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REVIEW ARTICLE

A comprehensive analysis of e-waste legislation worldwide

Rashmi Anoop Patil [1] · Seeram Ramakrishna [1,2]

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Abstract

The improper disposal and informal processing of e-waste have raised serious concerns for the environment and human health worldwide. A variety of legislative frameworks have been implemented to regulate e-waste management and upcycling in order to prevent environmental pollution and adopt resource reuse. Current e-waste legislation in different countries mostly include restrictions on e-waste import/export, regulations for recycling specific categories of e-waste, and Extended Producer Responsibility (EPR). This article serves as a comprehensive commentary to weigh the advantages and drawbacks of the different e-waste legislation enforced around the world. Though each country's e-waste legislation is enframed to address the country-specific problems, the legislation is mostly not holistic, leading to different management issues. A variety of e-waste management issues prevalent in most countries (with e-waste specific legislation) have been listed and categorized for better understanding of the status quo. Further, the article proposes a generic e-waste management model catering to requirements of countries around the world. The implementation of such a model for Europe, China, India, Japan, South Korea, Taiwan, and Australia has been illustrated to show that the model can suit both developed and developing countries with contrasting e-waste management issues. The challenges that would arise in implementing an effective legislation and mechanisms for overcoming these challenges have also been discussed. To conclude, the role of governing bodies in tackling the future e-waste problems has been highlighted. In total, the article promotes scaling up the feasibility and efficacy of the implementation of e-waste policies across the globe in the coming years.

Keywords E-waste · Legislation · Policy · E-waste management · E-waste upcycling

Introduction

Technological advances have generated considerable e-waste and their amounts are increasing at an alarming rate as the demand for a tech-savvy life is on the rise. In the past decade, global e-waste has been rising rapidly (Cui and Anderson 2016). It is estimated that nearly 50 million metric tons of e-waste was generated around the world in the year 2018 alone (Cui and Anderson 2016)! Such an enormous amount of e-waste is posing a challenge to the governments in keeping the environment rid of e-waste. Both developed and developing countries face the problem of managing and recycling e-waste, more so for the developing countries. This is because, in the majority of developing countries, the collected e-waste includes both domestically generated and illegally imported e-waste from developed countries (Widmer et al. 2005). The complexity of the issue increases due to the lack of awareness in the consumer community regarding efficient waste disposal, resulting in a significant portion of e-waste ending up in landfills along with other waste matter. Such informal practices lead to inefficient recycling of e-waste and hazardous materials associated with it, thus making it quintessential for every country in the world to enforce stricter e-waste management policies and procedures.

The onset of the twenty-first century has witnessed an enormous increase in the consumption of electronic and electrical equipment (EEE) as a result of economic development and industrialization, advances in electronics, communication and information technologies, and consumers' affordability. Most households have multiple home appliances such as

Responsible editor: Philippe Garrigues

✉ Rashmi Anoop Patil
rashmi.anoop33@gmail.com

Seeram Ramakrishna
seeram@nus.edu.sg

[1] Circular Economy Task Force, National University of Singapore, Singapore, Singapore

[2] Department of Mechanical Engineering, National University of Singapore, Singapore 117576, Singapore

refrigerators, washers, ovens, blenders, televisions, and air conditioners. Almost half of the world's population are connected to the Internet that has led to a huge consumption of information and communication technology (ICT) devices such as computers, smartphones, and tablets (Balde et al. 2017). Each consumer may own multiple ICT devices which is a major contributor to the global e-waste. Due to the rapidly evolving electronics technology, these devices become obsolete in a short span of time and the new device generations replace the old, generating e-waste at alarming rates. In addition to these household appliances and ICTs, e-waste also covers consumer and lighting equipment, electrical and electronic tools, toys, leisure and sports equipment, medical devices, monitoring and control instruments, and automatic dispensers.

The major hindrance for formal recycling of e-waste is the absence of a proper disposal and processing system, resulting in landfilling. This is also a cause for the prevalent and deep-rooted crude e-waste processing industry in low-income countries. The e-waste is illegally exported (as used equipment) from higher-income countries (such as the USA, Canada, Australia, and many European countries such as the UK, Germany, Belgium, Netherlands) to low-income Asian (China, India, Malaysia, Indonesia, the Philippines, Hong Kong) and African countries (Ghana, Nigeria, and other West African countries) (Balde et al. 2017; Sthiannopkao and Wong 2013). Along with the domestically generated e-waste, the e-waste imported from the developed countries is processed using crude and unsafe techniques such as open burning, coal-fired grill heating, and leaching using acid baths to extract high-value metals. Later, the residues resulting from crude processing are dumped in the landfills or nearby water bodies, polluting the environment (Sthiannopkao and Wong, 2013).

In addition to causing harm to the local environs and human health, the improper disposal and processing of e-waste also contribute to global warming and climate change as a result of significant carbon emissions. According to WorldLoop involved in sustainable e-waste management, for every 1 ton of e-waste collected and properly recycled, 1.44 tons of CO_2 emissions are avoided (WL 2013). The reduction in carbon emissions majorly attributes to the recovery of resources avoiding the energy-intense process of mining/producing virgin raw materials. Other factors such as avoiding crude processing and energy recovery from recyclables also reduce carbon emission. There is also an important economic component to the discussion. The total potential value of all raw materials present in e-waste was estimated at approximately 55 billion euros in 2016 (Balde et al. 2017). This means proper recycling of e-waste is not only an effort towards protecting the environment and human health but also a potential business opportunity. Recovering resources from e-waste and maintaining a closed-loop of resources also minimize the stress on the virgin resource supply chain. As industries encounter scarcity of resources and higher production costs, closed-loop production (Low et al. 2013; Low et al. 2014) becomes increasingly important. This gives rise to the need for energy-efficient and environmentally safe recycling of materials (Low et al. 2016) and remanufacturing/refurbishing end-of-life products (Low and Ng 2018).

To tackle the problem of growing e-waste and to take advantage of the e-waste generated, many countries have adopted e-waste legislation. The Global E-waste Monitor 2017 report by The United Nation's University (UNU) states that only 66% of the world's population (spread over 67 countries) are covered under e-waste legislation (Balde et al. 2017). However, more countries are planning and trying to adopt e-waste legislation. Asia is the largest producer of e-waste and most of the Asian countries are covered under e-waste legislation (Balde et al. 2017). In contrast, Africa generates least amount of e-waste and most African countries do not have an e-waste legislation (Balde et al. 2017). Moreover, both Asia and Africa face the problem of illegal import of e-waste for crude processing. Though the European Union has been the pioneer in framing the e-waste directives for the member nations, it is still trying to amend its regulations to effectively manage e-waste. The major issue in most countries with e-waste legislation is weak and inefficient law enforcement. The limited know-how regarding e-waste collection and recycling statistics due to the lack of legal liability has made it impractical to measure the effectiveness of the existing e-waste legislation. As there is no uniformity in e-waste legislation across all the countries, it is difficult to monitor e-waste recycling on a global scale. In this article, as illustrated in Fig. 1, we

1. first briefly discuss the current global e-waste scenario which includes the adverse effects of informal e-waste management,
2. compile and elaborate on the e-waste legislation implemented worldwide,
3. discuss the major issues in countries with e-waste legislation, and
4. then propose a generic model that includes all the stakeholders in e-waste management to analyze various issues and formulate an effective e-waste legislation.

The hazardous impact of e-waste on environment and human health

The adverse effects of informal e-waste processing on the environment and human health are discussed in this section to highlight the need for a formal and safe e-waste management system through effective implementation of regulations.

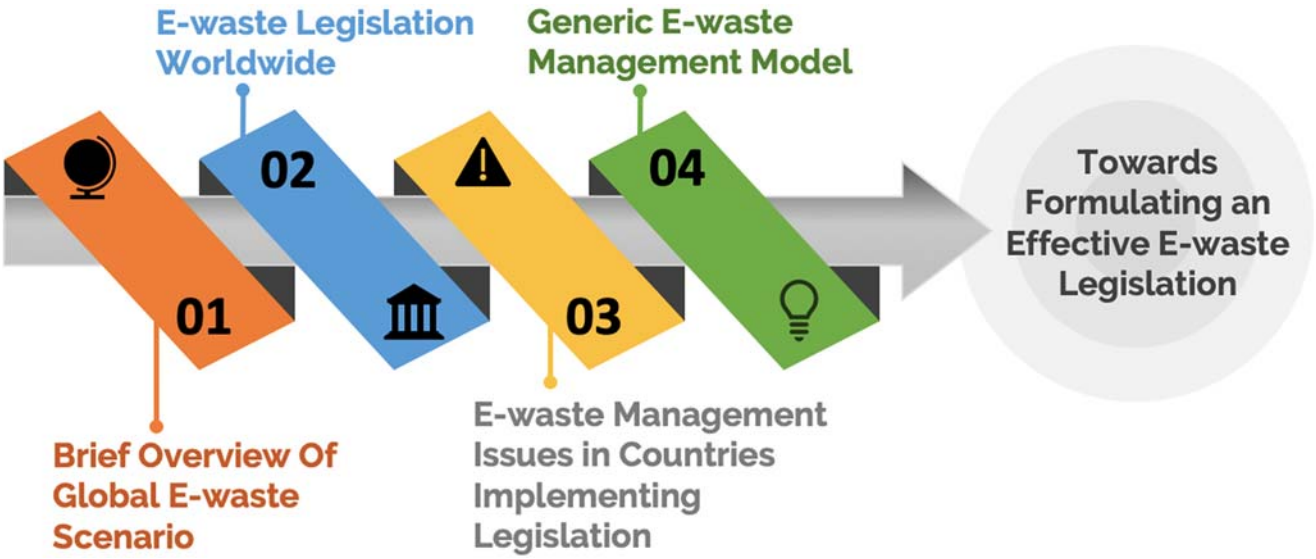

Fig. 1 Schematic illustration of the content of this article. First, a brief discussion on the current global e-waste scenario is presented, followed by details of the e-waste legislation implemented worldwide. Next, a discussion on the major e-waste management issues in countries with e-waste legislation is provided. Finally, a generic e-waste management model is proposed for formulating and implementing an effective e-waste legislation

The improper disposal of e-waste and crude processing methods for the extraction of precious metals have resulted in dangerous levels of environmental pollution (Robinson 2009; Wong et al. 2007; Song and Li 2014; Ha et al. 2009). Key environmental components such as soil, air, and water are being continuously contaminated with hazardous substances released from e-waste. Disposal of e-waste consisting of hazardous chemicals such as acids and heavy metals (for example, lead, mercury, cadmium, lithium, and beryllium) along with general waste in landfills results in leaching of hazardous substances into the soil, contaminating other biodegradable waste. This also affects the biome in the landfill vicinity resulting in toxic contamination of the food chain. In addition to this, residues resulting from open burning of e-waste and draining of toxic acids also degrade the soil fertility (Fu et al. 2008; Luo et al. 2011; Chakraborty et al. 2018; Ohajinwa et al. 2018).

The toxic chemicals and heavy metals leaching into the soil from landfills also contaminate the ground water table. Freshwater bodies such as lakes and rivers that serve as sources of water to the nearby towns are polluted with e-waste fragments and the residues of crude processing such as toxic ash, acids, hazardous chemicals, and heavy metals. Such polluted water is also used in agricultural activities, paving yet another way for the toxins to enter the food chain.

When e-waste fragments such as PCBs, cables, and wires containing polyvinyl chloride (PVC) are openly incinerated for extraction of valuable metals, the resulting smoke containing hazardous chemicals such as dioxins and acid fumes pollute the air. Combustion of e-waste also releases heavy metals like lead, cadmium, and mercury into the surroundings. The residual fly ash of burnt e-waste is also highly toxic and spreads in the air over the vicinity of burning sites (Leung et al. 2008).

The human health hazards caused by improper disposal and crude processing of e-waste are proven to be chronic and can be lethal. These health hazards are not only limited to the labors directly involved in scavenging and crude processing of e-waste (Caravanos et al. 2011) but also affect the human population coming in contact with the environment contaminated with e-waste and its toxic components (Huo et al. 2007; Zheng et al. 2008; Asante et al. 2012; Kim et al. 2018; Liu et al. 2018). Table 1 lists a few significant health hazards resulting from poor waste management of the most common toxins present in e-waste along with the specific disorders/diseases they cause.

E-waste legislation across the world

Policy design and implementation often constitutes a major portion of the strategic framework that aids a country in addressing its national issues. It ensures a systematic approach to address a problem both legally and uniformly throughout the country. As an important step towards sustainable e-waste management, around two-thirds of the world's population are covered under the e-waste legislation. Among the countries with e-waste legislation, the policies and regulations of the major players in e-waste generation and management such as the European Union (EU), the UK, the USA, Oceania (inclusive of Australia and New Zealand), and Asian countries (inclusive of China, India, Japan, South Korea, Taiwan, and Singapore) (Nnorom and Osibanjo 2008) are discussed in this section.

Table 1 Human health hazards caused by informal processing of e-waste

Element/chemical	Source	Human health hazards
Americium (radioactive) (N Kazzi et al. 2012)	Smoke alarms	Carcinogenic
Lead (Frazzoli et al. 2010)	Solder (printed circuit board), CRT monitor glass, lead-acid batteries	Causes impaired cognitive function, behavioral disturbances, attention deficits, hyperactivity, conduct problems, and lower IQ in children exposed to lead in developmental age
Mercury (Frazzoli et al. 2010)	Thermostats, fluorescent tubes, ccfl backlights in flatscreen monitors	Causes sensory impairment, dermatitis, memory loss, and muscle weakness. Exposure in utero causes fetal deficits in motor function, attention, and verbal domains.
Cadmium (Frazzoli et al. 2010)	Nickel-cadmium rechargeable batteries, photo resistors	The inhalation of cadmium can cause severe damage to the lungs and is also known to cause kidney damage. Cadmium is also associated with deficits in cognition, learning, behavior, and neuromotor skills in children.
Sulfur (Frazzoli et al. 2010)	Lead-acid batteries	Exposure results in liver damage, kidney damage, heart damage, eye and throat irritation.
Hexavalent chromium (Frazzoli et al. 2010)	Metal coatings to protect from corrosion	Carcinogen after occupational inhalation exposure, known to have cytotoxic and genotoxic effects.
Brominated flame retardants (BFRs) (Lyche et al. 2015)	Used as flame retardants in plastics in most electronics.	They affect the endocrine and reproductive system. Health effects include impaired development of the nervous system in children, thyroid problems, and liver problems.
Beryllium oxide (Wambach and Laul 2008)	Filler in some thermal interface materials such as thermal grease, used on heatsinks for CPUs and power transistors, magnetrons	Occupational exposures associated with lung cancer, other common adverse health effects are beryllium sensitization, chronic beryllium disease, and acute beryllium disease.
Polyvinyl chloride (PVC) (Man et al. 2013)	Insulation for electrical cables and commonly found in electronics	Occupational exposure to toxic byproducts is carcinogenic. Exposure and ingestion can result in reproductive and developmental health effects.

The Basel Convention

Awareness was created against the transboundary movement of hazardous waste due to incidents such as the Khian Sea waste disposal case (1986) at Haiti beach and the Koko case (1988) in Nigeria. Hazardous waste and ashes from developed countries were illegally shipped to developing countries in Asia and Africa. To address this issue, the United Nations (UN) brought together 186 countries, at the Basel Convention (held at Basel, Switzerland) to sign the treaty titled "Transboundary Movements of Hazardous Wastes and Their Disposal," in 1989 (Kummer 1999; Hackett 1989). The underlying objective of this treaty was environmental protection. This treaty banned the trade of hazardous waste from/to the member countries. Most of the members signed the treaty and enforced legislation, prohibiting the import and/or export of hazardous waste in their respective countries. The EU was a pioneer in implementing such legislation in their member nations. However, the USA has not ratified the treaty, even to date. After the Basel Ban, though the transboundary movement of hazardous waste has reduced, the treaty initiative has not been able to eliminate it completely. The illegal shipment of e-waste from developed to developing countries persists.

E-waste legislation in Europe

As soon as the Basel treaty came into existence, the EU Commission introduced the Waste Shipment Regulation (WSR) in 1993 (Jupille 1999; Pongrácz and Pohjola 2004). This prohibited the export of hazardous e-waste to the non-Organization for Economic Cooperation and Development (non-OECD) countries. Nearly a decade later, they introduced the Restriction of Hazardous Substances (RoHS) Directive 2012/95/EC. This directive emphasized changing the product design and packaging to reduce the use of hazardous substances and replacing them with environment-friendly materials. It also aimed to increase the recycling rate for the domestically generated Waste Electrical and Electronic Equipment (WEEE).

In 2012, the Commission of EU passed the WEEE Directive (2012/19/EU) in order to uniformly regulate e-waste management in its member nations. This directive is a comprehensive law for e-waste management which regulates the process of collection, recycling, and recovery of resources. This emphasizes that a systematic and separate collection of disposed EEE will enable higher recycling throughput, which in turn can yield a higher turnover of reusable e-waste fractions. The directive also enforces that processed e-waste must be accounted for and reported to the National Enforcement Authority. The WEEE Directive prescribes the member states

to encourage design and production of EEE that can be dismantled and recycled. To guarantee environmentally friendly processing, the WEEE Directive lays down treatment procedure requisites for specific materials and components of e-waste, and storage sites. The directive has also adopted the principle of Extended Producer Responsibility (EPR), in which the producers are entitled to take the responsibility of recycling their end-of-life products.

Every member state of the EU and other European countries such as the UK, Switzerland, and Norway has implemented national legislation to regulate e-waste management in accordance with their local ecosystems. The EU Commission is also helping and encouraging other European countries (outside of the EU) and Russia to implement a legal and institutional framework for e-waste management and addressing environmental concerns. The national policies for the EU and the UK are summarized in Table 2.

E-waste legislation in Asian countries

Asian continent represents a mix of countries at different stages of economic development. The economic condition of the countries influences their domestic e-waste production and management. For instance, China is the highest producer of e-waste in Asia and also a major destination for globally produced e-waste. Most of the Asian countries have been struggling with the illegal import of e-waste and informal e-waste processing for decades. Recently, many countries in Asia such as China, India, Japan, Korea, and Singapore have implemented e-waste legislation in order to regulate the e-waste management. EU Directives have been an inspiration to Asian countries in developing the framework for e-waste legislation (Terazono et al. 2006).

As a developing country, China was used as a dumping yard of used EEE and e-waste from developed countries such as the USA. Handling imported e-waste along with the growing domestic waste became a major concern. As the Basel Ban (on transboundary movement of hazardous materials and e-waste) and WSR in the EU came into existence, China imposed a ban on the e-waste imports. The Government of China then implemented laws to manage the domestically produced e-waste as listed in Table 3. These regulations also targeted reduction in the generation of WEEE and enabled recycling. The main objective of these laws was to check informal practices and standardize the e-waste recycling process through national and provincial management programs (Yu et al. 2010; Zhang et al. 2012). Recently, in 2012, like most European nations, China also adopted the EPR law to legally bind the manufactures in recycling the discarded equipment and using the recycled resources in their products.

Until 2011, there was no law in place specifically for e-waste management in India. Though there were many laws for environmental protection (as listed in Table 3) and management of hazardous waste, these laws fundamentally treated e-waste like any other solid waste. Consequently, there were no regulations in particular, for the processing of e-waste from collection to recycling. The e-waste legislation in 2011 implemented the EPR, mainly placing the responsibility of recycling e-waste on the manufacturers of EEE, an emulation of the European e-waste legislation.

E-waste legislation in Japan is constituted of two components: the first is the Law for the Promotion of Effective Utilization of Resources (LPUR) and the other is the Law

Table 2 National policies for e-waste management in the EU and the UK

Country	Policy year	Policy title	Objective
The European Union (EU)	1993 (amended in 2007) (Jupille 1999; Pongrácz and Pohjola 2004)	Waste Shipment Regulation (WSR)	Emphasizes that no EU member state is allowed to export e-waste classified as hazardous, to non-OECD countries.
	2002 (revised in 2006 and 2009) (European Parliament 2003; Cusack and Perrett 2006)	Restriction of Hazardous Substances (RoHS) Directive (2002/95/EC)	Restriction of the use of certain hazardous substances; changing product designs and increasing recycling rates of WEEE.
	2006 (European Parliament 2006)	The Battery Directive	Regulates the manufacture, disposal, and trade of batteries in the EU.
	2012 (Sthiannopkao and Wong 2013; Koh et al. 2012; European Parliament 2012)	WEEE Directive (2012/19/EU)	To regulate the collection, recycling, and recovery of e-waste in the member nations from disposal to reuse.
The United Kingdom (UK)	2003 (The National Archives 2003), 2007 (The National Archives 2007)	E-waste Packaging Directive: (i) The Packaging (Essential Requirements) Regulations 2003 and (ii) The Producer Responsibility Obligations (Packaging Waste) Regulations 2007	(i) Minimized packaging requirement, restriction of dangerous substances (such as heavy metals). (ii) Obligates reduction in packaging for all UK companies with > 2 million GBP turnover or with handling capacity of > 50 tons of packaging each year.

Table 3 National policies for e-waste management in China and India

Country	Policy year	Policy title	Objective
China	2000 (Chung and Zhang 2011; Hicks et al. 2005)	Ban on WEEE for managing waste import	Prohibits the import of second-hand electronic equipment and e-waste
	2006 (Chung and Zhang 2011)	The Law on the Prevention and Control of Environmental Pollution by Solid Waste (2004), Technical Policy on Control of WEEE	Aims to reduce the volume of e-waste, increase the reutilization rate for discarded EEE, and increase standards for e-waste recycling
	2007 (Chung and Zhang 2011)	The Cleaner Production Law (2002), The Ordinance on Management of Prevention and Control of Pollution from Electronic and Information Products	Reduction of use of hazardous and toxic substances in electronic appliances reducing the pollution generated in the manufacturing, recycling and disposal of these products
	2008 (Chung and Zhang 2011)	The Circular Economy Promotion law (2008), Administrative Rules on Prevention of pollution by WEEE	To prevent pollution caused by the storage, transport, disassembly, recycling, and disposal of e-waste
	2011 (Chung and Zhang 2011)	The Circular Economy Promotion law (2008), Collection and Treatment Decree on Waste Electrical and Electronic Equipment	Stipulates that e-waste should be collected through multiple channels and recycled by licensed recycling enterprises
	2012 (Chung and Zhang 2011)	Extended Producer Responsibility (EPR) system	Requires manufacturers to carry out environmentally safe management of their products after they are discarded
India	1986 (Ind 1986)	The Environmental Protection Act	Emphasizes on prevention, control, and abatement of environmental pollution
	2000 (Ind 2000)	The Ozone Depleting Substances (Regulation and Control) Rules	Regulates the export and import of EEE containing substances that can destroy ozone layer
	2008 (Ind 2008)	The Hazardous Wastes Management, Handling and Transboundary Movement Rules	Requires companies/individuals receiving, treating, transporting, or storing hazardous waste have to seek permission from the relevant State Pollution Control Board (SPCB) and bans the import of hazardous waste for disposal or dumping of e-waste
	2011 (Ind 2011; Bhaskar and Turaga 2018; Mehta 2018)	The E-Waste Management and Handling Rules	Regulates the e-waste management at every level of EEE life span from producers to recyclers

for the Recycling of Specified Kinds of Home Appliances (LRHA) (Table 4). The LPUR is similar to the EPR in promoting manufacturers to voluntarily be responsible for recycling of goods and reduction in waste generation. LRHA imposes stricter requirements on the recycling efforts of both the consumers and manufacturers of home appliances. Under this law, from October 2003 onwards, taxes were imposed on new computer purchases. Consumers desiring to recycle their older computers (purchased prior to October 2003) would pay a nominal fee to cover the recycling costs, thus requiring the equipment owners to be responsible for recycling their products.

The Ministry of Environment in Korea has introduced different systems like Waste Deposit-Refund System, the Eco-Assurance System (ECOAS), and EPR through its legislation (Table 4). In the Waste Deposit-Refund System, the consumer is required to pay a fee prior to recycling the waste, which is later refunded based on the value of extracted resources. The ECOAS restricts the use of hazardous substances in EEE and promotes recycling of e-waste inclusive of systemic management for life-cycle analysis of EEE. The EPR system imposes the producers to recycle the discarded products and report the statistics to the government.

Taiwan follows a simplistic approach through legislations towards e-waste management. A single law named "The Waste Disposal Act" governs the waste disposal and recycling procedures. This law has been amended periodically and has included the e-waste management within its scope in the recent years. The introduction of the "4-in-1 recycling program" under this act has been very successful and has won a lot of accolades from other governments. The 4-in-1 system involves the four main parties responsible for keeping the environment clean, namely the community residents, the recycling industry, the local government, and the newly established Recycling Fund (raised by collecting

Table 4 National policies for e-waste management in Japan, Korea, Taiwan, and Singapore

Country	Policy year	Policy title	Objective
Japan	2000 (Chung and Murakami-Suzuki 2008; Pariatamby and Victor 2013)	Law for the Promotion of Effective Utilization of Resources (LPUR)	Aims to establish a recycling-based economic system by reusing parts of collected products such as computers, strengthening collection methods, and introducing new measures to reduce wastes and extending product life span
	2001 (Chung and Murakami-Suzuki 2008; Pariatamby and Victor 2013)	Law for the Recycling of Specified Kinds of Home Appliances (LRHA)	Imposes obligations on home appliance manufacturers and retailers to ensure proper waste treatment and efficient use of resources
	2013 (JPN 2013; Balde et al. 2017)	Small Electrical and Electronic Equipment Recycling Act	Small electronic appliances such as mobile phones waste is managed under this law
Korea	1992 (Lee et al. 2007; Jang 2010; Park 2014)	Introduction of Waste Deposit-Refund System	A deposit is levied on products for their collection and recycling, and refunded based on the cost/number of products recycled (TV, washing machines)
	1993 (Park 2014; Xavier and Adenso-Díaz 2015)	Guideline for Improvement of Material/Structure of Products for Stimulating Recycling	Guideline on restriction of use of hazardous substances and recyclability rate
	2003 (Lee et al. 2007; Yoon and Jang 2006; Chung and Murakami-Suzuki 2008)	Extended Producer Responsibility (EPR) System	Producers should recycle e-waste for reuse and report the results to the government
	2007 (Jang and Kim 2010)	Resource Recycling of Waste Electrical and Electronic Equipment and Vehicles, Act	Aims to reduce the amount of WEEE going to landfills and incinerators, to achieve higher recycling amounts of all targeted products by adopting the EPR policy
Taiwan	1988 (amendment) (Lee et al. 2000)	Waste Disposal Act (WDA)	Manufacturers and importers bear financial responsibility for recycling by forming associations to fund recycling
	1997 (amendment) (Lee et al. 2000)	4-in-1 Recycling Program (Amended WDA)	Manufacturers and importers have to pay a recycling fee to the Environmental Protection Administration Taiwan (EPAT) and offer services for collection of waste including batteries, computers, electrical home appliances for recycling from the consumers.
	2001 (Tsai and Chou 2004)	Amendment to WDA	To clarify responsibilities of manufacturers, importers, and recyclers under the 4-in-1 program
Singapore	1999 (revised in 2003) (Bai and Sutanto 2002)	Environmental Protection and Management (Hazardous Substances) Act (EPMA)	Any person who wishes to import, sell or export, equipment or products containing any hazardous substance like lead, mercury, and cadmium, controlled under the EPMA must obtain a Hazardous Substances Licence.
	2016 (NVP 2018)	National Voluntary Partnership for E-Waste Recycling	Industry partners (Toshiba, HP, StarHub, Panasonic etc.) will continue to assume a leading role in spearheading recycling programs, with added support and recognition from NEA.

fees from the manufacturers and the retailers). With the aforementioned legislations in place (Table 4) and the efforts of an innovative entrepreneur community, Taiwan has set an example in efficient and safe recycling of e-waste.

Singapore serves as a strategic connecting point between the east and the west with significantly positioned harbors. Abiding by the Basel Ban, the government strictly regulated the shipment of hazardous waste through Singapore ports in the 1990s. The Environmental Management and Protection Act was implemented to regulate the disposal of hazardous waste (Table 4). The National Environmental Agency (NEA) has been monitoring and regulating waste management island-wide. In the past couple of years, Singapore's Ministry of the Environment and Water Resources has taken up initiatives to introduce a separate legislation for e-waste management that includes the EPR principle. In the interim, the NEA has set up the National Voluntary Partnership Program for e-waste recycling under which the volunteer partners in the form of organizations, producers, and retailers are creating awareness among the public and collect e-waste for recycling through the e-waste recyclers.

E-waste legislation in Americas

The Americas (inclusive of both the north and south continents) has been a producer of a huge amount of e-waste for decades. Especially, the higher-income regions, namely, the USA and Canada, are the highest producers of e-waste in the Americas, followed by Brazil and Mexico. Even with such a scenario, the USA has not ratified the Basel Ban and has no federal laws governing e-waste management until date (Kahhat et al. 2008). Some of the states have implemented e-waste laws in their territory, but lack uniformity. A few states have producer-take-back rules and landfill bans. This scenario has led to export of most of the e-waste generated to countries such as Mexico, China, and Africa (Kahhat and Williams 2012; Balde et al. 2017) where they are processed informally, polluting the environment. To tackle this problem, the US states do not have the jurisdiction over foreign trade zone to prevent export (Bader 1982; Sthiannopkao and Wong 2013). Therefore, without federal US legislation, e-waste export is considered legal and more the reason for the lawmakers to enframe and implement a federal legislation for e-waste management. However, the USA has exercised some generic measures for managing domestic e-waste through the Resource Conservation and Recovery Act (RCRA), regulations for recycling Cathode Ray Tubes (CRTs), and the National Strategy for Electronics Stewardship framework. The Environmental Protection Agency, USA, has undertaken a Sustainable Materials Management (SMM) Electronics Challenge initiative in partnership with Original Equipment Manufacturers (OEMs) and retailers, to take back used electronics and recycle it through certified recyclers (Kang and Schoenung 2005).

Canada accompanies the USA in lacking national legislation for e-waste management. However, most of the Canadian states have their own local e-waste regulations. Some of the e-waste mass is being recycled with the help of several organizations in a few Canadian provinces. Even major parts of Latin America are not covered under national policies for e-waste recycling. The only countries in Latin America with legislation for e-waste management are Bolivia, Chile, Colombia, Costa Rica, Ecuador, Mexico, and Peru. This development has taken place over the past decade and all the aforementioned countries have implemented the EPR principle. Some of the Latin American countries are also in the process of introducing their own legislation for e-waste management (Balde et al. 2017).

Lack of strict national policies in the Americas has led to the handling of e-waste recycling by the informal sector and private companies that recycle only profitable e-waste matter. The absence of regulations for e-waste recycling has resulted in environmental pollution at an alarming rate and illegal shipping of used EEE to developing countries from the USA.

E-waste legislation in Oceania

Oceania comprises of Australia, New Zealand, and the Pacific Island sub-region. Analogous to the Asian countries, these countries also have realized the importance of proper legislation in governing the e-waste management (Table 5). However, Australia is the only country in this region that has implemented a law specific to e-waste management. The Product Stewardship Act (2011) introduced in Australia specifically to recycle televisions and computers (Dias et al. 2018) has been a model for other countries in this region for enforcing the producer responsibilities in e-waste management. New Zealand and many other Pacific Island countries are following Australia in introducing product stewardship framework. Many of the island nations in this region have generic laws governing the general environmental protection through regulations on waste management (inclusive of e-waste). Some of the smaller countries in the Pacific region are collaborating with the EU to manage the hazardous waste (Balde et al. 2017).

E-waste legislation in Africa

Most of the African countries are economically under-developed and almost all the EEE (used and new) is imported from developed countries in the Americas, Europe, and China. With this, a huge amount of e-waste from different parts of the world are illegally shipped to many African countries where they are recycled using crude informal processes (Grant and Oteng-Ababio 2012) due to the absence of legislation for e-waste recycling. However, in the recent years, most of the African countries are concerned about the hazards of crude processing of e-waste (Schmidt 2006). They have realized the need for legislation and stricter regulations to control the illegal informal treatment of e-waste and making efforts to draft them. So far, only a few countries such as Kenya, Ghana, Madagascar, and Nigeria have introduced e-waste regulations. These regulations include a ban on e-waste import from other countries and the EPR principle. Many organizations are also liaising with the local authorities to control e-waste pollution (Balde et al. 2017).

South Africa is a developed country compared with other parts of Africa and has a different legislation in place for environmental protection, consumer protection, labor safety, and waste management which partially regulate e-waste issues. However, there is no legislation implemented specifically for e-waste management. The Government of South Africa and organizations such as the South African Waste Electrical and Electronic Enterprise Development Association (SAWEEDA) are currently in the process of framing a legislation for e-waste management (SAWEEDA 2018). There has been significant research and planning done in this regard and a legislation that includes regulations for e-waste disposal and processing, and EPR principle is expected to be implemented soon.

Table 5 National policies for e-waste management in Oceania

Country	Policy year	Policy title	Objective
Australia	2009 (Dias et al. 2018)	National Waste Policy	Reduce the amount of waste (including hazardous waste) for disposal, manage waste as a resource, ensure that waste treatment, disposal, recovery and reuse are undertaken in a safe, scientific, and environmentally sound manner, and contribute to the reduction in greenhouse gas emissions, energy conservation and production, water efficiency, and the productivity of the land
	2011 (Dias et al. 2018)	Product Stewardship Act	The framework includes voluntary, co-regulatory, and mandatory product stewardship to effectively manage the environmental, health, and safety impacts of products, and in particular those impacts associated with the disposal of products. National Computer and Television Recycling Scheme (NCTRS) is also reviewed under this law.
New Zealand	1991 (New Zealand Legislation 1991; MacGibbon, John and Zwimpfer 2006)	Resource Management Act	Local and regional authorities are responsible for managing resources and avoiding/mitigating adverse effects on the environment; mainly the landfilling of waste
	2002 (New Zealand Legislation 2002; MacGibbon and Zwimpfer 2006)	Local Government Act	Local authorities are required to write a waste management plan and establish bylaws in relation to the collection, transportation and disposal of waste

Extended producer responsibility and its implementation

As EPR is implemented as a primary component of e-waste legislation across the world, we provide a brief discussion prior to moving on to e-waste management issues. The OECD defines EPR as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle (OECD 2016). In practice, EPR requires producers to take responsibility for collecting end-of-life products for sorting and recycling. EPR schemes allow producers to take up either the financial responsibility required and/or to take over the operational and organizational aspects of the collection/recycling process. Producers can do so individually or collectively by assigning a third-party organization called the producer responsibility organization (PRO) for facilitating producers to collectively manage the take-back and most often arrange for the treatment of products (OECD 2016).

Four broad categories of EPR instruments are defined by OECD and are listed below (OECD 2016).

1. *Product take-back*: This tool puts the responsibility on producers or retailers for the end-of-life management of products. This is often implemented by establishing collection and recycling targets for a product or material. The take-back may be either a mandatory or voluntary action by the producers. The producers can also achieve their targets by giving incentives to consumers for returning the used product to a recognized retailer.
2. *Economic and market-based instruments* provide a financial incentive to implement EPR policy. They come in the following four forms:

- *Deposit-refund*: The consumer has to make an initial payment (deposit) at purchase which is partially or completely refunded when the product is returned to the producer/retailer at a specified location.
- *Advanced disposal fees* (*ADF*): A fee is charged to the consumer on certain products at purchase based on the estimated costs of collection and treatment. The fee is collected by either public or private entities and used to finance the post-consumer treatment of the designated products. Unused fees may be returned to consumers.
- *Material tax*: This is a tax levied on producers for using virgin materials, or materials that are difficult to recycle, or toxic materials, to create incentives for using secondary (recycled) or less toxic materials. Ideally, the tax is set at a level where it meets the treatment costs. The tax is used for the collection, sorting, and treatment of post-consumer products.
- *Upstream combination tax/subsidy* (*UCTS*): This is a tax imposed on producers which is subsequently used to subsidize waste treatment. It also provides the producers with subsidies to alter their product design and materials and a financing scheme that can support recycling and treatment.

3. *Regulations and performance standards* enforced on producers such as the use of a minimum quantity of recycled materials can encourage the take-back and recycling of end-of-life products. When used in combination with a tax, such standards can strengthen incentives for the redesign of products. The performance standards can be mandatory or voluntarily adopted by the industries themselves.
4. *Information-based instruments* are designed to indirectly support EPR programs by creating public awareness. Measures can include labeling of products and components, communicating to consumers about producer responsibility and waste separation, and informing recyclers about the materials used in products.

These EPR instruments have been implemented in a heterogeneous manner across the EU. Though the EU member countries follow the EU WEEE Directive, they differ in framing the laws and implementing them as per their country's requirements. While EU directives provide the enabling framework, national legislation by the member states specifies the operational aspects of EPR systems. However, all the EU members and other non-EU members have implemented take-back EPR systems for e-waste management (OECD 2016).

China put into effect an EPR for e-waste in 2012. It consists of general rules, tax administration, subsidy utilization, supervision, legal liability, and supplemental rules (Cao et al. 2016). It is applied to domestic EEE producers who are taxed by the State Administration of Taxation (SAT) of China and EEE importers who are taxed by the customs. These taxes are mainly used as subsidies for e-waste recycling and fees for management information systems (MIS) construction. The subsidies also encourage formal recycling enterprises to purchase e-waste from private traders as most of the e-waste are bought and disposed of by informal enterprises (Cao et al. 2016).

India included EPR in its e-waste legislation in 2011. The take-back system of the 2011 rules requires producers to set up collection centers, either individually or collectively for formal recycling and safe disposal. The producers, dismantlers, and recyclers are all mandated to register with the state pollution control boards (SPCBs) as authorized operators. The 2011 rules were amended and brought into effect since October 2016. The new rules, in addition to mandatory take-back requirements, specify collection targets as a percentage of sales of electronic equipment, with the targets becoming stricter over time. The rules also require the producers to set up a deposit-refund system (Turaga and Bhaskar 2017).

Japan's Home Appliance Recycling Law (HARL) specifies the roles of various stakeholders in its EPR regulation. The retailers are responsible for the collection, the producers are responsible for recycling the collected waste, and consumers pay a fee to partially cover the costs of recycling and transportation (Ogushi and Kandlikar 2007).

The EPR system in South Korea imposes a mandatory take-back, with the flexibility to choose either individual collection or PRO, with clear targets on recycling rates for regulated industries. Violation of the recycling rate targets can cost penalties up to 130% of standard recycling costs. The consumer is also obligated to pay a volume-based fee at the time of e-waste disposal (Manomaivibool and Hong 2014).

In North America, EPR programs in the USA and Canada are primarily enframed and implemented at the state or provincial level. The mandatory EPR in a few states (such as California, New York, and Vermont) is not quite robust as it is implemented only on a few specific products such as batteries, mercury thermostats, and switches. In others, the EPR is mostly voluntary or absent (OECD 2016). Such non-uniform policies across the country will lead to multiple issues in e-waste management. Hence, there is a need for a comprehensive mandatory EPR imposition by the federal government to complement the state or provincial laws. In Latin America and the Caribbean (LAC), countries such as Chile, Mexico, Brazil, Argentina, and Colombia have taken steps towards implementing EPR for some e-waste categories (OECD 2016).

E-waste management issues in countries with e-waste legislation

The effectiveness of any legislation depends on both its framework and enforcement. Any shortcomings in the development of a scientific and holistic framework and/or strict, well-coordinated enforcement lead to multiple issues in management. In the case of e-waste legislation, most countries do not cover the full-scope of e-waste management and its implementation suffers due to the absence of a strong law enforcement network. Even though ~66% of the world's population come under e-waste legislation, only ~20% of the total e-waste generated is recycled (UNE 2019; WEF 2019). A large portion of the total e-waste generated globally is unaccounted as a result of inefficient management. The major issues causing such inefficient e-waste management in different countries implementing e-waste legislation have been listed in Table 6. Consolidation of these issues provides a holistic perspective of different areas in which the legislative framework and enforcement need amendments. Further, these issues have been categorized into six broad types. Color codes have been provided for identification purpose to each of the types and are employed in the study of a generic e-waste management model in the next section.

The most common issues in e-waste legislative framework range from the incomplete listing of e-waste items to exclusion of major stakeholders in e-waste management. On the other hand, law enforcement issues range from improper inspections and assessments of e-waste processing to illegal

Table 6 Major e-waste issues of countries governed by e-waste management legislations

Country	E-waste issues
Europe[1] (Mohanty et al. 2015)	– Incompleteness of existing guidelines – Increasing number of illegal exports to less-developed nations, particularly in Asia and Africa due to lenient law enforcement and too low penalties. Limited personnel and financial capacity appear to be a general problem preventing better export controls. – Limited assessment of the effectiveness of the law implemented due to the lack of systematic reporting and gaps in the information exchange due to insufficient coordination and cooperation within the local law enforcement network (customs authorities and police). – Lack of inspection (of e-waste collection points, interim storage, recovery, and disposal operators) and risk assessment.
China (Lu et al. 2015)	– Current e-waste legal framework is fragmented and each regulation addresses a specific aspect of e-waste management. Many of the existing regulations were not developed through a systematic, experimental, and participatory approach, and they have therefore been found to be inadequate in several aspects. – Illegal import of e-waste and used electronics from developed countries. – China has the largest informal e-waste processing sector. However, there is no regulation to control the informal e-waste collection and treatment. – Enforcement of environmental protection regulations is weak and the environmental agency lacks the support of the private sector industries in the adoption of pollution prevention measures. – The formal e-waste processing sector struggles to collect adequate domestic e-waste in contrast with peddlers (collectors) from informal processing sector as there is no legal binding on the consumers for the proper disposal of e-waste. – The formal e-waste processing sector also suffers due to the lack of state-of-the-art equipment and technology and trained workforce for e-waste treatment as a result of inadequate financial resources and government support. – There is no assessment of environmental and human health risks caused due to the informal processing of e-waste.
India (Yadav and Bandyopadhayay 2015; Kumar and Karishma 2016)	– Illegal import of e-waste and used electronics from developed countries. – Prevalent crude processing of e-waste and using child labor for it. – Lack of public awareness or incentive schemes from governing bodies to regulate e-waste disposal leading to improper disposal of e-waste and landfilling. – The legislature does not have any non-compliance penalty for e-waste related offenses such as illegal e-waste trade and crude processing. – Lack of infrastructure and finances to set up proper e-waste processing. There is no collection or take-back mechanism in place and the present recycling facilities cannot handle the huge amount of e-waste generated.
Japan (Chung and Murakami-Suzuki 2008)	– Enforcement of financial obligation on consumers burdening them for e-waste recycling and minimal producer obligation to take back their products for recycling have led to a higher rate of illegal e-waste dumping. – There is an increase in illegal exports of e-waste and misconducts by retailers even after collecting the recycling fee from consumers to circumvent the financial liability.
South Korea (Chung and Murakami-Suzuki 2008)	– Environmental friendly treatment of hazardous substances is not mandatory in the producer responsibility system. – E-waste (mobile phones, CRTs, TVs) is illegally exported to East Asian developing countries.
Taiwan (Chung and Murakami-Suzuki 2008)	– No specific and holistic legislation for e-waste recycling. – Informal collectors have to be identified and registered for increasing the collection rate for formal recycling and reducing the negative competition between the registered and unregistered recyclers. – Environmental and safety standards for recycling should be raised.
Australia (Morris and Metternicht 2016)	– Illegal export of e-waste to Asian developing countries (Thailand, China). – E-waste categorized for recycling is limited to televisions and computers. – Lack of clarity on the roles of stakeholders (especially the local government) in e-waste recycling under the existing legislation – Inconvenient collection points for consumers and inconsistent collection services. – Low recycling targets and landfilling of e-waste. – Lacks auditing, reporting, and compliance measures in all stages of National Television and Computer Recycling Scheme (NTCRS).

[1] EU and non-EU countries such as the UK, Norway, and Switzerland

import/export of e-waste. In developing countries, the e-waste management suffers due to a lack of well-developed infrastructure, resulting from low budget allocation and insufficient planning. The seriousness of the e-waste problem further escalates with rampant crude processing. These major issues collectively contribute to the current low recycling rate, consequently causing loss of valuable materials. These major issues in e-waste management can be addressed through adequate amendments to legislation and implementation process for achieving a higher recycling rate.

In the case of European countries, each country has a different listing and categorization of WEEE for recycling. Some equipment listed by one country are excluded from another country's listing. This non-uniformity is misused for illicit trade. In addition to this, the guidelines provided to the local law enforcement authorities are not comprehensive and clear. For instance, there is no specific guideline on how to distinguish between WEEE and used EEE being transported (Mohanty et al. 2015). In some countries such as Germany, Greece, Italy, and Spain, there are no guidelines for the law enforcement agencies on inspection strategies. In addition to the shortcomings in the legal framework, strict implementation of the law has become difficult due to several practical difficulties such as an insufficient number of inspectors at the ports, lack of targeted training for waste monitoring and management authorities, shortage of technical equipment, and insufficient coordination and cooperation across competent authorities. With all these issues, when perpetrators of illegal e-waste trading activities are apprehended and convicted, the penalty can be low although the offense is serious and criminal.

In the case of Asia, most of the developing countries are confronting the issue of illegal import of e-waste. With this, they are also challenged with a lack of infrastructure and finances for formal e-waste recycling. China is the largest importer of e-waste from developed countries in Europe and the Americas and houses a rampant and deep-rooted crude e-waste processing industry. With this scenario, the e-waste legislation is fragmented and does not include all the stakeholders (Lu et al. 2015). Moreover, the enforcement of environmental protection law is weak. Neither is there an assessment of environmental and human health risk caused by the crude processing of e-waste nor inspections of formal e-waste collection, storage, and processing units. In India, the scenario is similar to China, except that the e-waste legislation framed is comparatively more comprehensive. However, there are other serious problems such as employing under-age labor for e-waste crude processing, lack of public awareness, and infrastructure for proper e-waste disposal (Yadav and Bandyopadhayay 2015; Kumar and Karishma 2016).

The e-waste management in Japan, South Korea, and Taiwan is comparatively well organized than that in China and India. They are equipped with state-of-the-art formal recycling facilities and stricter in e-waste collection processes. However, these countries are also dealing with issues arising due to their policies. Japan has illegal dumping and export issues as the financial obligation for recycling e-waste is on the consumers (Chung and Murakami-Suzuki 2008). In South Korea, there have been incidences of illegal exports of used/scrape phones and display equipment to the neighboring countries. But the more pressing issue is that the producers are not bound by law to follow an environmentally friendly treatment of hazardous substances (Chung and Murakami-Suzuki 2008). On the other hand, Taiwan is facing e-waste collection issues and lower standards set for safety and environmental protection as they consider e-waste along with the general waste under one single legislation (Chung and Murakami-Suzuki 2008).

The lack of holistic e-waste legislation in Australia has led to numerous issues in e-waste management. Since the recycling program is focused only on recycling televisions and computers, other categories of e-waste are either being landfilled or illegally exported to developing Asian countries. As there are no guidelines for the local authorities, collection, reporting, auditing, and compliance with the existing waste management rules have become major issues.

Generic e-waste management model

There is no standard model with fixed regulations to manage the e-waste for both developed and developing countries as each country's scenario differs from others. However, it is necessary to implement a holistic e-waste legislation and make amendments regularly to address the shortcomings learned from systematic regular assessments. The foremost rule in any e-waste policy has to be a strict ban on the import/export of e-waste and heavy penalty on illegal shipments. The ban on any transboundary movement of e-waste allows focusing on effective domestic e-waste management. In this article, we propose a closed-loop model as shown in Fig. 2 that includes all the isolated stakeholders of the e-waste management, namely, the government bodies and law enforcement network, producers and consumers responsible for the e-waste generation, the formal e-waste recycling industry, and the informal waste processing sector. Table 7 describes each block in the schematic and the role of each stakeholder in effective e-waste management. Such a system that strategically connects all the stakeholders requires cooperation and coordination at all levels ranging from the government, manufacturing industries, and the recycling sector to consumers.

To effectively manage domestic e-waste, the legislation should encourage both reducing and recycling the generated e-waste. Reduction in the amount of e-waste generated is possible when "repair and reuse" principle is embraced. This can be enforced though the legislation as guidelines

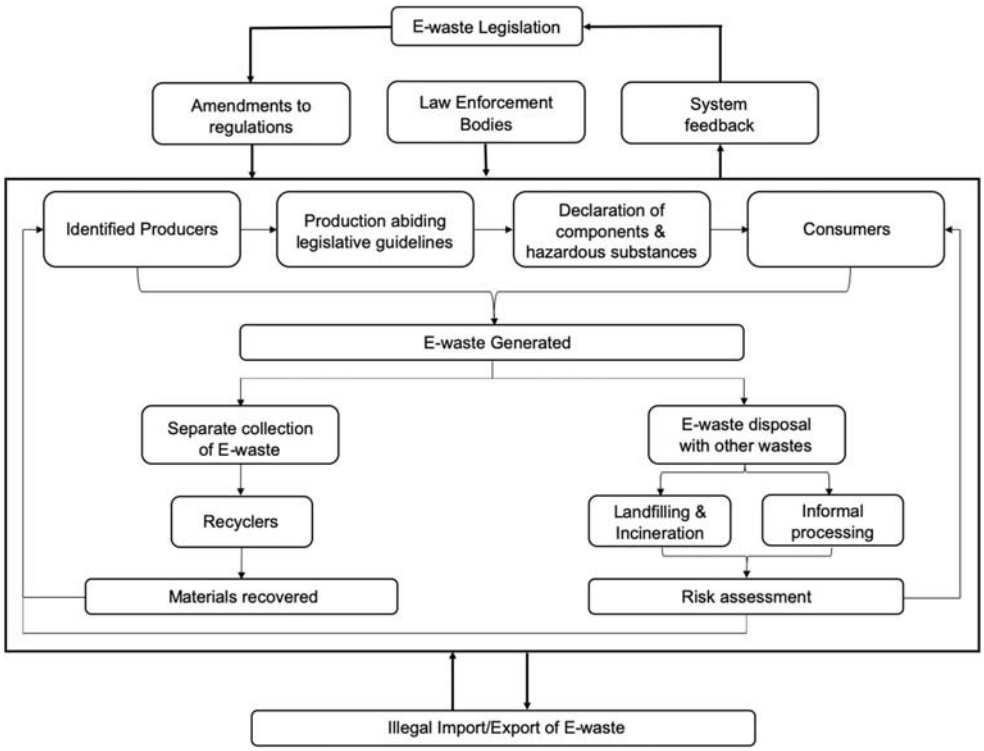

Fig. 2 Schematic diagram of the generic e-waste management model for implementing an effective e-waste legislation

for producers to design and manufacture products that can be refurbished. Government should also encourage consumers with incentives such as lower tax rates to buy refurbished models. The guidelines to producers must include a restriction on the usage of hazardous substances and virgin raw materials to encourage resource reuse. Most importantly, producers should be bound by law (instead of a voluntary choice) to follow the EPR principle which compels them to take back their products for recycling. With each purchase of EEE, the consumer has to sign an agreement by law to give back the product(s) after life to the producer for recycling. The formal recycling industry should be regulated through the legislation for implementing labor safety, processing standards, and environmental protection. The recycling industry must also be obligated to provide the recycling turnover (e-waste input > recovered reusable raw material) details.

This model aims to gradually abolish the informal e-waste processing through amendments based on regular feedback. The system feedback is completely based on the performance statistics of the formal recycling industry, and the environmental and human health hazards caused due to informal practices. The environmental risk assessment should include the analysis of air, water, and soil in the vicinity of e-waste crude processing facilities and landfills for contaminants such as heavy metals, hazardous chemicals (such as dioxins, furans in air, leachate in soil), acids, and chemical reagents used and disposed of after processing. The human health assessment should include a periodic complete medical evaluation of the workers (scavengers to handlers involved in the formal and informal e-waste processing industry) for occupational hazards and the general health assessment of the people residing in the vicinity of the processing sites. The risk assessment will be thorough with an estimate of the raw material wastage due to landfilling and informal processing of e-waste. These risk assessment statistics are provided to both producers and consumers to make them aware of their responsibilities in reducing the informal practices. This also gives a better perspective to frame guidelines for an effective implementation of EPR principle and the requisite infrastructure.

Implementation of the generic e-waste management model

To demonstrate the implementation of the proposed model, we have considered all the countries with e-waste legislation issues. By doing so, we get to discuss and address a variety of issues prevalent in the developed counties of Europe and Australia as well as the numerous problems of e-waste management in developing economies such as China, India, and other Southeast Asian countries. Although both cases contrast each other in e-waste management issues, our model provides clarity in understanding the e-waste legislation–related issues

Table 7 Description of e-waste legislation assessment and implementation strategy shown in Fig. 2

Box	Description
E-waste legislation	Holistic e-waste legislation should include a complete ban on e-waste import/export and crude processing, enforce EPR principle compulsorily, and encourage formal recycling industry and consumers for their responsible actions.
System feedback	A dynamically changing system such as the e-waste management needs regular feedback regarding the performance of the system, and challenges encountered based on systematic assessment.
Amendments to regulations	Regular amendments to the regulations depending on the feedback are essential to achieve effective implementation of legislation.
Law enforcement bodies	Local government, police, customs that prevent illegal activities, and a special government office that involves in the auditing and risk assessment of domestic e-waste management system.
Identified producers	All the major and small-scale producers of EEE have to be identified and registered under a governing body for assessment and accountability.
Production abiding legislative guidelines	All identified producers have to follow the guidelines provided for the design and production of EEE.
Declaration of components and hazardous substances	Producers should declare all the material components and hazardous substances used in manufacturing the EEE.
Consumers	Consumers need awareness regarding the environmental and health hazards caused by poor e-waste management and should responsibly dispose of the e-waste.
E-waste generated	E-waste constitutes both EEE production waste and after-life waste.
Separate collection of e-waste	Proper disposal and separate collection of e-waste is the key to achieving a better recycling rate.
Recyclers	All the component materials from most to least valuable have to be extracted by following formal and safe methods.
Materials recovered	The raw materials recovered in the recycling process supplied back to the producers. This reduces the stress on the supply chain of virgin raw materials.
E-waste disposal with other wastes	A major portion of e-waste generated is disposed of with general solid wastes making it difficult for recycling. This improper disposal is due to the lack of consumer awareness, producer responsibility, and infrastructure for separate collection.
Landfilling and incineration	Landfilling of e-waste with other biodegradable wastes cause environmental pollution due to leaching of hazardous substances into the soil and water bodies in the vicinity of the landfill, eventually affecting human health. Incineration of e-waste leads to the release of toxic chemicals such as dioxides into the atmosphere.
Informal processing	Crude processing of e-waste involves open burning, acid leaching processes for the extraction of precious metals. This results in environmental pollution, contaminating air, water bodies, and soil in the vicinity of processing. It is also highly dangerous for the health of the laborers involved in crude processing and people living in the vicinity.
Risk assessment	There is a need for the estimation of the quantity of each raw material wasted and the serious environmental and health hazards caused by e-waste improper disposal and crude processing. This gives a clear perception of the situation for creating consumer awareness and indicates the compelling need for making necessary changes to the system through legislation and governance.
Illegal import/export of e-waste	It needs to be stopped through vigilance and penalization. This will lead to proper accountability of the domestic e-waste management.

and helps find solutions in each case. The color coding is differentiated based on the e-waste issue category as listed in Table 8. This provides a holistic view of different e-waste management issues and the stakeholders responsible for each of them. Figure 3 a–g show the different issues in Europe, China, India, Japan, South Korea, Taiwan, and Australia respectively mapped (with color-coded dots) to the responsible boxes in the proposed e-waste management model.

The major e-waste management issues in European countries are due to weak law enforcement as the e-waste legislation is quite comprehensive (includes various aspects of e-waste management). A lack of strict law enforcement decreases the effectiveness of the implemented law. This is evident from Fig. 3a as most of the issues in the system are related to law enforcement. The blue dots related to the e-waste legislation signify the incomplete legislative framework such as a partially inclusive list of e-waste types for recycling. This can be identified from system feedback and necessary periodic amendments to the legislation can solve the issue. The red dot shows the presence of illegal export of e-waste to developing countries of Asia and Africa. This is an outcome of weak law enforcement (by the customs) at the ports and the coastline. This can be solved by strengthening the law enforcement bodies at the ports and establishing a proper communication network between different departments. The major drawback in the system is the inefficiency of the government body overseeing the

Table 8 Major categories of global e-waste management issues and the boxes (Fig. 2) that have to be addressed to solve the issues

E-waste Issue Categories	**Boxes** (from Fig. 2)	Color code
1. Non-comprehensive recycling laws (don't cover the full scope of e-waste management)	E-waste Legislation, System feedback, Amendments to regulations	
2. Poor services and public engagement for environmentally sound e-waste management	Identified Producers, Consumers, Separate collection of E-waste	
3. Outdated recycling technology and lack of finances leading to low recovery of materials	Recyclers, Identified Producers	
4. Weak auditing, assessment and compliance measures for implementation of legislation	Law Enforcement Bodies	
5. Prevalent informal e-waste management system including landfilling/incineration and crude extraction of materials	Consumers, E-waste disposal with other wastes, Risk assessment	
6. Illegal import/export of e-waste	Law Enforcement Bodies	

e-waste management. This has resulted in a poor risk assessment of informal practices in e-waste processing and insufficient inspections of formal e-waste processing facilities. These issues can be overcome by deploying more personnel for frequent inspections and assessments with detailed documentation of each aspect of e-waste management.

China serves as a perfect example for a country with myriad categories of e-waste management issues in the presence of an e-waste-specific legislation. This status quo is a consequence of non-comprehensive e-waste legislation and weak law enforcement. This is evident from Fig. 3b where both e-waste legislation and law enforcement boxes are marked with multiple dots. The legislative framework does not encompass all the stakeholders and comprises a collection of rules and guidelines which are not developed in a systematic and investigatory manner (Ye et al. 2009). To add to this, the law enforcement bodies are weak and do not compel the stakeholders to be accountable to their responsibilities. The shortcomings of the legislative framework known from the system feedback are marked in blue. Regular amendments to the legislation to address the issues and to bring all the stakeholders under single governance should be of paramount importance to China. Rampant illegal import of e-waste from developed countries as a result of poor vigilance at the borders by law enforcement bodies is marked in red. The deep-rooted informal e-waste processing sector is not bound by law and is marked in gray. Consumers too are used to selling the e-waste to collectors belonging to the informal processing sector as there are no legal restrictions and it is more profitable than handing the e-waste to the formal recyclers. The environmental and human health consequences of the informal processes are also being neglected. These complex problems due to e-waste crude processing should be addressed through legislative amendments. The formal e-waste recycling sector has less recognition and suffers due to the absence of legal binding for mandatory separate e-waste collection (highlighted in orange). The formal sector also lacks the latest equipment to handle the e-waste throughput. Consumers are not being engaged and educated regarding their activities in e-waste management. This is marked in purple and needs immediate attention to reduce informal practices. Environmental risk assessment of informal practices which is a responsibility of the governing bodies is lacking too (highlighted in light green).

India has implemented a quite comprehensive (inclusive of all stakeholders) legal framework for e-waste management but fails to enforce the same effectively (Yadav and Bandyopadhayay 2015; Kumar and Karishma 2016). This is majorly due to weak law enforcement and a lack of consumer awareness which is evident from Fig. 3c. The significant weakness in the legal framework is the omission of penalization aspects in case of non-compliance acts. This is one of the reasons for the prevalent illegal crude processing and illegal imports (red dot). The lack of formal e-waste collection systems and consumer awareness has resulted in landfilling and crude processing (gray and purple dots). Though the EPR take-back instrument is included in the law, it is poorly

practiced. As a developing country, the Indian formal e-waste recycling industry suffers due to a lack of finances (indicated in orange) to develop the required infrastructure.

Japan's e-waste management system has two major problems—illegal exports and landfilling (Chung and Murakami-Suzuki 2008), shown in Fig. 3d. These issues have originated as a result of their policy which imposes financial and physical responsibilities on consumers and retailers/producers. The consumers are obligated to pay a partial/complete recycling fee which has resulted in landfilling issues to mostly avoid the fee payment (gray dots). On the other hand, retailers/producers who are responsible for the recycling of collected e-waste sometimes indulge in illegal exports to cut the recycling costs (red dot). Hence, Japan needs stricter law enforcement and penalization in case of non-compliance.

The South Korean EPR law (using take-back instrument) is not comprehensive and does not include all the stakeholders and their responsibilities (Chung and Murakami-Suzuki 2008). It does not obligate the producers/recyclers for environmentally friendly treatment of hazardous substances and e-waste as shown in Fig. 3e (purple dot). This leads to informal disposal and treatment of hazardous e-waste to achieve cost-cutting. Since there is no strict ban on e-waste import/export, the law enforcement authorities (customs) are not able to control exports of used and end-of-life EEE to neighboring low-income countries (red dot). These issues can be addressed by modifying the law from EPR to an all-inclusive one.

Taiwan does not have a separate e-waste management law (Chung and Murakami-Suzuki 2008). Since e-waste is considered under the general waste management law, it becomes difficult to regulate recyclers to follow standard procedures. Also, there are issues in the collection process as the law does not compel the consumers to dispose of their e-waste only through registered collectors. These issues are depicted in Fig. 3f. The only solution is to enframe comprehensive e-waste legislation.

Australia is an example of a country with non-comprehensive e-waste legislation with multiple issues such as lack of clarity on the roles of stakeholders. This is evident from Fig. 3g. The NTCRS is very limited and covers only televisions and computers (blue dot) (Morris and Metternicht 2016). This has resulted in illegal exports of other categories of e-waste to low-income Asian countries (red dot). This has

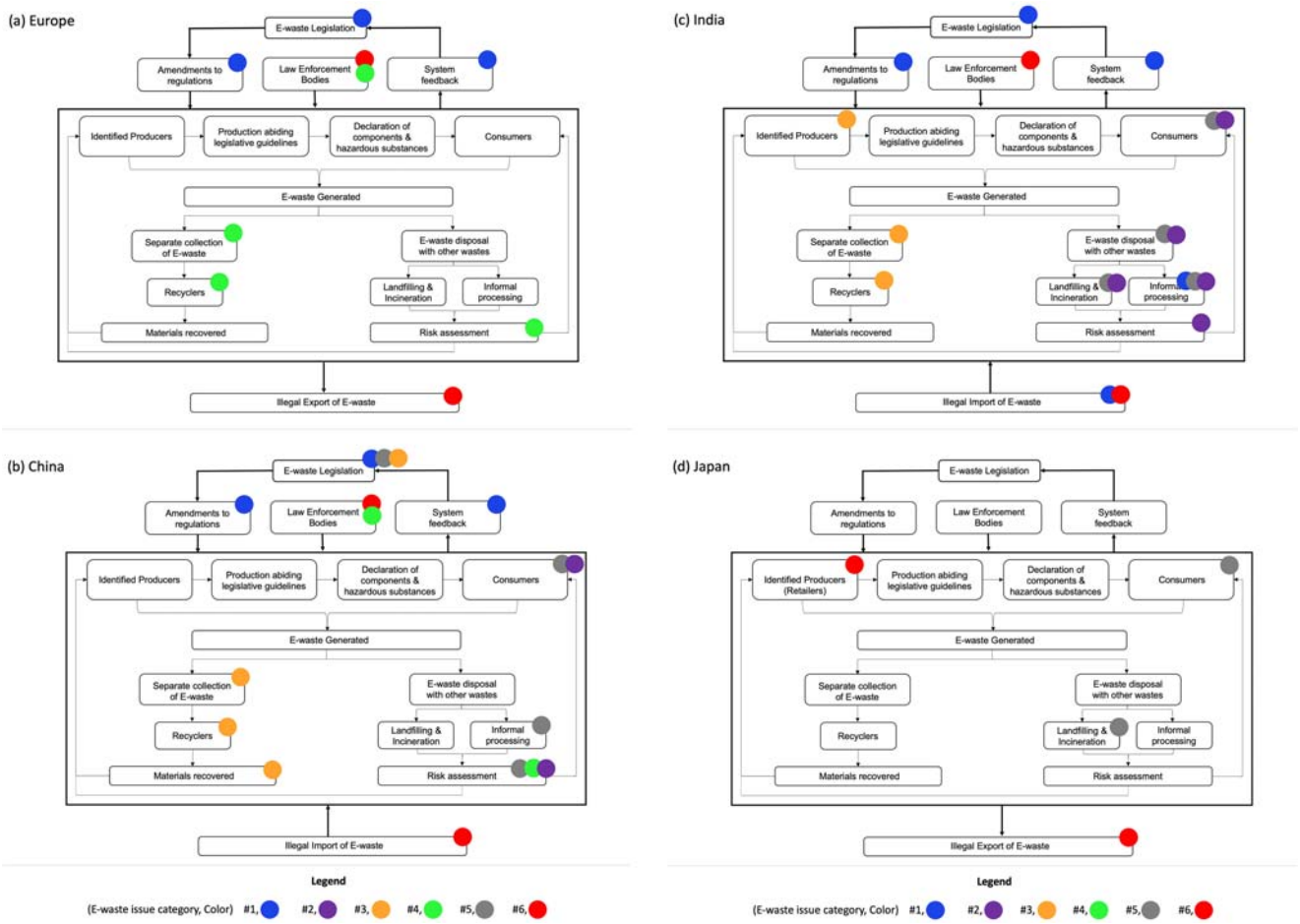

Fig. 3 Towards formulating an effective e-waste legislation: Schematic diagram of the proposed generic e-waste management model for countries with e-waste legislation—**a** Europe, **b** China, **c** India, **d** Japan, **e** South Korea, **f** Taiwan, and **g** Australia

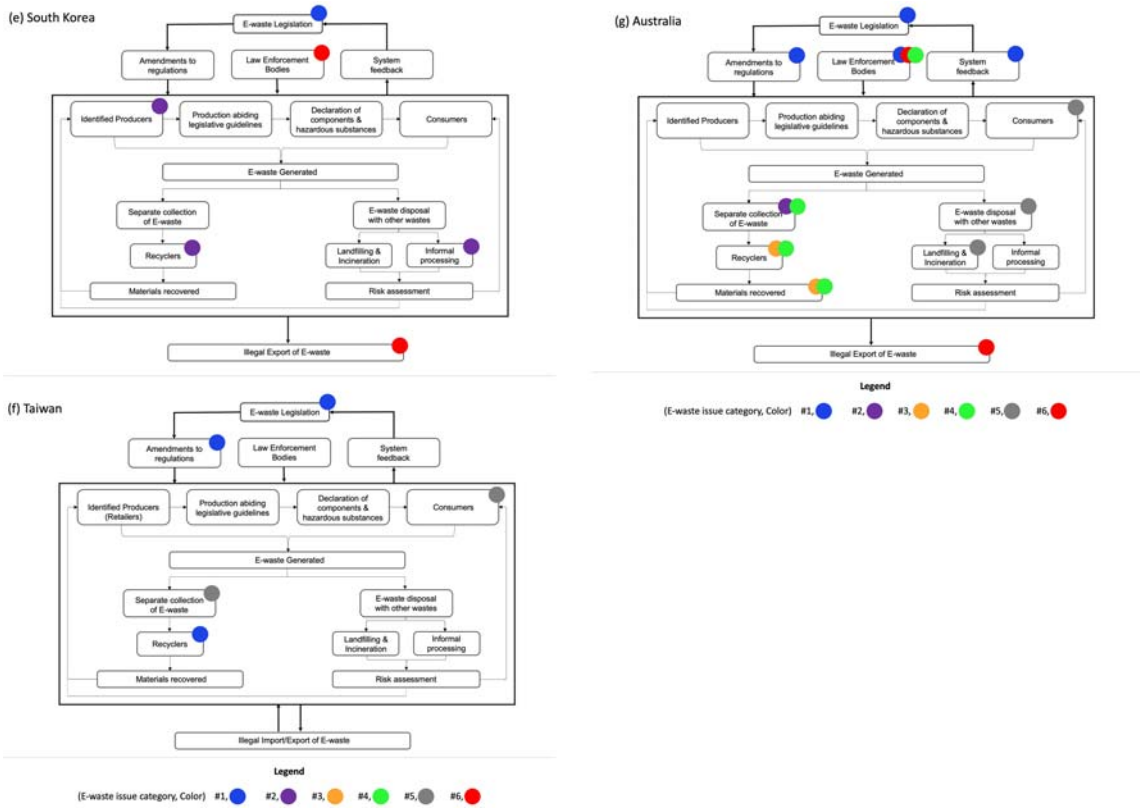

Fig. 3 (continued)

hindered law enforcement from taking strict measures against the illegal trades. There have been no proper infrastructure and rules for separate collection and treatment of e-waste. The lack of consumer awareness has led to the disposal of e-waste with general solid waste, consequently ending up in landfills (gray dots). Insufficient auditing of e-waste collection, recycling, and materials recovered by the authorities has resulted in non-compliance with NTCRS rules (green dots). In addition, the recycling of e-waste (TVs and computers) is poor (purple dot) and due to the low recycling target, the material recovery rate is low (orange dot). This points to a comprehensive legal framework for e-waste that should be implemented based on the system feedback.

Challenges and future directions of e-waste management

The discussion in the above sections clearly shows that many countries that are still not covered under e-waste legislation have to enframe and implement policies as suited to them. This is crucial for controlling the global transboundary movement and crude processing of e-waste. Countries with existing e-waste legislation have to strengthen their current laws through regular systematic assessments and amendments. However, the implementation of e-waste legislation by all the countries will not be sufficient to solve the e-waste mess at the global level. There is a need for an international council to overlook and coordinate e-waste management throughout the world. The lack of uniform global standards for the manufacturing of EEE and recycling e-waste has posed challenges for many countries in framing their e-waste policy. The international council can also provide guidelines inclusive of uniform global standards to the manufactures of EEE and e-waste recyclers.

Even though legislation is a driving factor that influences the e-waste recycling rate, the global economics of recycled materials controls the e-waste recycling industry. The success of e-waste recycling depends on how profitable it is. If the recycling cost (inclusive of infrastructure, labor, and energy consumed) is higher than the mining/production cost of virgin raw materials, then the demand for recycled raw materials could fall back. This results in the recycling of only the expensive and scarcely available raw materials. Recycling cost also increases due to the low yield of the extracted materials. To achieve efficient and profitable e-waste recycling, there is a need for innovation and new technologies that can address recycling challenges such as the separate collection of e-waste, disassembly, and material segregation. Technologies that can automate e-waste recycling, increase the throughput, and lower the energy consumption will be key for sustainable e-waste recycling in the future, and the governments should encourage such innovations through funding and incentives.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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