote consumers' participation, which is one of an important factor in e-waste management (Zeng, et al., 2016). Therefore, customer behavior regarding e-waste disposal and return-to-manufacturer system needs to be explored. In conclusion, there are plenty of research opportunities to be explored to improve e-waste management and practice in developing countries, especially in Indonesia.

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