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# A Comparative Analysis of E-Waste Management Systems

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**Abstract**

Material resources are an important source of income and employment, forming the physical basis of the economy. Their value varies across countries regarding their physical and chemical characteristics, abundance, and rarity. Economic growth means increased demand for raw materials, energy, and additional natural resources. Therefore, the use of raw materials and the associated production and consumption processes have environmental, economic, and social impacts both within countries and across national boundaries. If the product life cycle is not appropriately managed, there will be an increase in the quantities that end up as waste. Indeed, today, countries are facing an increasing problem that closely concerns both the economy and the environment. This problem involves waste electrical and electronic equipment. In today's economic landscape, e-waste is the fastest-growing type of hazardous solid waste globally. Tackling this issue necessitates international collaboration, economic incentives that safeguard labour, and management strategies that reduce adverse effects on resources, the environment, and public health. Accordingly, the main goal of this study is to investigate e-waste management practices across selected countries (Australia, Brazil, China, Germany, Ghana, India, Japan, South Korea, Switzerland, Türkiye, and the USA) and formulate policy recommendations.

**Keywords** E-waste · sustainable production · sustainable consumption · circular economy · eco-industrial park

**JEL Classification** O44 · Q56 · Q01

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## A Comparative Analysis of E-Waste Management Systems

Material resources are an important source of income and employment, forming the physical basis of the economy. Their value varies across countries regarding their physical and chemical characteristics, abundance, and rarity. Economic growth means increased demand for raw materials, energy, and additional natural resources. If the product life cycle (extraction, transportation, production, consumption, recovery, and disposal) is not appropriately managed, there will be an increase in the quantities that end up as waste. Therefore, the utilisation of raw materials and the associated production and consumption processes have environmental, economic, and social impacts both within countries and across national boundaries (OECD, 2021). Today, countries are facing an increasing problem that closely concerns both the economy and the environment. This problem involves waste electrical and electronic equipment (e-waste or electronic waste). In today's economic landscape, e-waste is the fastest-growing type of hazardous solid waste globally (Yang et al., 2017; Qu et al., 2019). Tackling this issue necessitates international collaboration, economic incentives that safeguard labour, and management strategies that reduce adverse effects on resources, the environment, and public health.

At this point, the e-waste problem, which has a complex structure, can be summarised in three aspects:

(i) Increasing volumes and types of e-waste: Developed countries (DCs) often export their e-waste to emerging/developing countries (ECs) due to strict environmental regulations and high labour wages. While this problem is solved at the national level for DCs, the lack of well-established facilities for processing e-waste in ECs causes the problem to persist at the global level (Puckett & Smith, 2002; Cobbing, 2008; Robinson, 2009; Kiddee et al., 2013).

(ii) Economic value potential: Considering the valuable substances contained in e-waste, it is seen that it has a significant economic resource potential. Because the proportion of iron, copper, aluminium, palladium, silver, gold, and other metals in e-waste is over 60%. Each old-generation computer contains 4 grams of gold. Similarly, 1 ton of e-waste contains 0.2 tons of copper (Widmer et al., 2005; Hagelüken, 2006; Cui & Zhang, 2008; Tsydenova & Bengtsson, 2011).

(iii) Environmental and health impacts: Along with its increasing quantity and volume, e-waste poses significant risks to the environment and human health because of the numerous toxic heavy metals and organic pollutants it contains (Kuper & Hojsik, 2008; Schluep et al., 2009; Tsydenova & Bengtsson, 2011; Kiddee et al., 2013). In addition to primary emissions from hazardous materials present in e-waste, secondary and tertiary emissions may occur due to uncontrolled disposal and recycling activities (Schluep et al., 2009).

E-waste is acknowledged as a valuable economic resource due to the precious metals it contains, yet only 15% of the estimated e-waste generated worldwide is recycled (Heacock et al., 2016). In addition, inefficient management of e-waste leads to the loss of secondary resources and increases the mining required to produce primary resources.

To set the stage, the next section examines e-waste management practices in selected countries. This is followed by a comparative analysis that includes an evaluation based on public awareness levels and critical focal points in e-waste governance, such as take-back strategies, resource depletion, and environmental and health impacts. The final section concludes the paper by deriving the key findings and offering targeted policy recommendations.

## E-Waste Management in Selected Countries

Effectively and efficiently managing the increasing volume of e-waste—considering both cost and environmental impact—is a complex challenge. While some DCs have established organised systems for collection, sorting, recycling, disposal, and monitoring, many others are still seeking solutions to mitigate the adverse environmental effects of e-waste processing and recovery. The key factors for creating an effective e-waste management system include:

(i) Specialised logistics (reverse logistics systems) are essential for the collection, processing, recycling, recovery, and transportation of e-waste from its source to the disposal site.

(ii) E-waste contains numerous toxic substances that pose significant risks to human health and the environment, necessitating special handling for its disposal to reduce environmental impacts.

(iii) E-waste is a valuable source of metals like gold, silver, and copper, which can be recovered and reintegrated into the production cycle.

Considering the first two points, the difficulty of reverse logistics management and the fact that decontamination practices are too costly or unprofitable prevent the private sector from taking the initiative on its own. Therefore, the public authority has an important role to play in creating, supporting, sustaining, and regulating cost-effective technologies addressing e-waste management to establish both reverse logistics systems and appropriate processing facilities. It is also significant for countries to adapt management policy tools/approaches to create a sustainable e-waste management system. These are life-cycle analysis (LCA), material flow analysis (MFA), multi-criteria analysis (MCA), and extended producer responsibility (EPR).

Depending on the level of development and awareness of countries, different methods and scenarios of e-waste management naturally vary from region to region (Peagram et al., 2014; Williams, 2016). In this context, three typical e-waste management approaches can be identified and categorised (Huisman et al., 2019; Shittu et al., 2021).

(i) First approach (countries with advanced e-waste awareness): Countries with e-waste legislation exists and e-waste management formally collected and documented.

(ii) Second approach (countries with moderate e-waste awareness): There is a legal framework for e-waste, but there is a formal and informal collection of e-waste.

(iii) Third approach (countries with low e-waste awareness): Countries where there is no legal framework for e-waste and it is disposed of directly with household waste without separation.

Table 1 presents a thorough country-specific overview of e-waste management. The selection of these countries is based on (i) their conformity with the above-mentioned classification of the level of e-waste awareness, (ii) their representativeness to countries with similar socioeconomic structures, (iii) and the fact that they are the countries with the largest number of studies in e-waste management research.

**Table 1**

*Country-based review of e-waste management*

| Laws/Regulations | Remarks on e-waste management |
|---|---|
| ***Australia***[1]<br>i. National Waste Policy (2009)<br>ii. Product Stewardship Act (2011) | In Australia, where more than half of e-products (EEE) are imported, the NTCRS imposes responsibilities on importers, manufacturers, and distributors for recycling in e-waste management. |

[1] **Notes**

Premalatha et al., 2014; Golev et al., 2016; Dollisson et al., 2017; Golev & Corder, 2017.

| Laws/Regulations | Remarks on e-waste management |
|---|---|
| iii. Product Stewardship (for TVs and computers) Regulations (2011)<br>iv. National Television and Computer Recycling Scheme (2011) | In Australia, the recent establishment of the regulatory framework has succeeded in diverting a significant amount of e-waste from landfills. However, due to the lack of an effective recycling industry despite the technological infrastructure and the lack of a mechanism to incentivize recycling, most e-waste collected is exported overseas for processing. This is said to result in an economic loss of 40%–50% of the potential revenue from recycling (approximately 100 million dollars per year).<br>*Main issue:* Export of electronic waste to ECs. |
| ***Brazil***[2]<br>i. National Solid Waste Policy (PNRS) (2010) | The law mandates that manufacturers and importers of e-products, along with distributors and resellers, establish and implement reverse logistics systems.<br>A significant challenge for implementing this reverse logistics process in Brazil is the collection system. Over half a million waste collectors operate in Brazil, and they serve as the primary metal scrap collectors in the country.<br>In Brazil, current technology only allows the recycling of components with lower total value. High-value materials, such as computer motherboards, are sorted and processed in different countries, thus transferring the largest share of the value generated by this activity to other countries.<br>Although Brazil has not yet fully developed the required infrastructure for e-waste recycling, it has considerable potential to adapt pre-processing and, to some degree, post-processing technologies to meet its needs through technology and knowledge transfer.Brazil's realisation of this potential is based on its sustainable innovation system. There are three types of partnerships in this system: (i) joint projects, (ii) organisational learning systems, and (iii) governance (public-private-academia) networks.<br>*Main issue:* Lack of technology, effective reverse logistics system, and government support; export of valuable e-waste parts to DCs. |
| ***China***[3]<br>i. Law on the Prevention of Environmental Pollution from Solid Waste (1996)<br>ii. Notification on the Importation of the Seventh Category of Wastes (2000)<br>iii. Notice on Strengthening the Environmental Management of WEEE (2003)<br>iv. Ordinance on the Management of Waste Household Electrical and Electronic Products Recycling and Disposal (2006)<br>v. Management Measure for the Prevention of Pollution from Electronic Products (China RoHS) (2006)<br>vi. Regulation for the Management of the Recycling and Disposal of Waste Electrical and Electronic Products (China WEEE) (2009) | The majority of e-waste, both locally generated and imported, is processed in numerous small informal or unregistered workshops. In 2007, about 700,000 individuals were employed in China's e-waste recycling sector, with 98% working informally.<br>As a developing country with relatively low labour costs and lax environmental regulations, China has become a destination for some DCs to export their e-waste.<br>Economic incentives, resource demand, and the legal system support this trend. Thus, China, the world's largest e-product exporter and e-waste importer, plays an important role in global e-waste recycling.<br>The regulations in China aim to (i) establish a multi-channel recovery system (an integrated system consisting of individual efforts, organisations, and government waste recycling systems) and centralised disposal of e-waste, (ii) clearly and accurately label refurbished or remanufactured e-products when they are placed on the market, and (iii) establish a special fund for e-waste recycling and processing to subsidise operators.<br>*Main issue:* Import of e-waste; lack of an official reverse logistics system; informal and primitive recycling process. |

[2] Schluep et al., 2009; Mazon et al., 2012; Oliveira et al., 2012; Souza et al., 2015; Souza et al., 2016; Demajorovic et al., 2016; Azevedo et al., 2017; Oliveira Neto et al., 2017; Rodriguez-Bello & Estupinian-Escalante, 2020; Oliveira Vieira et al., 2020; Dias et al., 2022; Santos & Ogunseitan, 2022.

[3] Li et al., 2006; Yang et al., 2008; Yu et al., 2009; Wang et al., 2010; Yu et al., 2010; Mayyas et al., 2012; Lu et al., 2015; Guo et al., 2016a; Gu et al., 2017; Doan et al., 2019; Zeng & Li, 2019; Liu et al., 2020; Tian et al., 2022.

| Laws/Regulations | Remarks on e-waste management |
|---|---|
| ***Germany***[4]<br>i. Act Governing the Sale, Return, and Environmentally Sound Disposal of Electrical and Electronic Equipment (ElektroG) (2005) | ElektroG defines and regulates responsibilities for (i) design, (ii) collection, (iii) take-back obligation, (iv) remediation and recycling, (v) financing, (vi) monitoring and reporting, and (vii) labelling and consumer information.<br>The public agency (EAR – Stiftung Elektro-Altgeräte-Register) organises the process from e-waste collection to recovery targets. It is mandatory for producers to register with the EAR.<br>*Main issue:* Export of electronic waste to ECs. |
| ***Ghana***[5]<br>i. Hazardous and Electronic Waste Control Management Bill (2016) | Ghana permits the import of e-waste sold to individuals and businesses as used electronics and spare parts.<br>In Ghana, scrap dealers collect e-waste directly from households. These e-waste dealers, tasked with recycling, processing, refurbishing, reusing, and disposing of e-waste, often use rudimentary methods like hammers and stones for dismantling. Additionally, manual sorting of hazardous materials and open burning of e-waste, which pose risks to human health, are prevalent practices. As a result, these methods contribute to significant environmental and health issues.<br>*Main issue:* Lack of technology, effective reverse logistics system, and government support; informal and primitive recycling process. |
| ***India***[6]<br>i. Hazardous Waste Management and Handling Rules (2010)<br>ii. E-waste Management and Handling Rules (2011) | India experiences a significant influx of e-waste from domestic sources and informal imports. The country has become a primary destination for an estimated 50,000 tons of used electronic products (UEEE) and e-waste annually imported from OECD countries. Regulations have been established to promote environmentally sound recovery of e-waste and to minimise the disposal of toxic waste.<br>In 2011, the EPR was introduced to raise awareness of the hazardous nature of e-waste components. In 2018, these regulations were revised and updated as the E-Waste Management Amendment Rules. To ensure proper oversight, a registration system was established for producer responsibility organisations (PROs), allowing them to operate under the supervision of the Central Pollution Control Board. India is working on legislative measures to curb unregistered e-waste imports and promote environmentally sound management of e-waste.<br>The key challenges in e-waste management in India include: (i) a lack of technical expertise in e-waste; (ii) insufficient data inventory on e-waste generation; (iii) inadequate stringent rules and regulations; (iv) a shortage of environmentally sound recycling facilities; and (v) limited awareness and market information.<br>*Main issue:* Import of e-waste; lack of an official reverse logistics system; informal and primitive recycling process |
| ***Japan***[7]<br>i. Home Appliance Recycling Law (2001) | E-products used in Japan are largely exported to other Asian countries as second-hand products, and e-waste is exported to other parts of Asia (Afghanistan, Philippines, Hong Kong, Cambodia, Malaysia, Myanmar, and Vietnam) for recycling, especially China.<br>Since almost all e-waste in Japan is generated in the country, e-waste management (LCA, MFA, MCA, and EPR) under HARL can be expressed as follows: (i) Consumers pay transportation/collection and recycling fees when they drop off their used products to finance collection, transportation, and recycling costs. (ii) Retailers are responsible for collecting used household appliances, and (iii) producers are responsible for recycling them. |

[4] Rotter et al., 2009; Walther et al., 2010; Ongondo et al., 2011; Chaudhary & Vrat, 2018.

[5] Oteng-Ababio, 2012; Oteng-Ababio & Amankwaa, 2014; Asante et al., 2016; Amuzu, 2018; Owusu-Sekyere et al., 2018; Oteng-Ababio & Grant, 2020; Adanu et al., 2020; Grant & Oteng-Ababio, 2021.

[6] Tanskanen, 2012; Kwatra et al., 2014; Borthakur & Govind, 2017; Sinha-Khetriwal, 2019; Turaga et al., 2019; Arya & Kumar, 2020.

[7] Chung & Murakami-Suzuki, 2008; Dempsey & McIntyre, 2009; Goosey, 2009; Shinkuma & Huong, 2009; Bo & Yamamoto, 2010; Yoshida & Terazono, 2010; Hotta et al., 2014.

| Laws/Regulations | Remarks on e-waste management |
| --- | --- |
| | *Main issue:* Export of electronic waste to ECs. |
| ***South Korea***[8]<br>i. Act on the Promotion of Conservation of Resources (1992)<br>ii. WEEE Act (2007) | It requires local distributors, manufacturers, and importers of consumer goods to set up an account for depositing recycling fees based on the amount of e-waste that must be processed. Additionally, they must either create their own recycling facilities or partner with trusted recycling companies or industry cooperatives to achieve the official recycling goals established by the governing authority. They will face financial penalties if the goal is not met. Retailers and suppliers must also gather and deliver discarded equipment for free if the customer buys a comparable product.<br>In South Korea, two key practices in waste management are integrated within the LCA framework. The first is the Allbaro System, which tracks the complete life cycle of products, from collection to disposal, through an online platform. The second is the ECOAS, which focuses on reducing the environmental impact of e-products and vehicles by managing their entire life cycle—from design and production to disposal—and encourages waste reduction and recycling efforts. Since the implementation of ECOAS, the use of hazardous materials has been reduced, and the recycling rate of e-waste has steadily improved.<br>*Main issue:* Export of electronic waste to ECs. |
| ***Switzerland***[9]<br>i. The legislation on the Return, Taking Back, and Disposal of Electrical and Electronic Appliances (ORDEE) (1998) | Switzerland is recognised as the pioneering country in establishing the world's first official e-waste management system.<br>The organised collection and management of e-waste began prior to the enactment of legislation, driven by voluntary initiatives from PROs formed in 1992 through collaborative efforts of manufacturers and importers. ORDEE established the legal foundation for e-waste recovery in Switzerland under the EPR framework, which shifts the responsibility for e-products across their entire life cycle—from take-back and recycling to disposal—from consumers and authorities to producers.<br>The recycling system is funded through an Advanced Recycling Fee (ARF) that consumers pay when purchasing new products. This fee is accumulated into a recycling fund, which is managed by PROs to cover the costs of collection, transportation, and recycling.<br>*Main issue:* Export of electronic waste to ECs. |
| ***Türkiye***[10]<br>i. Directive on the Restriction of the Use of Certain Hazardous Substances in EEE (2008)<br>ii. Directive on the Control of WEEE Equipment (2012) | According to the national legislation prepared in line with the EPR system in Türkiye, it is expected that a significant portion of the management costs of e-waste will be covered by the producers. Producers are financially responsible for the collection, transportation, sorting, recycling, and recovery of e-waste. They are also obliged to take necessary measures to prevent the processing of e-waste using primitive methods, unregistered exports, and imports.<br>Some producers fulfil their responsibilities through PROs. In Türkiye, there are currently three PROs licenced by the Ministry of Environment, Urbanisation and Climate Change. These are: (i) Electrical and Electronic Recycling and Waste Management Association (ELDAY), (ii) Association of Lighting Equipment Manufacturers (AGID), (iii) and Association of Informatics Industrialists (TUBISAD).<br>The key issues that must be addressed to enhance e-waste management in Türkiye include: (i) informal sector activities, (ii) monitoring and tracking the volume of e-products introduced to the market and the e-waste generated, (iii) limited public sector capacity, (iv) limited public awareness, (v) limited and |

[8] Chung & Murakami-Suzuki, 2008; Kahhat et al., 2008; Jang & Kim, 2010; Lee & Na, 2010; Silveira & Chang, 2010; Rhee, 2016; Fayustov, 2020.
[9] Lindhqvist, 2000; Sinha-Khetriwal et al., 2009; Duygan & Meylan, 2015; Ylä-Mella & Román, 2019.
[10] Andiç et al., 2012; Tari & Alumur, 2014; Aras et al., 2015; Öztürk, 2015; Kazancoglu et al., 2020; Ayçin & Kayapinar, 2021.

| Laws/Regulations | Remarks on e-waste management |
|---|---|
| | insufficient processing facilities, (vi) insufficient circular economy practices, and (vii) and insufficient collection infrastructure.<br>*Main issue:* Lack of technology, effective reverse logistics system; export of valuable e-waste parts to DCs. |
| ***United States of America***[11]<br>i. The Electronic Waste Recycling Act of California (2003)<br>ii. E-Waste Programme in State of Maine (2006)<br>iii. Producer Responsibility Bill in 15 States of the United States (2007) | Since there is no federal regulation pertaining to e-waste, state laws in the USA vary in how e-waste is managed. In 2003, California implemented a management structure that mandated that e-product consumers bear financial responsibility for end-of-life (EoL) management. In 2004, the state of Maine implemented an e-waste law based on the EPR. This law mandates that producers, consumers, and municipalities share responsibility for managing e-waste . In the USA, many programmes and initiatives are in place for managing e-waste. One example of such an initiative is the National Strategy for Electronics Stewardship (NSES). This programme aims to reduce the volume of e-waste exported to ECs, encourage ecologically safe EoL handling of e-waste, and support ideas like eco-design in electronics manufacturing.<br>The initiative makes it possible to reduce e-waste exports to developing nations, promote ecologically safe EoL handling of e-waste, and support ideas like eco-design/sustainable design in the production of electronic devices. The US-EPA's Sustainable Materials Management (SMM) programme is another endeavour. Original equipment manufacturers and the US-EPA work together to collect e-waste from customers. It also encourages the recycling of e-waste at authorised recycling facilities, even in areas without e-waste takeback legislation, and supports the purchase of certified "green" electronics, particularly by government agencies.<br>Out of the 21 states and cities in the USA, 15 (Connecticut, Hawaii [with ARF bills], Illinois, Massachusetts [with ARF bills], Maryland, Minnesota, Nebraska, New Jersey [with ARF bills], New York, Oregon, Rhode Island, South Carolina [with ARF bills], Tennessee, Vermont, and New York City) have enacted EPR bills.<br>*Main issue:* Export of e-waste to ECs; need for a federal e-waste law; lack of an effective reverse logistics system. |

Table 1 presents a comparative overview of e-waste management systems across selected countries, categorised by their regulatory frameworks, implementation practices, and primary challenges.

As observed, DCs such as Australia, Germany, Japan, South Korea, and Switzerland generally exhibit well-structured legal frameworks grounded in EPR, supported by LCA and other management tools. These countries often enforce producer obligations, offer recycling incentives, and operate centralised monitoring systems. However, a common challenge among them is the continued export of e-waste to ECs, resulting in value loss and environmental concerns.

In contrast, emerging countries like Brazil, India, and Türkiye demonstrate partial implementation of formal regulations and EPR frameworks but face critical challenges such as insufficient reverse logistics infrastructure, limited technological capacity, and heavy reliance on the informal sector for collection and pre-processing. While Brazil and India show promise through public-private-academic collaboration and evolving regulatory mechanisms, significant infrastructural and technical gaps remain.

Other ECs, such as China and Ghana (notably through their informal sectors), serve as major destinations for imported e-waste, where informal and rudimentary recycling methods prevail. These practices pose

[11] Billinghurst, 2005; Gregory & Kirchain, 2007; Hanselman & Pegah, 2007; Kollikkathara et al., 2009; Elisha, 2010; Jody et al., 2010; Silveira & Chang, 2010; Skinner et al., 2010; Fehm, 2011; Ongondo et al., 2011; Atasu & Van Wassenhove, 2012; Olds, 2012; Oliveira et al., 2012; Zhong, 2012; Shumon et al., 2014; Borthakur & Govind, 2017; Schumacher & Agbemabiese, 2019; Biedenkopf, 2020; Andeobu et al., 2021.

serious environmental and health risks due to manual dismantling, open burning, and the lack of regulatory enforcement.

The USA represents a unique case. Despite notable state-level initiatives and programmes like the NSES, the absence of a federal e-waste regulation has led to fragmented and inconsistent practices nationwide.

Overall, while legal frameworks and formal systems for e-waste management are increasingly being adopted worldwide, key challenges persist. These include the dominance of informal sectors, technological and infrastructural limitations, and the transboundary movement of e-waste, particularly from DCs to ECs.

## Comparative Analysis

This section offers an evaluation of e-waste awareness in selected countries, highlighting key areas of focus (take-back strategies/policies, resource depletion, environmental impact, and health concerns) that must be addressed in e-waste management.

### Evaluation of Selected Countries with E-Waste Awareness Levels

There are notable disparities in e-waste management between DCs and ECs. Not all countries have laws or technologies in place to regulate the handling and disposal of e-waste. To compare the level of e-waste awareness within the countries examined in this study:

(i) Countries with advanced e-waste awareness: This group includes Australia, Germany, Japan, South Korea, Switzerland, USA, and countries with a similar socioeconomic structure (such as Canada, France, Italy, Norway, and UK).

(ii) Countries with a medium level of e-waste awareness: This group includes Brazil, China, India, Türkiye, and countries with a similar socioeconomic structure (such as Argentina, Malaysia, and Taiwan).

(iii) Countries with low levels of e-waste awareness: This group includes Ghana and other African countries with similar socioeconomic structures.

### Evaluation of Selected Countries in terms of Focal Points to be Considered in E-Waste Management

Studies on e-waste management generally have three common themes. These are: (i) take-back strategies/policies, (ii) resource depletion, and (iii) environment and health.

### Take-back strategies/policies

Take-back strategies involve the systems, supporting policies, and regulations required to collect and manage e-waste. The primary challenge is likely the lack of infrastructure (sufficient technology), particularly in low-income countries across Africa, South America, Asia, and Europe (Schluep et al., 2008). Increasing e-waste at the global level, together with imports, whether legal or informal, is accumulating in the regions mentioned and especially in the countries analysed in this study. On the other hand, the biggest challenge for DCs is not technological capacity but legislation and compliance (Huisman et al., 2006; Huisman & Magalini, 2007). For DCs, it is more important how comprehensive their regulations are.

Looking at DCs and ECs, three main policies are implemented in e-waste management (Oteng-Ababio & Amankwaa, 2014). The first is the EPR policy adopted by the EU, where producers and importers are held financially responsible for their products. The second is Japan's EPR policy based on the "end-user pays principle," where retailers are obligated to accept e-waste from consumers (physical responsibility), while consumers bear the financial responsibility by covering the costs of collection and recycling (Widmer et al., 2005; Aizawa et al., 2008). The third is a "hybrid policy" adopted by the USA, based on limited or full EPR, with a range of government regulations (Gregory & Kirchain, 2007; Kahhat et al., 2008).

Research on LCA, MFA, MCA, and EPR approaches to e-waste management is expanding. Each of these tools has distinct characteristics when applied to e-waste management, which are outlined in Table 2. In addition to the countries in Table 2, these policy instruments have been used by other DCs and ECs as decision-making tools for environmental issues, including e-waste management[12].

**Table 2**

*Policy approaches/instruments for e-waste management and related studies*

| Policy Approaches | Benefit | Country | References |
|---|---|---|---|
| LCA[13] | -Assesses the effects of resource use and supports eco-friendly design and product innovation.<br>-Examines the environmental impact of the product.<br>-Evaluates the environmental and economic aspects of products during the EoL cycle.<br>-It is effective in making better decisions on waste disposal. | Australia | (Sirait et al., 2012; Soo & Doolan, 2014) |
| | | Brazil | (Souza et al., 2016) |
| | | China | (Duan et al., 2009; Hong et al., 2015) |
| | | Germany | (Barba-Gutierrez et al., 2008) |
| | | Ghana | (Chen et al., 2020) |
| | | India | (Ahluwalia & Nema, 2007) |
| | | Japan | (Nakamura & Kondo, 2006) |
| | | South Korea | (Kim et al., 2004; Choi et al., 2006) |
| | | Switzerland | (Hischier et al., 2005; Scharnhorst et al., 2005; Wäger et al., 2011) |
| | | Türkiye | (Ozkan et al, 2018) |
| | | USA | (Deng et al., 2011) |
| MFA[14] | -Tracks the waste life cycle and domestic and international flows.<br>-Calculates e-waste generation.<br>-In addition to countries that export e-waste, the application of MFA is crucial in e-waste management, particularly in ECs like China, Ghana, and India, which serve as destinations for e-waste imports. | Australia | (Golev et al., 2016) |
| | | Brazil | (Araújo et al., 2012) |
| | | China | (Liu et al., 2006a; Long et al., 2013; Habuer et al., 2014; Gu et al., 2017; Guo & Yan, 2017) |
| | | Germany | (Chancerel et al., 2009) |
| | | Ghana | (Dzah et al., 2022; Owusu-Sekyere et al., 2022) |
| | | India | (Streicher-Porte et al., 2007) |
| | | Japan | (Aizawa et al., 2008; Yoshida et al., 2009) |
| | | South Korea | (Jang & Kim, 2010) |
| | | Switzerland | (Hischier et al., 2005; Wäger et al., 2011) |
| | | Türkiye | (Kazancoglu et al., 2020) |
| | | USA | (Kahhat & Williams, 2012; Lam et al., 2013; Althaf et al., 2021) |
| | | Australia | (Islam & Huda, 2020) |

[12]See Argentina (Villalba, 2020); Belgium (Eygen et al., 2016; Vanegas, et al., 2017); Canada (McKerlie et al., 2006); Chile (Steubing et al., 2010); Colombia (Streicher-Porte et al., 2009); Denmark (Parajuly et al., 2016); France (Vadoudi et al., 2015; Bahers & Kim, 2018); Indonesia (Andarani & Goto, 2014); Italy (Favot et al., 2018); Lithuania (Gurauskiene & Stasiskiene, 2011); Mexico (Cordova-Pizarro et al., 2019); Netherlands (Börner & Hegger, 2018); Nigeria (Nnorom & Osibanjo, 2008); Pakistan (Rasheed et al., 2022); Portugal (Ford et al., 2016); Spain (Queiruga et al., 2008); Sweden (Kalmykova et al., 2015); Taiwan (Lu et al., 2006); Thailand (Manomaivibool & Vassanadumrongdee, 2011); United Kingdom (Mayers et al., 2005; Gottberg et al., 2006).

[13]Van Mier et al., 1996; Pollock & Coulon, 1996; Satake & Oishi, 1998; Ueno et al., 1999; Yanagitani & Kawahara, 2000; Kim et al., 2001; Prek, 2004; Andræ et al., 2005; Socolof et al., 2005; Park et al., 2006; Bakri et al., 2008; Munoz et al., 2009; Hischier & Baudin, 2010.

[14]Zeschmar-Lahl, 2004; Liu et al., 2006a; Streicher-Porte et al., 2007; Shinkuma & Huong, 2009; Yoshida et al., 2009.

| Policy Approaches | Benefit | Country | References |
|---|---|---|---|
| MCA[15] | -Helps to make optimal decisions on environmental issues.<br>-Used to select the best location for the collection and recycling of e-waste. | Brazil | (Guarnieri et al., 2020; Oliveira Vieira et al., 2020) |
| | | China | (An et al., 2015; Liu et al., 2019) |
| | | Germany | (Wittstruck & Teuteberg, 2012) |
| | | Ghana | (Chen et al., 2020) |
| | | India | (Chaudhary & Vrat, 2017) |
| | | Japan | (Chiang et al., 2011; Vlachokostas et al., 2021) |
| | | South Korea | (Kim et al., 2009) |
| | | Switzerland | (Duygan & Meylan, 2015) |
| | | Türkiye | (Bereketli et al., 2011; Kaya, 2012; Erdoğan et al. 2015) |
| | | USA | (Hula et al., 2003) |
| EPR[16] | -Based on the Polluter Pays Principle.<br>It is an environmental policy that holds producers, importers, and consumers of products accountable at various stages for their management in an environmentally and economically sound manner.<br>-Germany, Switzerland, Japan, and South Korea have made significant progress in the EPR policy. | Australia | (Davis & Herat, 2010; Lodhia et al., 2017) |
| | | Brazil | (Oliveira et al., 2012; Neto et al., 2019) |
| | | China | (Cao et al., 2016) |
| | | Germany | (Roller & Führ, 2008) |
| | | Ghana | (Daum et al., 2017; Faibil et al., 2023) |
| | | India | (Manomaivibool, 2009) |
| | | Japan | (Chung & Murakami-Suzuki, 2008) |
| | | South Korea | (Lee et al., 2007) |
| | | Switzerland | (Sinha-Khetriwal et al., 2009) |
| | | Türkiye | (Kazancoglu et al., 2020) |
| | | USA | (Sachs, 2006) |

Table 2 provides a comparative overview of key policy approaches and decision-making instruments applied to e-waste management across a range of developed and emerging countries. The four principal policy tools identified are LCA, MFA, MCA, and EPR. Each approach offers distinct benefits and has been adopted to varying degrees depending on national contexts.

- LCA is widely employed to evaluate the environmental and economic impacts of e-products throughout their life cycles. It supports eco-design, resource efficiency, and informed waste disposal decisions. Countries such as Australia, Germany, Japan, South Korea, Switzerland, and the USA use LCA extensively, reflecting their advanced focus on environmental sustainability.
- MFA tracks the generation, domestic flow, and transboundary movement of e-waste, making it crucial for countries involved in e-waste import and export, particularly emerging economies like China, Ghana, and India. MFA facilitates the quantification and monitoring of e-waste streams, informing policy and infrastructure development.
- MCA aids optimal decision-making by evaluating multiple environmental and socioeconomic factors. It is employed for site selection in collection and recycling operations and is applied in both DCs and ECs countries.

[15] Queiruga et al. (2008); Rousis et al. (2008).

[16] Glasbergen, 1998; Meadowcroft, 1998; Lindhqvist, 2000; Coglianese & Nash, 2001; OECD, 2001; Fishbein, 2002; Walls, 2004; Widmer et al., 2005; Kautto, 2006; Rossem et al., 2006; Walls, 2006; Toffel et al., 2008; Hickle, 2014; Massarutto, 2014; Kunz et al., 2018; Murthy & Ramakrishna, 2022.

- EPR underpins environmental accountability by assigning producers, importers, and consumers financial and operational responsibilities for e-waste management. EPR is firmly established in countries such as Germany, Switzerland, Japan, and South Korea and is progressively being integrated into emerging economies such as Brazil, China, Ghana, India, and Türkiye.

In this framework, it is essential to develop and enforce comprehensive legislation and policies aimed at minimising the adverse environmental and health impacts of e-waste on a global scale. Such measures should include prohibiting the transfer of UEEE to ECs, which often lack the infrastructure to manage these wastes safely. Additionally, raising awareness among producers and consumers regarding the harmful effects of e-waste pollution is crucial to fostering more responsible production, consumption, and disposal practices worldwide. The following table summarises some concrete benefits of applying LCA, MFA, MCA, and EPR across selected countries to improve e-waste management.

**Table 3**

*Benefits of e-waste management tools*

| Country | Policy approaches and key benefits |
|---|---|
| Australia[17] | LCA guided cleaner production, cutting PC energy use by 42% and $CO_2$ by 40%, and supporting MobileMuster's toxicity reduction and high collection rates. MFA identified printed circuit boards (PCBs) as 4% of e-waste by weight but 40% of metal value, revealing that only 66% of recoverable metals were reclaimed. MCA optimised a national drop-off network of 36 points, covering 95% of the population with improved equity and logistics. EPR under the NTCRS recycled 130,000+ tonnes with a 95% recovery rate; social enterprises handled up to 43% of volume, while reverse logistics improved traceability and cost efficiency. |
| Brazil[18] | LCA revealed that informal recycling routes caused higher environmental burdens, while hydrometallurgical processes showed 50%–60% lower impacts compared to smelting. MFA identified e-waste misclassification and critical material loss in informal sectors, highlighted fast-growing streams such as computers (105,000 tonnes), and prompted improved flow modelling and risk mitigation. MCA enabled optimal treatment route selection across device types, balancing technical feasibility, costs, and environmental risks, and prioritised 32 logistics barriers. EPR under the PNRS boosted recycling access through shared responsibility models, though 4.3 million batteries were diverted and domestic pre-treatment helped reduce costs, persistent coverage gaps and weak take-back logistics remain. Studies also noted the lack of PCBs recycling technology and called for investment in local processing and hydrometallurgical battery solutions. |
| China[19] | LCA studies in cities like Beijing and Tianjin showed that over 60% of e-waste mass is recyclable metal—mainly copper, aluminium, and iron—helping reduce landfill pressure and boost material recovery. MFA revealed that five product types (TVs, fridges, washers, air conditioners, and PCs) made up 83% of total e-waste, which rose from 5.5 million tonnes in 2013 to a projected 20 million tonnes by 2040. MCA optimised facility siting with ideal collection radii between 173 and 239 km, improving logistics and cost efficiency. EPR rollout in 2011 led to 43M units being dismantled by 2013, with a 90% collection rate for TVs. Subsidies under the WEEE fund raised profitability to $2.5 per TV, generating $90M annually for formal recyclers. |
| Germany[20] | LCA studies guided optimal dismantling of devices like TVs and fridges, showing that recovering metals and plastics reduced energy use and $CO_2$ emissions compared to incineration. It also revealed optimal transport distances to maximise recycling benefits. MFA revealed that small appliances and information and communication technology (ICT) equipment contained valuable materials—especially gold and palladium—yet improper disposal and informal exports led to substantial losses, with over 35% of precious metals lost during shredding processes. MCA approaches helped rank recycling strategies by balancing cost, hazard potential, and |

[17] Horne & Gertsakis, 2006; Davis & Herat, 2008; Davis & Wolski, 2008; Davis & Herat, 2010; Ongondo et al., 2011; Sirait et al., 2012; Soo & Doolan, 2014; Fernando & Rupasinghe, 2016; Golev et al., 2016; Golev & Corder, 2017; Lodhia et al., 2017; Islam & Huda, 2018; Golev et al., 2019; Islam & Huda, 2020.

[18] Veloso et al., 2005; Araujo et al., 2011; Araújo et al., 2012; Oliveira et al., 2012; Migliano et al., 2014; Souza et al., 2016; Oliveira Neto et al., 2017; Andrade et al., 2019; Albuquerque et al., 2020; Guarnieri et al., 2020; Oliveira et al., 2020; Oliveira Vieira et al., 2020; Rodriguez Bello & Estupiñán Escalante, 2020; Souza, 2020; Santos & Ogunseitan, 2022.

[19] Li et al., 2006; Liu et al., 2006a; He et al., 2008; Duan et al., 2009; Yu et al., 2009; Wei & Liu, 2012; Long et al., 2013; Habuer et al., 2014; Hong et al., 2015; Li et al., 2015; Guo & Yan, 2017; Gu et al., 2017; Liu et al., 2017; Chen et al., 2018; Cao et al., 2016; Doan et al., 2019; Liu et al., 2019.

| Country | Policy approaches and key benefits |
|---|---|
| | environmental gain, supporting design-for-recycling in the electronics sector, and enabling eco-based contractor selection. Germany's EPR scheme, structured through a Clearing House model, achieved high recovery rates—over 80% for large appliances—while pushing producers to improve design and reduce packaging waste. The Clearing House, EAR (Elektro-Altgeräte Register), acts as the official national platform to register producers, monitor compliance, and coordinate take-back logistics. Additionally, EPR proposals incorporating digital product identification systems were projected to cut administrative costs by €700,000 over nine years. However, enforcement challenges and free-riding risks highlighted the need for clearer accountability in shared systems. |
| Ghana[21] | LCA studies showed that open burning and informal dismantling at sites like Agbogbloshie resulted in high toxic emissions, particularly from plastics and circuit boards, underscoring the need for formalised, safer recycling alternatives. MFA revealed that over 215,000 tons of e-waste were processed annually, but 95% of it was handled informally, leading to losses of valuable metals like copper and aluminium and uncontrolled environmental contamination. MCA approaches suggested prioritising formal–informal integration models, where informal actors handle collection and dismantling, while the formal sector manages refining and safe disposal. Ghana's evolving EPR framework, supported by international non-governmental organisations (NGOs) and draft legislation, aims to improve stakeholder responsibility, yet enforcement, funding, and infrastructure remain major implementation challenges. |
| India[22] | LCA studies highlighted that informal recycling practices, such as open burning and acid leaching, significantly elevate dioxin and heavy metal emissions, posing severe health risks. LCA-driven reuse strategies were shown to extend computer lifespans by 33% and reduce environmental impact by 49%. MFA revealed over 2 million tons of e-waste generated annually, with major cities like Mumbai and Delhi contributing most of it. Informal recycling dominates—handling up to 90%–95%—leading to substantial losses in valuable metals like gold and copper. MCA analyses emphasised integrating informal sector collectors—responsible for nearly 90% of collection—into formal systems to ensure safer handling and improved recovery, and identified Bhiwadi as the optimal site for precious metal recovery, with potential savings of ₹410 crore. EPR implementation remains weak despite legal frameworks since 2011; challenges include low awareness, informal sector dominance, and limited producer compliance. However, effective EPR enforcement could enable the formal treatment of up to 140,000 tonnes annually. |
| Japan[23] | LCA-guided recycling programmes significantly lowered environmental impacts from home appliances and electronics, cutting emissions and reducing hazardous substances, while also decreasing overall costs. MFA revealed doubled reuse rates and a threefold increase in exports, along with effective tracking and management of e-waste streams. Recycling rates surpassed 50% by 2006, driven by efficient collection and targeted recovery of precious metals and plastics. MCA supported safer, lead-free product design and systematic evaluation of recycling technologies, optimising infrastructure choices based on cost, efficiency, and environmental outcomes. Japan's comprehensive EPR policies mandated producers' responsibility for take-back, recycling, and disposal. As a result, over 51% of discarded appliances were formally processed, illegal dumping declined significantly, and traceability improved through digital manifest systems. |
| South Korea[24] | LCA studies using tools like SimaPro showed that cathode ray tube monitors and PCBs contributed the most to environmental burdens due to their high energy demand and emissions during dismantling and treatment. Notably, copper was identified as the most valuable recycled material. MFA assessments mapped material flows of appliances, revealing that while 69% of waste large household appliances entered formal collection, |

[20] Lindhqvist, 2000; Walther & Spengler, 2005; Roller & Führ, 2008; Barba-Gutierrez et al., 2008; Chancerel et al., 2009; Dimitrakakis et al., 2009; Rotter et al., 2009; Walther et al., 2010; Deubzer, 2011; Wittstruck & Teuteberg, 2012; Kiddee et al., 2013.

[21] Prakash et al., 2010; Amoyaw-Osei et al., 2011; Oteng-Ababio, 2012; Grant & Oteng-Ababio, 2013; Oteng-Ababio & Amankwaa, 2014; Oteng-Ababio et al., 2014; Asante et al., 2016; Daum et al., 2017; Owusu-Sekyere et al., 2018; Quaye et al., 2019; Oteng-Ababio & Grant, 2019; Bimir, 2020; Chen et al., 2020; Dzah et al., 2022; Owusu-Sekyere et al., 2022; Owusu-Twum et al., 2022; Faibil et al., 2023.

[22] Sinha-Khetriwal et al., 2005; Ahluwalia & Nema, 2007; Streicher-Porte et al., 2007; Manomaivibool, 2009; Wath et al., 2010; Dwivedy & Mittal, 2010, 2010a; Dwivedy & Mittal, 2012; Wath et al., 2011; Kwatra et al., 2014; Dwivedy et al., 2015; Ganguly, 2016; Kaur & Goel, 2016; Yadav et al., 2016; Chaudhary & Vrat, 2017; Borthakur & Govind, 2017, 2017a, 2018; Bhaskar & Turaga, 2017; Awasthi & Li, 2017; Awasthi et al., 2018; Turaga et al., 2019; Arya & Kumar, 2020; Barapatre & Rastogi, 2021; Dutta & Goel, 2021; Jeyaraj, 2021; Panchal et al., 2021.

[23] Nakamura & Kondo, 2006; Aizawa et al., 2008; Chung & Murakami-Suzuki, 2008; Yoshida et al., 2009; Chiang et al., 2011; Sthiannopkao & Wong, 2013; Islam & Huda, 2019; Herat, 2021; Vlachokostas et al., 2021.

| Country | Policy approaches and key benefits |
|---|---|
| | about 17% leaked to informal sectors, resulting in metal losses and inefficient recovery. Additionally, 42% of mobile phones remained in storage, limiting recovery potential. MCA applications emphasised design-for-recycling strategies and suggested multi-criteria decision analysis models to enhance the selection of sustainable treatment options. South Korea's EPR system—initially implemented in 2003—mandates producers to meet collection and recycling quotas and is supplemented with radio-frequency identification (RFID)-based tracking systems, which have enabled the treatment of 850,000 units and a 25% annual growth in formal recycling, improving accountability and data reliability. |
| Switzerland[25] | LCA studies demonstrated clear environmental benefits of e-waste recycling, with significant reductions in ecological impacts compared to incineration, especially regarding toxic substances and emissions. MFA analysis identified high efficiencies in the recovery of valuable metals, such as copper, gold, and aluminium, within established national recycling systems, significantly reducing reliance on primary resources. MCA evaluations emphasised the integration of advanced technologies like RFID-based tagging to optimise waste sorting processes, increasing efficiency in recycling logistics and transparency. Switzerland's pioneering EPR system, operational since the 1990s through PROs like SWICO and S.EN.S., has achieved near-total recovery rates and substantially lowered recycling costs via an ARF, effectively minimising illegal disposal and promoting extensive producer responsibility. |
| Türkiye[26] | The LCA highlighted the environmental and economic potential of recovering precious metals and minimising hazardous substances through regulated recycling practices. MFA revealed substantial volumes of e-waste generation in Türkiye, emphasising the need for improved data systems and recycling infrastructure to reduce informal processing. MCA studies recommended enhancing cooperation between local authorities and recycling entities and improving public awareness to optimise e-waste management. Türkiye's EPR regulations, aligned with EU WEEE directives, established mandatory collection and recycling targets, but implementation challenges persist, particularly due to limited consumer awareness and collection facilities. |
| USA[27] | LCA applications indicated centralised recycling systems significantly reduced transport emissions and improved environmental outcomes compared to curbside collection. MFA revealed that despite declining total e-waste mass, critical metals like cobalt and indium increased, necessitating targeted recycling approaches. MCA supported optimising product disassembly, notably increasing energy recovery by over 50% compared to shredding methods. EPR remains fragmented due to state-level regulations, limiting uniform enforcement and effective recycling. Challenges persist due to outdated weight-based collection targets, lack of incentives for eco-design, and insufficient measures addressing lightweight electronics, underscoring the need for cohesive national standards and updated performance metrics. |

As shown in Table 3, the integration of LCA, MFA, MCA, and EPR across diverse national contexts underscores that successful e-waste management depends less on the mere adoption of these tools and more on the coherence, enforcement, and institutional capacity behind them. Countries that combine quantitative analysis (via LCA and MFA) with strategic planning (via MCA) and robust regulatory frameworks (via EPR) tend to achieve higher recovery rates, reduced emissions, and more circular resource flows. However, the presence of informal recycling, weak enforcement, and fragmented governance continues to undermine progress, especially in ECs. The comparison reveals that technological solutions alone are insufficient; infrastructure investment, stakeholder coordination, and transparent monitoring mechanisms significantly improve outcomes when they support policy. Therefore, an integrated, enforceable, and context-sensitive approach is essential to translate policy instruments into tangible environmental and economic benefits.

[24] Kim et al., 2004; Choi et al., 2006; Yoon & Jang, 2006; Lee et al., 2007; Kim et al., 2009; Jang & Kim, 2010; Park et al., 2014; Kim et al., 2018; Rhee, 2016.

[25] Hischier et al., 2005; Scharnhorst et al., 2005; Sinha-Khetriwal et al., 2005; Streicher-Porte, 2006; Binder et al., 2008; Wäger et al., 2011; Wath et al., 2010; Wath et al., 2011; Duygan & Meylan, 2015; Chaudhary & Vrat, 2018; Islam & Huda, 2019.

[26] Tınmaz & Demir, 2006; Tuzkaya et al., 2011; Bereketli et al., 2011; Kaya, 2012; Banar et al., 2009; Banar et al., 2014; Aras et al., 2015; Erdoğan et al. 2015; Özkır et al., 2015; Ozkan et al, 2018; Temel et al., 2018; Şahan et al., 2019; Kazancoglu et al., 2020; Akyüz & Kumaş, 2022.

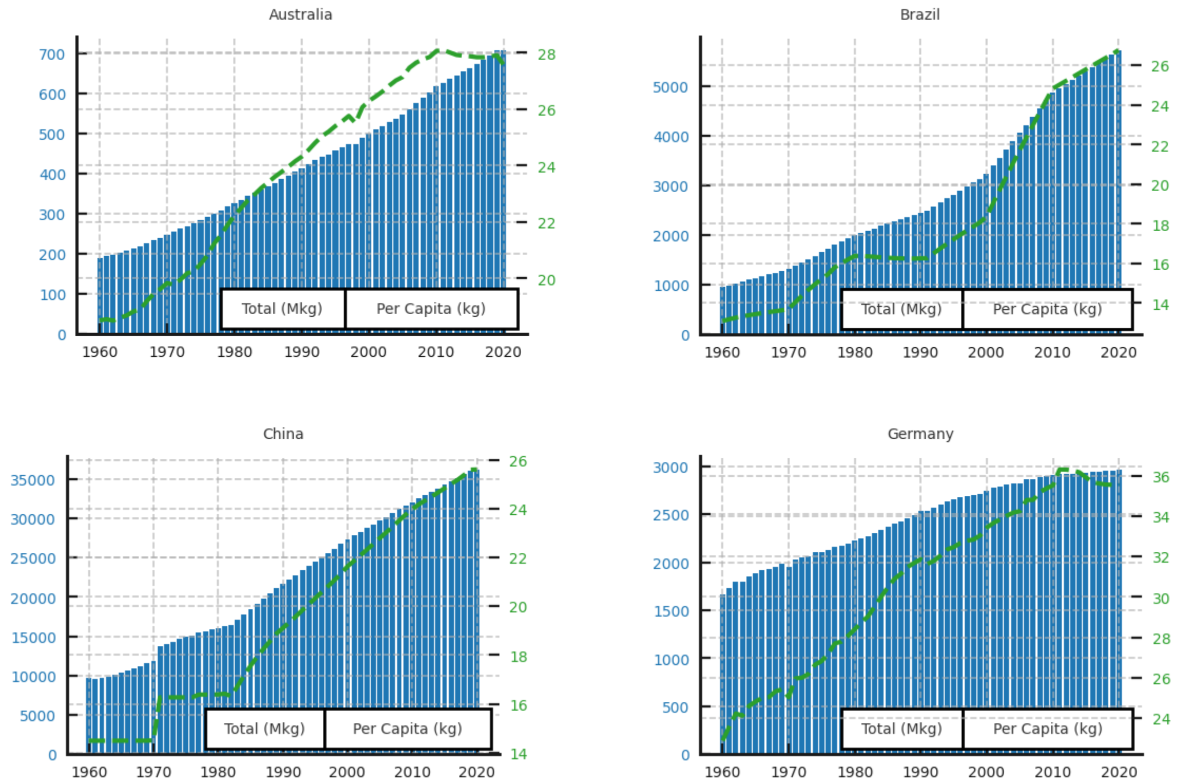
[27] Billinghurst, 2005; Hula et al., 2003; Sachs, 2006; Kahhat et al., 2008; Ezroj, 2010; Deng et al., 2011; Kahhat & Williams, 2012; Garlapati, 2016; Seeberger et al., 2016; Doan et al., 2019; Leclerc & Badami, 2020; Althaf et al., 2021.

## *Resource Depletion*

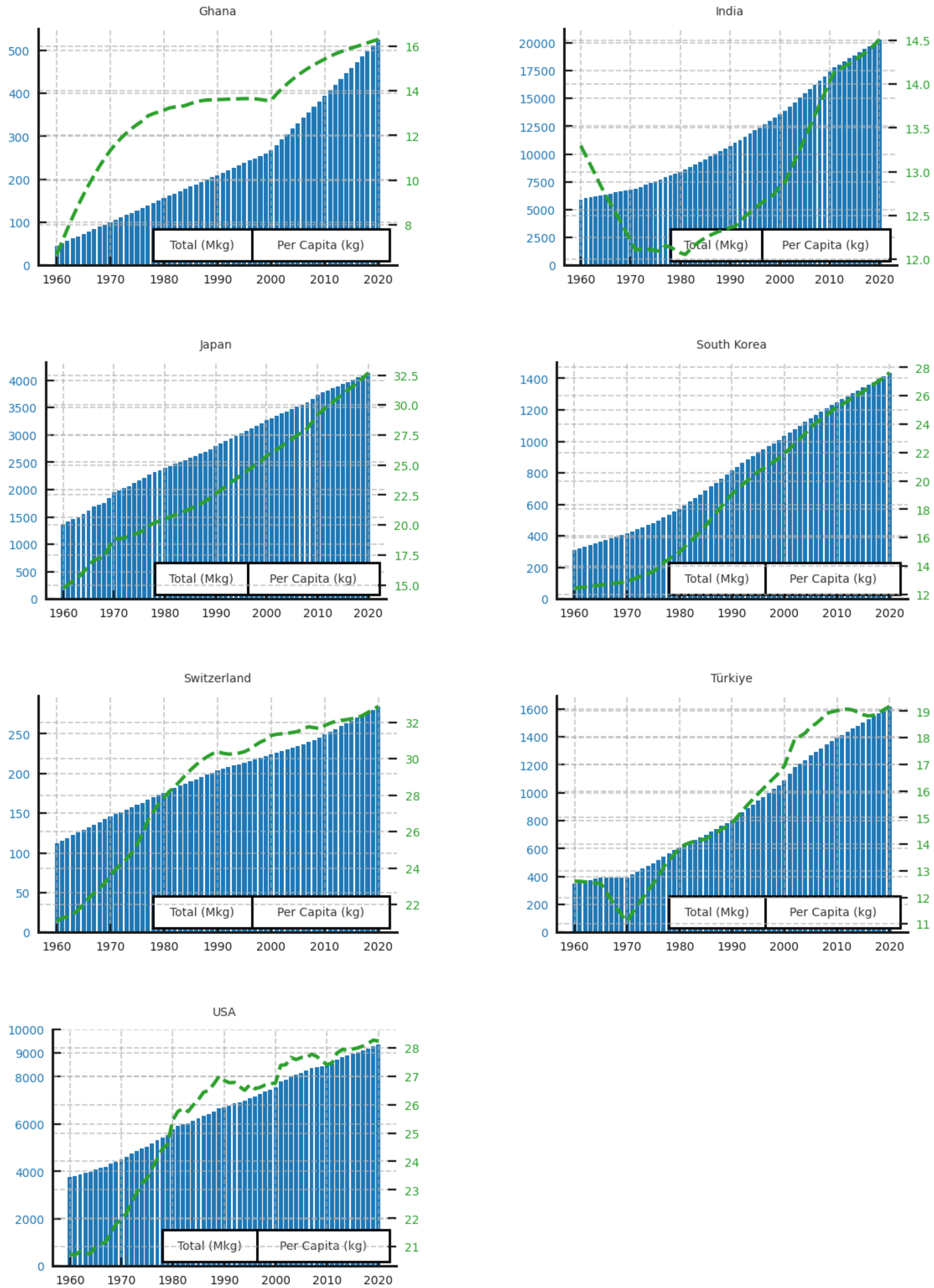
It is evident that the ECs chosen for this study are encountering rising levels of e-waste and significant management difficulties. Although the per capita generation of e-waste in ECs is lower than in DCs, certain ECs where the total volume produced exceeds that of DCs, due to factors like population size and market scale, as shown in Figure 1.

**Figure 1**

*E-waste production amount in selected countries (1960-2020)*[28]




[28]Various approaches have been developed to calculate the amount of e-waste. The most common of these approaches is to know the number of devices used. However, when accurate data on these numbers are not available, estimates based on market data and lifetime are used. The accuracy of estimates of the amount of e-waste largely depends on the average lifetime of these devices and their ability to represent the consumer trend in a country (Dwivedy & Mittal, 2010). In this direction, the amount of e-waste can be calculated with the formula [E =(M.N)/L] when there are minimum data such as the number of products, average weights, and lifetime of e-products. Here, E (kg/year) represents the amount of e-waste generated, *M* (kg) represents the weight of the product, N represents the number of products in use, and *L* (year) represents the average life of the product (Robinson, 2009; Chung et al., 2011; Öztürk, 2015). While the data for the variables *M* (kg) and *L* (year) used in the formula while calculating the amount of e-waste were created using Robinson (2009), the number of households was taken as the basis for the *N* variable, and the number of households for countries was created using the Helgi Library database and Yi (1986).




**Source:** Estimated by the authors based on the data and formula stated in Notes (28) and Table A1.

All countries/regions of the world have different degrees of impact on resource depletion. In much of Europe, Australia, and North America, the rate at which electronic devices are discarded significantly contributes to resource depletion, as producing new items to replace those deemed obsolete necessitates the extraction of raw materials. In other regions, limited efforts to recover materials mean that resources are similarly wasted. Additionally, the practice of stockpiling e-waste at home rather than properly disposing of it in both DCs and ECs effectively prevents valuable materials from being reintroduced into the recycling loop. The importance of raw material access has led the EU to create a list of potentially critical raw materials (EurActiv, 2009). Table 4 presents a selection of these critical raw materials, including data on their production, reserves of critical metals, annual demand for e-product manufacturing, and their respective weight quantities in electronic products. Table 5 shows the leading producers and importers of these precious metals.

**Table 4**

*'Potentially critical' raw materials: global production, reserves, and quantities in e-products*

| **Element**[29] | **Silver Ag** | **Gold Au** | **Cobalt Co** | **Copper Cu** | **Palladium Pd** | **Antimony Sb** |
|---|---|---|---|---|---|---|
| Total production (t/y) | 20000 | 2500 | 58000 | $15x10^6$ | 230 | 130000 |
| Demand for EEE (t/y) | 6000 | 300 | 11000 | $4.5x10^6$ | 33 | 65000 |
| Demand/total production (%) | 30 | 12 | 19 | 30 | 14 | 50 |
| Total reserves* (Kt) | 550 | 52 | 8300 | 890000 | 70000 | 2100 |
| Weight in EEE (g) | 4.5139 | 0.5989 | 3.16 | 8687.8 | 0.1836 | 10.1608 |
| Price ($/kg)** | 744 | 64177 | 34 | 9 | 45436 | 11 |
| Value in EEE (billion, $) | 4.46 | 19.25 | 0.37 | 40.5 | 1.49 | 0.71 |

**Source:** Adapted from Huisman et al., 2008; Meskers & Hagelüken, 2009; Ongondo et al., 2011; USGS, 2023.

Tables 4 and 5 collectively highlight the critical role of certain raw materials in electronics production and the global imbalances in their supply and demand. Materials such as gold, silver, cobalt, copper, palladium, and antimony are extensively used in electronic devices, with significant economic value embedded—estimated at approximately USD 66.7 billion annually. Despite their relatively small quantities of products, high market prices, particularly for gold and palladium, make their recovery from e-waste economically vital. However, the insufficient recovery and stockpiling of e-waste hinders the reintegration of these resources into production cycles. Furthermore, the concentration of raw material production in a limited number of countries (such as China, Congo, and Russia) and the high import dependency of others (such as 83% for antimony and 72% for cobalt) reveal strategic vulnerabilities in global supply chains. These dynamics underscore the urgency of developing effective e-waste recycling systems and circular economy strategies, especially in countries heavily reliant on imports for critical raw materials.

[29]* Refers to the part of the reserve that can be economically extracted or produced. ** Dollar/kg prices dated 24.04.2023 are taken, and fractions are not included. t/y: tonnes per year. Kt: kiloton. g: gram.

**Table 5**

*Leading producers and importers of precious metals*

| Metals | Producers (2024) | Importers (2018-2023) | Net import dependency as a percentage of total calculated consumption (2018-2024, average %) |
|---|---|---|---|
| Silver (Ag) | Mexico, China, and Peru | Mexico, Canada, Poland, Chile, Switzerland, and South Korea | 71 |
| Gold (Au) | China, Australia, Russia, and Canada | Switzerland, Mexico, and Canada | - |
| Cobalt (Co) | Congo, Indonesia, and Australia | Norway, Canada, Finland, and Japan | 72 |
| Copper (Cu) | Chile, Congo, Peru, and China | Chile, Canada, Mexico, and Peru | 39 |
| Palladium (Pd) | Russia, South Africa, and Canada | Russia, South Africa, Italy, Germany, and Belgium | 35 |
| Antimony (Sb) | China, Russia, and Tajikistan | China, Belgium, India, and Bolivia | 83 |

**Source:** Adapted from USGS, 2023; USGS, 2024; USGS, 2025.

In addition to precious metals, e-products also contain rare metals such as Terbium (Tb), Yttrium (Y), Praseodymium (Pr), Europium (Eu), Lanthanum (La), Neodymium (Nd), Gadolinium (Gd), Gallium (Ga), and Indium (In) (Schüler et al., 2011; Cucchiella et al., 2015). Because extracting these metals is both challenging and hazardous, their production is limited to a few regions, particularly in China. China's implementation of export quotas on these metals could pose future risks to their availability and supply (Wilburn, 2012). As a result, these metals are strategic resources essential for national economic and technological development (Wang et al., 2017).

In this context, e-waste permits could be used as a mechanism to ensure a fair distribution of environmental responsibility for e-waste, based on each country's e-waste production and considering the environmental burden per capita. An e-waste emissions trading system might be introduced to reduce e-waste emissions, establishing a cap on the total e-waste produced globally and by individual countries. An international governing body could set a per capita limit for e-waste and allocate a corresponding number of permits to each country. If a country exceeds its allocated amount, it would be required to purchase permits from others to remain compliant with the global emissions trading system. This system would be akin to carbon emissions trading, which is implemented in various countries. However, unlike carbon, e-waste is not only a pollutant but also contains many hazardous materials. Consequently, its recycling process could release harmful substances and carbon emissions into the environment. Given the complexities and uncertainties in calculating and trading e-waste based on emissions, an alternative approach could involve an emissions trading system based on per capita e-waste generation (Yang et al., 2021).

Permit systems and taxes could be integrated to further mitigate the environmental impact of e-waste. One key issue is the cross-border movement of e-waste, particularly the export of e-waste from DCs to ECs, often driven by economic factors. However, ECs frequently rely on informal e-waste recycling practices, which can lead to greater environmental harm and incur higher costs than anticipated. To address this, a tax could be imposed on countries exporting e-waste, aimed at compensating or offsetting the environmental damage caused. This tax could cover the carbon emissions produced during both the transportation and recycling of e-waste. Another approach for holding countries accountable for the e-waste they generate—especially after it is sent abroad for processing—is to invest in the e-waste recycling industries of the destination countries. By doing so, they could support the development of more advanced and formal recycling technologies, thereby reducing negative environmental impacts (Rucevska et al., 2015; Yang et al., 2021).

E-waste holds economic value through the recovery of secondary materials, which helps conserve diminishing primary raw materials. Since the linear economic model leads to greater waste generation, realising this economic value necessitates a closed-loop (circular) economic model. However, while many countries focus on managing municipal solid waste, e-waste management often receives less attention. Few countries allocate sufficient budgets for e-waste management, as the infrastructure for e-waste recycling and treatment requires significant capital investment (Rautela et al., 2021). For this reason, it is suggested that mobile e-waste recycling facilities that can be established in some cities can be effective both to raise awareness in the society, establish an affordable system, and develop a circular economic structure (Song et al., 2015; Zeng et al., 2015).

## *Environment and Health*

Although e-waste can be viewed as a source urban mine of valuable materials, it also contains toxic substances that can pose serious environmental and health hazards (Ahirwar & Tripathi, 2021). The main reasons for this are: (i) processing of e-waste with primitive methods in countries with a large informal economy in the e-waste sector (Table 6), (ii) unregistered e-waste exports from DCs to ECs, (iii) and e-waste imports by ECs despite the lack of appropriate technology for e-waste recycling. While Brazil, China, Ghana, and India stand out here, the fact that no measures are taken in this regard increases the likelihood of these practices spreading to other countries in Africa, Asia, and South America (Puckett & Smith, 2002; Mundada et al., 2004; Brigden et al., 2005; Puckett et al., 2005; Leung et al., 2006; Bi et al., 2007; Huo et al., 2007; Wong et al., 2007; Leung et al., 2008; Luo et al., 2009; Ye et al., 2009; Sepúlveda et al., 2010; Liu et al., 2022).

**Table 6**

*Comparison of selected countries within the framework of given criteria*

| Country | Value attributed to UEEE | | Dominant sector | | Legal regulation on e-waste | |
|---|---|---|---|---|---|---|
| | Waste | Precious | Formal | Informal | Yes | No |
| **Australia** | √ | | √ | | √ | |
| **Brazil** | | √ | | √ | √ | |
| **China** | | √ | | √ | √ | |
| **Germany** | √ | | √ | | √ | |
| **Ghana** | | √ | | √ | √ | |
| **India** | | √ | | √ | √ | |
| **Japan** | √ | | √ | | √ | |
| **South Korea** | | √ | √ | | √ | |
| **Switzerland** | √ | | √ | | √ | |
| **Türkiye** | | √ | | √ | √ | |
| **USA** | √ | | √ | | √ | |

**Source:** Adapted from Borthakur & Govind, 2017; Quaye et al., 2019; Owusu-Twum et al., 2022.

The complexity of the composition of e-products poses significant new challenges for recycling, thus requiring technical solutions. This is because recovering certain materials often results in the unavoidable loss of others (Reuter & Verhoef, 2004). The complexity of the materials, along with significant logistical challenges and disorganised recycling processes, can make the entire recycling chain unprofitable, depending on the type of product. This is increasingly triggering informal e-waste exports from developed European countries, the USA, and Japan to ECs. The economic drivers of these informal exports have several aspects: (i) avoiding taxes and (ii) avoiding investment and labour costs (Kellenberg, 2012). On the other hand, e-waste with valuable materials compensates for the cost disadvantages. This leads the exporting country to make a choice based on the recycling value of e-waste. If components from a significant portion of e-products can be sold for reuse in the importing country, the revenue generated can, in many cases, offset the system's inefficiencies. The remaining bulk, which cannot be reused, is often sold to informal operators in importing countries (especially in Asia) or is simply incinerated or dumped in landfills (especially in Africa) (Rochat et al., 2007).

In the 1970s and 1980s, DCs exported hazardous waste to ECs for final disposal, leading to substantial environmental pollution. The Basel Convention came into force in 1992 to address this problem. However, there are two points within this structure that are ethically controversial. The first is that hazardous waste exports for final disposal have been replaced by waste trade for reuse and recycling (Liu et al., 2006; Wong et al., 2007; Bisschop, 2012; Sthiannopkao & Wong, 2013; Breivik et al., 2014; Ilankoon et al., 2018). The second is the incidence of child labour in informal e-waste industries in these regions, with children suffering significant health problems (Grigg, 2004; Huo et al., 2007; Leung et al., 2008; Perkins et al., 2014; Pascale et al., 2016; Zeng et al., 2016; Zeng et al., 2020; Lebbie et al., 2021).

While ECs are implementing countermeasures to address e-waste imports and ensure environmentally sound treatment, these efforts require increased action at the local, regional, national, and international levels. This is primarily due to the complex transnational supply chain of e-products. In this regard, Europe and North America could play crucial roles in reducing hazardous emissions from global e-waste and facilitating the recovery of valuable materials by closely monitoring e-waste flows to their final destinations and preventing unregistered or questionable exports.

The representative DCs and ECs selected in this study hold significant environmental and market value. These countries possess substantial financial resources and abundant natural wealth. They also make up a large portion of the world's population, land area, and gross domestic product (GDP), underscoring the need for responsible e-waste management. While this focus is particularly highlighted in the selected countries, it can be argued that similar challenges are faced by other nations across different continents, based on the criteria used to choose these countries.

## Conclusion and Recommendations

The analysis reveals that each of the ECs examined in this study faces challenges in one or more key areas of e-waste management: (i) the organisation of e-waste systems, including separation, collection, transport, and recovery; (ii) the development of appropriate infrastructure for disposal; and (iii) the regulation of hazardous substances contained in e-waste. In developed countries (DCs), the predominant approach remains the export of e-waste to developing nations, resulting in Asia and Africa becoming primary destinations for discarded electronics.

Overall, the findings show that the rapid growth of e-waste generation exceeds the capacity of existing collection and disposal systems. This gap is driving an increase in informal and often unsafe recovery practices. The lack of a comprehensive framework for tracking and regulating hazardous waste further complicates effective e-waste management, as observed in the countries included in this study.

The conclusions drawn from this analysis are broadly applicable to other countries with similar socioeconomic conditions:

(i) To effectively address the e-waste challenge, each country must develop a recycling system that aligns with its available resources as well as its economic and social context. This includes building a material recovery infrastructure and addressing income disparities between developed and emerging countries. For instance, in Ghana, financial, legal, and sociocultural limitations hinder the direct adoption of models from developed countries. A more practical approach is to formally recognise and regulate the informal sector by integrating it into the official system through inclusive stakeholder engagement. Rather than imposing prohibitions on informal practices, Ghana would benefit from gradual integration strategies that channel national and international resources towards formalisation, without marginalising existing informal operations.

(ii) ECs should adopt e-waste regulations that are tailored to their specific needs while drawing on the experiences of more advanced systems. For example, Australia's approach—adapting Japan's e-product recovery targets, Switzerland's clearly defined roles for key actors, and the European collection and recycling framework—serves as a valuable model for other nations seeking to build effective, context-sensitive e-waste management systems.

(iii) To transform component materials into valuable inputs for future products and reduce reliance on raw materials, countries should incorporate life-cycle analysis (LCA), material flow analysis (MFA), multi-criteria analysis (MCA), and extended producer responsibility (EPR) approaches into their e-product regulations. In Türkiye, for example, EPR is explicitly referenced in current e-waste legislation. However, for the system to mature, it is crucial that LCA, MFA, and MCA are also clearly defined, conceptually integrated, and actively promoted among e-product manufacturers. These approaches are vital for the development of a reverse logistics system. Although Türkiye has made progress—increasing the number of licenced e-waste processing facilities from 21 in 2011 (Öztürk, 2015) to 107 in 2021 (ÇŞİB, 2022)—collection rates remain low, with only 10.9% of e-waste collected in 2020 (ÇŞİB, 2020). This indicates that while regulatory frameworks exist, implementation and system development are lagging. Similar findings were noted in earlier fieldwork by Erol et al. (2010). Applying these analytical approaches not only supports technological innovation but also helps build a comprehensive e-waste database and inform the design of fiscal instruments, such as taxes on e-products. A public policy framework that integrates these tools enables a full assessment of the e-waste lifecycle—from production to disposal—allowing for the more effective use of command-and-control instruments, economic incentives, and market-based tools like tradable recycling credits. In doing so, product- and process-based policies can be more strategically aligned within e-waste management systems.

(iv) An effective and practical monitoring system is essential for tracking the movement and treatment of e-waste, similar to the domestic system implemented in South Korea. In addition, coordinated international action is needed to curb cross-border shipments of e-waste to ECs that lack the infrastructure and technical capacity to manage hazardous materials safely. To achieve this, integrated global organisations should be established to monitor and regulate the generation and transboundary movement of specific e-waste streams worldwide.

(v) Governments in both DCs and ECs should adopt targeted marketing and awareness strategies to promote responsible e-waste collection. These efforts should aim to educate producers and consumers alike on the environmental and health hazards associated with improper disposal, as well as the benefits of recycling and resource conservation. Public-private partnerships and community engagement programmes can play a key role in promoting formal e-waste channels, thereby reducing reliance on informal and unsafe disposal practices.

(vi) Finally, the concept of an ecoindustrial park (EIP) focuses on transitioning from a linear model of production to a closed-loop system that minimises both waste and pollution. Globally, several case studies[30]

[30]See for examples of EIP: *Gladstone, Kwinana* (Australia) (Beers et al., 2007); *Ecopark Hartberg* (Austria) (Liwarska-Bizukojc et al., 2009); *Styria* (Austria) (Chertow, 2007; Ashton et al., 2017; Domenech et al., 2019); *Burnside* (Canada) (Geng & Côté, 2002; Lambert & Boons, 2002; Wright et al., 2009); *BNEIDP, SCIP* (China) (Zhang et al., 2009; Yune et al., 2016); *Guitang* (China) (Zhu et al., 2007); *Lubei EIP* (China) (Wang et al., 2010a); *MCIP* (China) (Guo et al., 2016); *QJIS* (China) (Sun et al., 2017); *SIP* (China) (Mathews & Tan, 2011); *TEDA* (China) (Shi et al., 2010; Zhang et al., 2013; Yu et al., 2014); *Kalundborg* (Denmark) (Ehrenfeld & Gertler, 1997;

—most notably *Kalundborg* in Denmark—have demonstrated the viability of EIP and provided valuable incentives for establishing similar systems for e-waste or integrating them into existing industrial zones. E-waste, due to its material composition and high recovery value, is particularly well-suited for such systems. For Türkiye and other ECs, the development of EIP could play a critical role in advancing circular economy practices and technological infrastructure. In this context, mandating the inclusion of e-waste processing facilities within existing Organised Industrial Zones (OIZs) could promote inter-firm collaboration and more efficient material recovery.

Incorporating e-waste into the EIP model is also essential from a global competitiveness perspective, as many DCs with advanced recovery technologies import valuable e-waste streams. Turkish regulations allow for the export of e-waste when domestic recovery capacity is lacking and prohibit the import of hazardous waste under the Basel Convention. However, non-hazardous e-waste materials may be imported under regulatory control. Establishing proper infrastructure would enable Türkiye to engage in the controlled import of high-value, non-hazardous e-waste, opening opportunities for income generation, job creation, and technological advancement. To support this, public authorities could incentivize private investment by subsidising the development of EIP focused on e-waste processing.

In sum, for ECs in particular, addressing persistent challenges in e-waste management—such as limited infrastructure, dominance of the informal sector, and weak policy enforcement—requires the following context-specific solutions:

- Integrate the informal sector through licencing, capacity-building, and incentives to promote formal participation in e-waste recovery.
- Deploy mobile recycling units (MRUs) to extend collection and pre-processing services to rural and underserved regions.
- Establish a national e-product tracking system to monitor the life cycle of electronics and enforce producer responsibility.
- Implement phased EPR targets with compliance schedules tailored to company size and product category.
- Promote eco-design and green procurement using tax credits, R&D support, and mandatory standards for public institutions.
- Conduct region-specific awareness campaigns and integrate e-waste topics into school curricula to foster long-term behavioural change.
- Support local recyclers with grants or co-financing mechanisms to improve infrastructure and ensure environmental compliance.
- Create a national e-waste fund, financed by Advanced Recycling Fee or EPR contributions, to support recycling infrastructure, data systems, and innovation.

These measures align with circular economy principles and can help ECs build a sustainable, inclusive, and transparent e-waste management systems.

Chertow, 2000; Jacobsen, 2006; Chertow & Ehrenfeld, 2012; Branson, 2016; Valentine, 2016; Ashton et al., 2017); *Crewe Business Park* (England), *Value Park* (Germany), *The Environmental Park* (Italy) (Valentino, 2015); *Naroda* (India) (Singhal & Kapur, 2002; Bain et al., 2010); *Porto Margherafpar* (Italy) (Mannino et al., 2015); *Kawasaki* (Japan) (Berkel et al., 2009); *RiVu, Moerdijk, INES* (Netherlands) (Heeres et al., 2004); *The Kleefse Waard* (Netherlands) (Eilering & Vermeulen, 2004); *MIP* (South Korea) (Kim, 2007); *Ulsan* (South Korea) (Park et al., 2008; Behera et al., 2012); *NRIE* (Thailand) (Panyathanakun et al., 2013); *Lin-Hai IP* (Taiwan) (Li et al., 2015); *Brownsville, Devens, Fairfield* (USA) (Veleva et al., 2015; Veleva et al., 2016).

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# Appendix

**Table A1:** Information on the e-products used in the creation of the total e-waste series

| Classification | | E-products | Wt of item (kg) | Typical life (year) |
|---|---|---|---|---|
| 1 | Temperature exchange equipments | | | |
| | | Air conditioning | 30 | 15 |
| | | Dehumidifying | 10 | 10 |
| | | Freezers | 50 | 20 |
| | | Heat pumps | 50 | 20 |
| | | Refrigerators | 60 | 20 |
| 2 | Screens | | | |
| | | Laptops | 1 | 7 |
| | | LCD photo frames | 0.5 | 10 |
| | | Monitors | 2 | 15 |
| | | Notebooks | 1 | 7 |
| | | Screens | 1 | 15 |
| | | Televisions | 10 | 15 |
| 3 | Lamps | | | |
| | | Compact fluorescent lamps | 0.2 | 15 |
| | | Fluorescent lamps | 0.5 | 10 |
| | | High intensity discharge lamps | 1 | 15 |
| | | Low pressure sodium lamps | 0.5 | 10 |
| | | Straight fluorescent lamps | 0.5 | 10 |
| 4 | Large equipments | | | |
| | | Appliances for knitting and weaving | 5 | 20 |
| | | Clothes dryers | 40 | 15 |
| | | Cookers | 5 | 20 |
| | | Copying equipment | 10 | 20 |
| | | Dish washing machines | 50 | 15 |
| | | Electric hot plates | 1 | 10 |
| | | Electric stoves | 20 | 25 |
| | | Large appliances which automatically deliver products and money | 100 | 20 |
| | | Large coin slot machines | 100 | 30 |
| | | Large computer-mainframes | 500 | 20 |
| | | Large monitoring and control instruments | 10 | 25 |
| | | Large printing machines | 200 | 20 |
| | | LED | 0.05 | 25 |
| | | Luminaires | 1 | 15 |
| | | Photovoltaic panels | 10 | 30 |
| | | Washing machines | 50 | 15 |
| 5 | Small equipments | | | |
| | | Appliances for sewing | 5 | 20 |

| Classification | E-products | Wt of item (kg) | Typical life (year) |
|---|---|---|---|
| | Calculators | 0.1 | 10 |
| | Carpet sweepers | 2 | 10 |
| | Clocks and Watches | 0.1 | 10 |
| | Computers for biking, diving, running, rowing, etc. | 0.5 | 5 |
| | Electric kettles | 1 | 10 |
| | Electric knives | 0.5 | 10 |
| | Electric shavers | 0.5 | 10 |
| | Hi-fi equipment | 5 | 20 |
| | Irons | 1 | 20 |
| | Microwaves | 15 | 10 |
| | Radio sets | 2 | 15 |
| | Small appliances which automatically deliver products | 0.5 | 15 |
| | Small equipment with integrated photovoltaic panels | 0.1 | 25 |
| | Small monitoring and control instruments | 0.5 | 15 |
| | Smoke detectors | 0.1 | 10 |
| | Sound recorder | 1 | 10 |
| | Thermostats | 0.2 | 20 |
| | Toasters | 1 | 15 |
| | Vacuum cleaners | 4 | 15 |
| | Video cameras | 1 | 10 |
| 6 Small IT and telecommunication equipments | | | |
| | GPS | 0.1 | 10 |
| | Mobile phones | 0.1 | 10 |
| | Personal computers | 5 | 10 |
| | Pocket calculators | 0.1 | 10 |
| | Printers | 3 | 10 |
| | Routers | 0.5 | 10 |
| | Telephones | 1 | 10 |

**Source:** Authors' internet research based on EU WEEE Directive (2012/19/EU).