Journal of Environmental Management 323 (2022) 116181

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

On the implementation of the circular economy route for E-waste management: A critical review and an analysis for the case of the state of Kuwait

S.M. Al-Salem [a,*], Gary Anthony Leeke [b], Mohammed Sherif El-Eskandarany [c], Maarten Van Haute [d], Achilleas Constantinou [e], Raf Dewil [f,g], Jan Baeyens [f,h]

[a] Environment & Life Sciences Research Centre, Kuwait Institute for Scientific Research (KISR), P.O. Box 24885, Safat, 13109, Kuwait
[b] School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham, UK
[c] Energy and Building Research Centre, Kuwait Institute for Scientific Research (KISR), Safat, 13109, Kuwait
[d] Q8 Research, Kuwait Petroleum Research and Technology B.V., Moezelweg 251, 3198, LS, Europoort Rotterdam, Netherlands
[e] Department of Chemical Engineering, Cyprus University of Technology, 57 Corner of Athinon and Anexartisias, 3036, Limassol, Cyprus
[f] Department of Chemical Engineering, KU Leuven, J. De Nayerlaan 5, Sint-Katelijne, Waver, 2860, Belgium
[g] Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK
[h] Beijing Advanced Innovation Centre for Soft Matter Science and Engineering, Beijing University of Chemical Technology, Chaoyang District, Beijing, 100029, China

ARTICLE INFO

Keywords:
E-Waste
E-Plastics
MFA
Kuwait
Recycling

ABSTRACT

Electronic waste (e-waste) has become one of the major causes of environmental concerns due to its large volume, high generation rate and toxic environmental burdens. Recent estimates put e-waste generation at about 54 million tonnes per annum with figures reaching approximately 75 million tonnes per annum by 2030. In this manuscript, the state-of-the-art technologies and techniques for segregation, recovery and recycling of e-waste with a special focus on the valorisation aspects of e-plastics and e-metals which are critically reviewed. A history and insight into environmental aspects and regulation/legislations are presented including those that could be adopted in the near future for e-waste management. The prospects of implementing such technologies in the State of Kuwait for the recovery of materials and energy from e-waste where infrastructure is lacking still for waste management are presented through Material Flow Analysis. The information showed that Kuwait has a major problem in waste accumulation. It is estimated that e-waste in Kuwait (with no accumulation or backlog) is generated at a rate of 67,000 tpa, and the imports of broadcasting electronics generate some 19,428 tonnes. After reviewing economic factors of potential recovered plastics, iron and glass from broadcasting devices in Kuwait as e-waste, a total revenue of $399,729 per annum is estimated from their valorisation. This revenue will open the prospect of ventures for other e-waste and fuel recovery options as well as environmental benefits and the move to a circular economy.

1. Introductory remark

In this high-tech digital era, electronic waste (e-waste) has become one of the major causes of environmental concerns due to its sheer large volume, high generation rate and toxic environmental burdens (Rocha and Penteado, 2021; Perea et al., 2021; Charitopoulou et al., 2022). Recent estimates put global e-waste generation at a rate of about 54 million tonnes per annum (Mtpa) (Forti et al., 2020) with figures reaching some 75 Mtonnes by the year 2030 (Madhav et al., 2022). Fig. 1 shows a projection of e-waste with respect to each year till 2030. E-waste also occupies a large volume of the global solid waste (SW) stream where it is estimated to comprise 5% of it globally (Hazra et al., 2019). It is essential to define e-waste and what constitutes to be such, especially that its definition seems to vary depending on region or country. The best definition of e-waste that encapsulates all major products deemed to be at their end-of-life stage, was laid out by the European Commission's (EC) (2012) directive. The directive defines e-waste as all waste of electrical and electronic equipment (EEE) that are rendered to be with no value or discarded at the end of their service life (EC, 2008), i.e., EEE that a holder discards or intends to or is required to

* Corresponding author.
E-mail address: ssalem@kisr.edu.kw (S.M. Al-Salem).

https://doi.org/10.1016/j.jenvman.2022.116181
Received 29 July 2022; Received in revised form 1 September 2022; Accepted 2 September 2022
Available online 12 September 2022
0301-4797/

discard. Table 1 shows the main definitions which are used and followed in the logical thinking of this work based on the EC's directives and are considered to be most comprehensive.

Due to the recent estimated trends of e-waste accumulation and its special nature, it is therefore paramount to segregate it properly and avoid its landfilling at all cost especially when considering its environmental toxicity. It is also critical to understand the fact that the majority of e-waste contains highly valuable materials, including precious metals, that are essential to recover for sustainable practices to avoid over-mining and exploiting natural resources. Henceforth, it is encouraged the world over to start adopting new strategic thinking that encapsulates environmental protection with a more energy and economic turnover that will help boost the *circularity* concept. Implementing such concepts would essentially require a systematic change and an evolution to the economy and society alike (Aminoff and Sundqvist-Andberg, 2021). This is also especially true for the Asian continent whereby many countries still struggle to entice the public to participate in e-waste management programs and start implementing effective strategies for such (Kuah and Wang, 2020). Sengupta et al. (2022) stated as an Asian example that only one-third of e-waste is processed by formal recyclers in India. On the other hand, Kumar et al. (2022) showed that in emerging economies such as many Asian ones; regulations and e-waste policies are considered to be amongst the main enablers. In this work, the state-of-the-art technologies and techniques for recovery and recycling of e-waste are presented after a critical review with special focus on the valorisation aspects of e-plastics and e-metals. This is done comprehensively after depicting major types of e-waste and its components. We also present for the first-time prospects of implementing such technologies in the State of Kuwait for the recovery of materials and energy from such types of SW where infrastructure is lacking still for waste management. The article focuses on aspects dedicated to enhance circularity and shifting away from conventional linear economy, which has become a major research topic nowadays (Pan et al., 2022; Lee, 2022). The article finally concludes with an insight into environmental aspects and regulation/legislations that could be adopted in the near future for e-waste management.

1.1. Methodology

A detailed review of available technical literature was conducted in a sequential step-wise order that involved reiterations of literature searches at each step which are summarised in Fig. 2 for the reader's consideration. The first step was divided into two sub-tasks that went parallel to each other, and were in the first part (Step 1.1. - Fig. 2) the technical literature related to e-waste recovery, separation and segregation, quantities and generation rates, metal and materials recovery. The gaps in research and development (R&D) were also identified and a summary of available industrial and bench scale techniques of materials recovery is shown. The second part (Step 1.2. - Fig. 2) focused on the regulatory information and laws/by-laws/frameworks dedicated to e-waste, globally and with special emphasis on EU regulations since it is considered to be the most technically advanced and well documented. Various keywords were also cross-checked in the literature search, and to achieve the required information for Step 2 (technologies/industrial and bench-scale summary), a search of various databases was conducted. These include Sciencedirect, SCOPUS and IEEE Xplore; in addition to, Google Scholar. The search includes peer-reviewed journal articles, conference proceedings, books and book chapters, patents and technical research reports. The four main keywords used in the database search were as follows: E-Waste, E-Plastic, Hazardous Waste and WEEE. Figs. S1–S3 of the Supplementary Materials File shows the main results of the database search conducted in this work for the keywords considered. The keyword 'Circular Economy' was not documented, as it was separately searched after first cross-checking with each keyword of relevance as a combination.

1.2. Rationale and search results analysis

The recorded references (post database search) indicated a tangible increase after the year 2018 (over 30% by number). The range of search

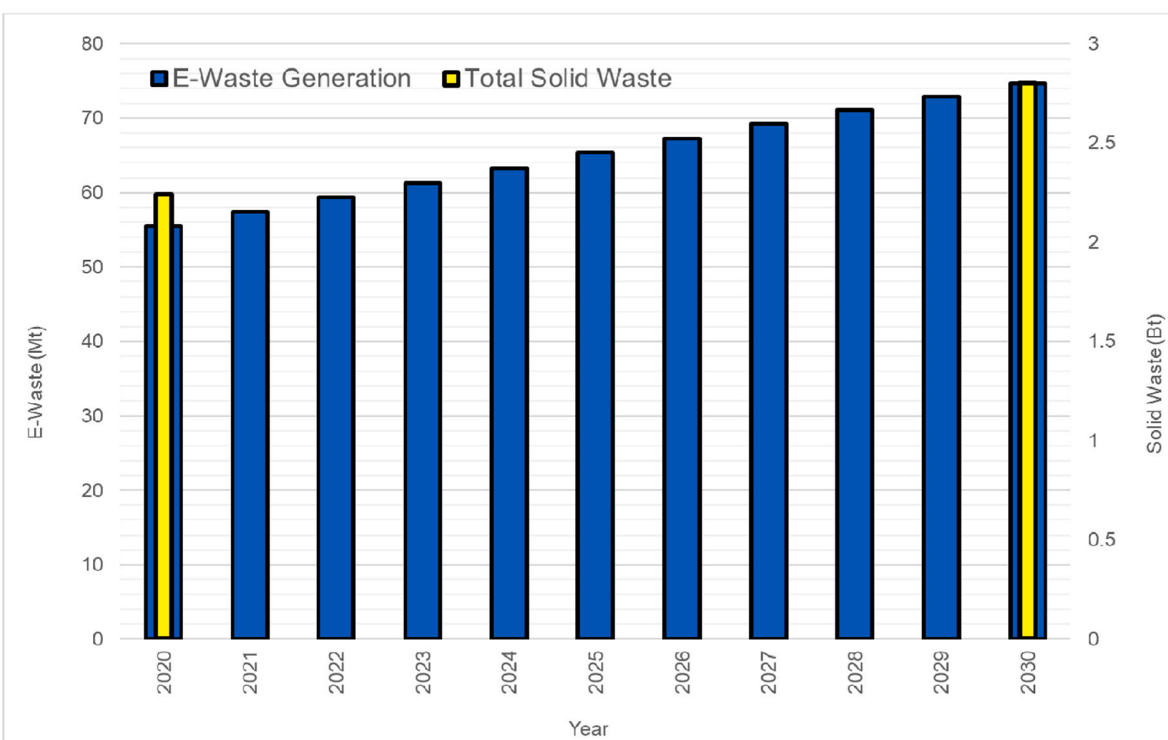

Fig. 1. E-Waste (million tonnes, Mt) and total solid waste (billion tonnes, Bt) generation as a function of the projected year between 2020 and 2030. Data Source: Forti et al. (2020), Shittu et al. (2021) and Kaza et al. (2021). Note to reader: Secondary axis is used for solid waste including biomass.

Table 1
Main definitions followed in this work.

Terminology/Definition[a]		Reference
Waste	Substance/object that the holder discards or intends/required to discard	EC (2008) - Directive 2008/98/EC
Hazardous Waste	"Waste which displays one or more of the properties listed in Annex III of the same directive", e.g., Explosive, Oxidising, Harmful, Toxic, Ecotoxic, etc. E-Waste in general falls in this category.	
By-Product	"Substances/objects resulting from a production process not primarily aimed at producing such substances or objects".	
Electronic Waste (E-Waste)	"Electrical or electronic equipment which are waste (as described above) including all components, sub-assemblies and consumables which are part of the product at the time of discarding". An older definition also exists and is quite common based on EU Directive 2002/96/EC which defines e-waste as "obsolete equipment that is dependent on electric currents or electromagnetic fields to work properly and equipment for the generation, transfer and measurement of such current"	EC (2012) - Directive 2012/19/EU EC (2002) - Directive 2002/96/EC Jirang and Roven (2011) Tanskanen (2013)
Plastics in Electronics (E-Plastics)	Plastic content in end-of-life devices.	Elliot (2017)
Electrical and Electronic Equipment (EEE)	Equipment which is dependent on electric currents or electromagnetic fields in order to work.	EC (2012) - Directive 2012/19/EU
Circular Economy (CE)	"An economy system that is constructed from production-consumption systems which maximises the service produced from the material and energy". It is also an umbrella for the various R's: reduce, repair, recycle, remanufacture and refurbish-life cycle thinking, cradle-to-cradle, circular design. It follows the key concept of prolonging the life of waste material whilst preserving its value. The original concept originates from Boulding's (1966) view of the earth as a sphere of ecosystem from space with no exchange of matter.	Lehmann et al. (2022), EC (2019a, 2019b; 2020)
Linear Economy (LE)	"economy based on the take-make-dispose philosophy associated with primary and virgin resources"	Luthra et al. (2022)

Note to reader.
[a] Indicates direct quote from definition source.

by years of publication was between 2016 and 2022 (May 20th). This range was selected for two reasons. Firstly, it covers the majority of literature that encompasses the circular economy (CE) concept which migrated to technical references mainly after 2016 in a noticeable manner. The second is due to the fact that before 2016, no substantial search results were available on the terms WEEE and E-Waste in some databases such as IEEE Xplore. In the year 2015, the first circular economy action plan was published by the EU (EC, 2015) that showed tangible objectives with specific deadlines and timeframes. This is a clear reason behind the increase of technical literature post 2016. Fig. S1 shows the results obtained in Sciencedirect, where an increase of almost double was noticed for the keywords search between the years 2016–2021. The least number of documents was noticed for the term WEEE, 322 for the year 2016 and 300 for 2022 (till the month of May). The number of documents in SCOPUS was much less in general for all keywords searches, in some cases less than fivefold, such as the case of the keyword search "e-waste" (Fig. S2). Fig. S3 was scant with related literature but contained important conference proceedings that were also cross checked with those found on online open sources. The documents were also categorised further for both industrially appropriate technologies and R&D work that is still in development, as it will be shown later in this communication.

1.3. Country/site specific implementation

In addition to reviewing state of the art techniques of recovery for e-waste, this work aims at transferring knowledge and knowhow to the State of Kuwait. The country's waste management status is also summarised and reviewed, in addition to, main environmental and economic indicators. This was undertaken to achieve the goal of this work where we can recommend the best practice for e-waste management and how this can help reduce local environment burdens and boost the waste economy and less reliance on fossil fuels. The details and rationale for choosing Kuwait as a prime candidate for such, will be shown at later stages of this work. The circular economy aspect where it is implemented for Kuwait is also detailed.

2. E-waste constituents, sources and management

2.1. E-waste types and components

Over the past decade, the amount of e-waste generated from households and businesses has increased drastically. The fact that accessibility of electronic devices and reduction in their retail prices, has contributed greatly to its rapid generation rates. Furthermore, high income and GDP regions have always been associated with high SW generation rates (Al-Salem et al., 2018). Technological advances have also contributed greatly in e-waste generation. A prime example of which are mobile phone devices, whereby in the year 2020 it was estimated that over 14 billion mobiles were in circulation. This number increased to about 15 billion devices in 2021 and is projected to reach 18.2 billion 2025 (Statita, 2021a). The United Nations Environment Programme (UNEP) have also recently indicated that mobile phones are likely to increase eighteen times; and that both personal computers and television sets are to be present by five and two times higher in e-waste, respectively (Leung, 2019). If generation rates of e-waste by region or nation are considered, China is the largest when it comes to countries ranked as high producers of e-waste where it is estimated that it generated over 10 Mt in 2019 followed by the US (7 Mt) (Statita, 2021b). Asia is also the highest producing region of the world ranking first with about 46.5% of total e-waste generation in accordance with recent statistics (Fig. 3. a.). The Americas and Europe follow with estimates of 24.5% and 22.4%, respectively. However, to judge the ever-increasing e-waste rates; it is best to view them as per capita for each country. This is to give a better understanding of how consumer behaviour, policies and environmental awareness contribute to the SW component accumulation. When put in such context, China only produced a mere 7.2 kg per capita in 2022 (Statita, 2022). However, Norway ranks first globally (26 kg per capita) followed closely by the UK (24 kg per capita) (Fig. 3. b.). It is estimated that each EU citizen generates about 20 kg of e-waste annually (Zoeteman et al., 2010). Furthermore, the average household in the US uses 34 electronic devices which results in a 5 kg family average of e-waste from domestic appliances alone (Tanskanen, 2013). Table S1 further depicts e-waste generation rates with respect to regions around the world, in addition to other key statistics, e.g., value of raw materials, collection rate, etc., with a description of methods for calculation of collection estimates and recovery (%).

E-waste is typically categorised based on its type, composition or its size. Various categories exist for e-waste that are reported in numerous

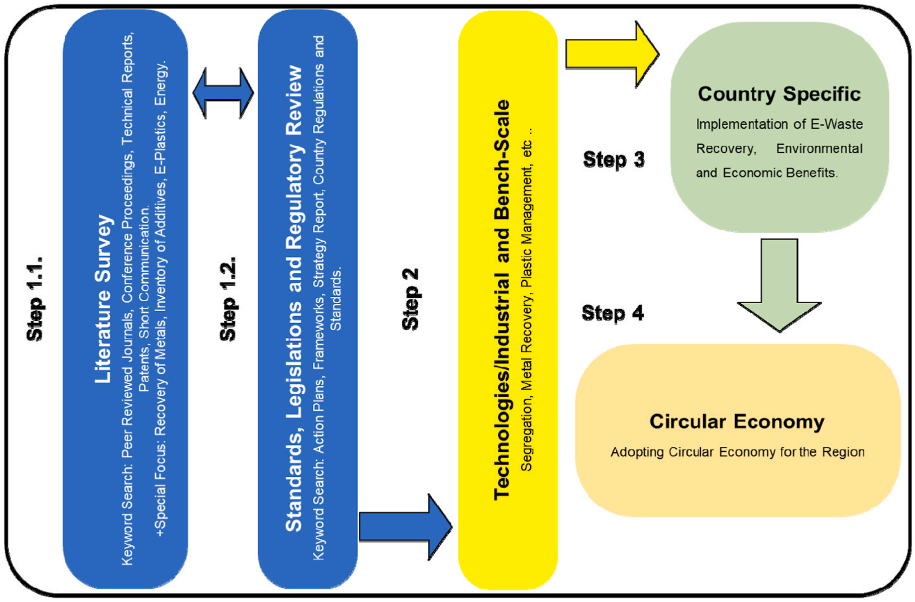

Fig. 2. Schematic Depiction of the Methodology Undertaken in this Work.

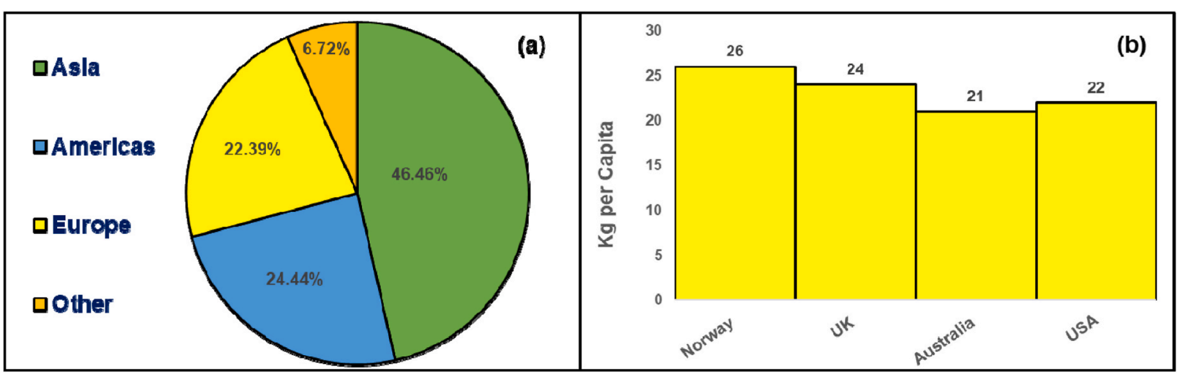

Fig. 3. E-Waste generation rate (a) by percentile distribution among world regions and (b) per capita generation for every million tonnes. Data source: Statita (2021a, 2021b; 2022).

technical reports and scientific literature. As e-waste encompasses electrical and electronics machinery, it could be categorised based on either its physical composition or by electrical equipment which makes up about 50% of its constituents worldwide (e.g., electrical appliances). The other 50% of the electronic waste covers monitors, television sets, etc. (Schwarzer et al., 2005; Hossain et al., 2015). E-waste is often classified based on its size or level of hazardousness (e.g., levels of persistent organic pollutants (POPs), heavy metals or additives, see Table 1 for hazardous waste classification). The UK government for example categorises and classifies e-waste based on presence of hazardous substances (i.e., POPs, mercury, etc.) which could be from either household, industrial or commercial sources and will also comprise LEDs, halogen and incandescent containing hazardous substances (UK GOV, 2022). The EU classification, on the other hand, dismisses to date batteries and does not include them in categories of e-waste. Nonetheless, a major part of household generated e-waste is made up of batteries and appliances. Alkaline and lithium-ion batteries are typically found in municipal solid waste (MSW) when not properly managed and segregated. They include zinc anode (Zn) in the form of powder, potassium hydroxide (KOH) pastes and magnesium dioxide (MnO_2), in addition to graphite cathode (Anholeti et al., 2022). The amount of Zn and Mn alone in such devices make up about 20 and 30 wt%, respectively (Hamade et al., 2020; Forti et al., 2020). Fig. 4 classifies e-waste based on categories and types of various origins which are standardised across the majority of developed countries.

E-waste is a non-homogeneous mixture of various chemically toxic chemicals and physical texture containing hundreds of hazardous substances (Williams, 2016). Furthermore, e-waste can be grouped into five main categories as described by Shittu et al. (2021) as per the following: Ferrous metals, Non-ferrous metals, Glass, Plastics and other materials (typically inert). Metals are the most toxic substance and make up the largest part of EEEs by size and weight (Ongondo et al., 2011a, 2011b; Ongondo and Williams, 2011; Baldé et al., 2015; Beigl et al., 2017). Plastics (or as referred to in recent works, e-plastics - see Table 1) make up about 30% of e-waste (Hossain et al., 2015; Nagajothi and Felixkala, 2015). Metals comprise between 40 and 60% of e-waste, whilst hazardous pollutants make up about 2.7% (Nagajothi and Felixkala, 2015). E-Waste could be considered as an urban mine of high value (Shittu et al., 2021; Tanrıverdi, 2021). It should be recognised that metals present in e-waste are of high value as precious and rare elements that have a high market value (Islam et al., 2020). Table S2 summarises the market price of common metals found in e-waste which could be found in the Supplementary Materials File. Typical metal constituents in e-waste are gold (Au), silver (Ag), platinum (Pt), palladium (Pd), rhodium (Rh), lead (Pb), copper (Cu), iron (Fe), tin (Sn) arsenic (As), mercury (Hg) and aluminium (Al). All of these metals are toxic to soil and ground water when e-waste is not handled properly. The main source of the above metals is in the glass used in electronics, cathode ray

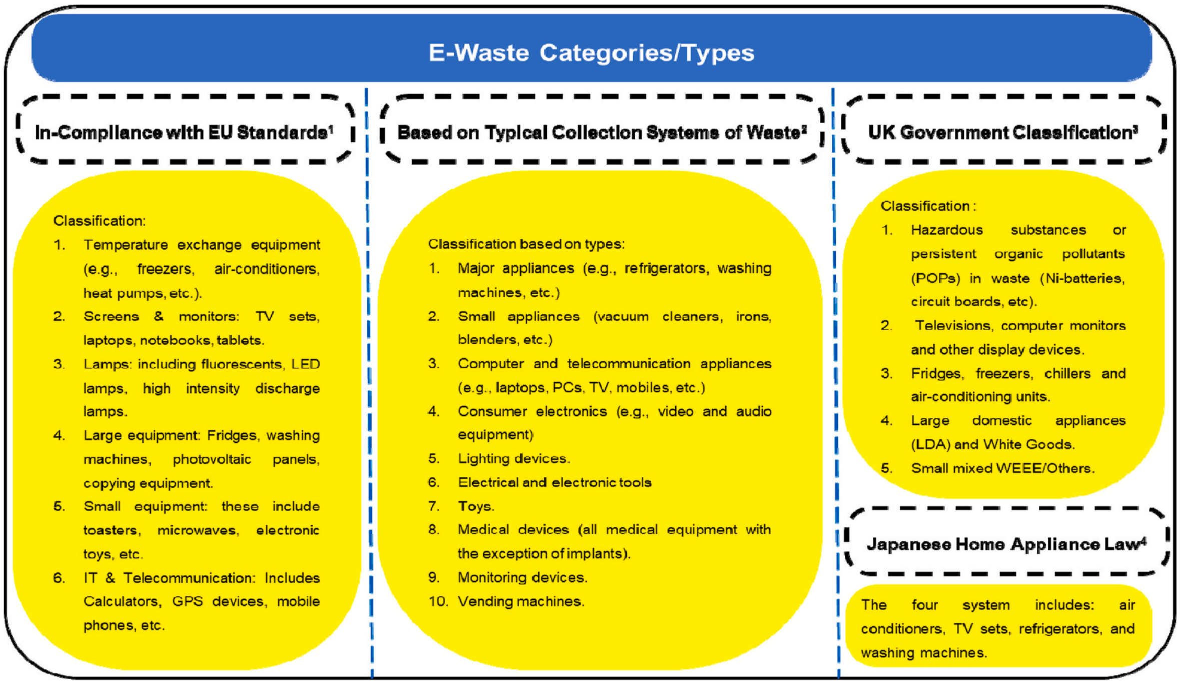

Fig. 4. E-Waste Common Classifications/Types. Note for reader: 1. Based on EU system in-accordance with EU Directive 2003/108/EC (EC, 2003a) and Forti et al. (2020), which excludes batteries to date. 2. Based on the Danish collection and recycling system of E-Waste (Pedersen, 2019). 3. Based on HM Government classification of waste types in the UK namely considering hazardousness of components (UK GOV, 2022). 4. Based on Japan's collection and appliance recycling law of 2001 (Yoshida and Yoshida, 2013).

tubes, switches, monitors and screens, batteries and solders (Matthews et al., 1996; Burstall, 1997; Lau et al., 2001). E-waste can be categorised based on the material flow analysis (MFA) from various points of origin where the chain of generation is depicted in a bottom-up approach via distinct levels of hierarchical layers (Nagajothi and Felixkala, 2015). This approach also facilitates the level of interaction with the various stakeholders involved and could be applied to different regions or countries.

E-waste also includes various interconnected components that also have a potential for recovery such as wire coating and cables. Phthalates are present in such components in the form di (2-ethylhexyl) phthalate (DEHP), diisononyl phthalate (DINP) and dibutyl phthalate (DBP), amongst other types (Otake et al., 2001; Fromme et al., 2004). Other compounds such as chlorinated ones, are also present in e-waste such as polychlorinated biphenyls which are released from capacitor dielectrics, hydraulic fluids, printing inks, plasticizers and transformer oils. These chlorinated compounds will also produce polychlorinated biphenyls in the combustion of e-waste containing PVC (Sivaramanan, 2013). Table S3 shows the major chemical compounds found in e-waste with potential impact on surrounding environments and require handling in dedicated process lines.

2.2. E-plastics

EEE contains a large proportion of plastics which are an essential part of the design of such equipment providing insulation, support frames and safety measures. The plastic material provided in casings or as a part of EEE is commonly referred to as 'e-plastics' nowadays, which are an essential material with potentially high value for recovery in end-of-life devices ranging between 10 and 30 wt% depending on the device (see Table 1 - Barouta et al., 2022, Wäger et al., 2012; Tanskanen, 2013, Esposito et al., 2020; Gómez et al., 2020, Charitopoulou et al., 2022). The major part of these e-plastics is of a thermoplastic nature, applicable for mechanical or chemical recycling with potential for fuel and energy recovery (Martinho et al., 2012). Furthermore, the EU WEEE Directive 2012/19/EU (EC, 2012) sets minimum recovery targets that should be met in allotted timeframes which present additional constraints on Governments and recyclers alike. According to Annex V of the aforementioned Directive, 75–85% of WEEE should be recovered; and 55–80% should be recycled depending on the type of e-waste. This presents quite a challenge on recyclers, as the majority of material recovery facilities (MRFs) are geared towards metals recovery or material separation for combined heat and power generation (Al-Salem et al., 2014a, 2014b; Palmieri et al., 2014). E-plastics also present a technical challenge for mechanical recycling using conventional physical treatment methods I due to its heterogeneity and the presence of a large number of additives used to tailor its use (Maris et al., 2015). The readers are referred to Al-Salem (2019) for a detailed list of additives used in plastics engineering and their application. Furthermore, a summary of major polymeric constituents and additives are detailed in Fig. 5. In addition, MRFs typically rely on SW segregation using manual separation or laser techniques. In the case of e-waste, identification of plastic types is carried out based on the codes printed on the equipment which might cause confusion when handling large volumes of waste (Beccagutti et al., 2016).

E-plastics are made of a complex (and a heterogenous) mixture of polymers and additives (Fig. 5) (Wäger et al., 2012; Dimitrakakis et al., 2009a, 2009b; Maris et al., 2015; Peeters et al., 2014; Schlummer et al., 2005, 2007; Stenvall et al., 2013). Major fractions of e-plastics have also been associated with toxic effects and health related issues which also limits their re-use potential despite their recyclability (Gómez et al., 2020). Different constituents of plastics are present in different products. Wang et al. (2018) showed that TV sets can contain a range of 20.6–27.3% of plastics in their make. Furthermore, Singh et al. (2020) stated that waste mobile phones can contain 25–55% of plastics; and that household appliances can contain anything between 20 and 40% of plastics. A prime example of e-plastics accumulation as a major component of SW could be traced back to the amount of Cd, Pb and Hg accumulated from the disposal of obsolete personal computers (PCs) between 1994 and 2003. More than 500 million PCs were deemed

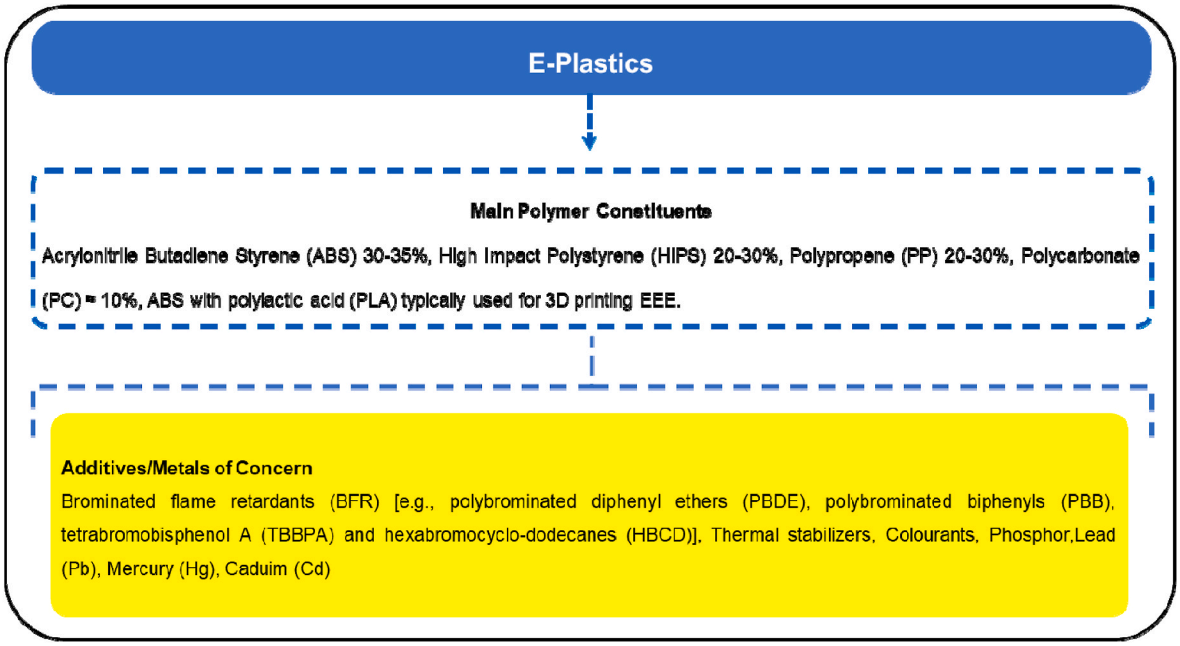

Fig. 5. Major Constituents of E-Plastics (Additives and Polymers of interest). Data Source: Al-Salem (2019), Gómez et al. (2020), Charitopoulou et al. (2022).

obsolete in that timeframe which resulted in the accumulation of 2.872 million tonnes of e-plastics that contained 718,000 tonnes of Pb, 1363 tonnes of Cd, and 287 tonnes of Hg (Herat, 2007; Widmer et al., 2005). In addition, e-plastics contain flame retardants (FRs) that makes it imperative to separate e-plastics from regular other household plastic solid waste (PSW) when considering recycling options. Brominated flame retardants (BFRs) are one of the largest marketed and consumed FR which account for 19% of its market and is estimated to be over 2.39 million tonnes worth \$12.81 billion (FRM, 2022; FRs, 2022). The main consumer of this market is the Asian region due to their large EEE production where some 40% of FRs in such appliances are made of BFRs (Tange and Slijkhuis, 2009). The most widely used BFRs are tetrabromobisphenol-A (TBBPA) and polybrominated diphenyl ethers (PBDEs), particularly decabromodiphenyl ether (Gómez et al., 2020) (Fig. 5). Various regulations govern the FRs market which also limit their use in further recovery and recycling processes of e-waste. The most notable regulations of such chemicals are derived from internationally recognised governing bodies such as Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH), US Environmental Protection Agency (EPA), Restriction of Hazardous Substances (RoHS) and EU WEEE Directive (FRM, 2022). These restrictions which typically limit FRs to well below 1%, and the fact that e-plastics exhibit good tensile strength and flexural modulus; makes them a prime candidate for use in construction and building applications as substitutes or fillers for slab or concrete (Schlummer et al., 2006; Buekens and Yang, 2014; Luhar and Luhar, 2019; Siddique et al., 2008; Saikia and De Brito, 2012; Gu and Ozbakkaloglu, 2016, Senthil Kumar and Baskar, 2018). Furthermore, the increasing control on phthalate plasticizers, heavy metals, alkylphenols, brominated flame retardants and POPs in e-plastics (and e-waste in more generic terms), limits their recycling options and makes it harder to establish a viable market for them (Alassali et al., 2020a; 2020b, 2020c; Barouta et al., 2022). It should be noted that the majority of FRs, namely BFRs are characterised as POPs and their use is limited nowadays as previously depicted (Altarawneh et al., 2019). Tetrabromobisphenol A (TBBPA) and hexabromo cyclo-dodecanese (HBCD) are the most common BFRs accounting for more than 50% of its application by volume, in accordance with recent estimates (Charitopoulou et al., 2021). In addition, toxic brominated substances are also commonly known to migrate to the liquid fraction of pyrolysis products from e-plastics (e.g., pyro-oil) which also hinders their chemical recycling options and puts further restrictions on their use (Charitopoulou et al., 2021). This restricts brominated e-plastics from further material and products recovery, and makes their safe handling a requirement in the majority of e-waste protocols (Benedetti et al., 2017, see footnote of Table S3).

The control of the integrity and quality of e-plastics is paramount to its potential use and market value, in addition to its potential recyclability. MRFs that can manage to sustain a good practice whilst maintaining a good quality plastics product stream, can potentially sell e-plastics for 0.4 € per kilogram (Cafiero et al., 2021). This is a high price considering that conventional PSW is sold for 0.245 € per kilogram as of mid-2022 prices (Euro Stats, 2022). Therefore, it is a must that recyclers not only breakeven but maintain a good quality to their recyclates (i.e., recycled e-plastics) to have a viable market. This also explains the reasoning why the majority of reclaimed ABS and HIPS is sold for filament in additives application in 3D printing (Carneiro et al., 2015). These 3D printing filaments are typically sold at a price range between 20 and 50 € per kilogram (Cafiero et al., 2021).

2.3. Major segregation and pre-treatment technologies

Various amounts of household items are discarded alongside commercial SW where e-waste is typically mixed with such and most probably get segregated and recycled under inferior conditions (Forti et al., 2020). This can only lead to the loss of valuable components in e-waste which are not dealt with properly due to poor segregation. An international consortium led by the UN which involves a number of internationally recognised waste management authorities and academic bodies has recently published their latest report on global e-waste monitoring statistics (Forti et al., 2020). They have declared that undocumented e-waste leads to 50 tonnes of Hg and 71 ktonnes of BFRs accumulation in undocumented waste released to the environment and is associated with toxic impact and health related issues. E-waste is typically managed in one of four scenarios: (Williams, 2016; Baldé et al., 2015, 2017; Shittu et al., 2021; Forti et al., 2020):

- Scenario 1 (*formal documentation and collection*): This is the so-called optimal scenario where e-waste is collected in accordance with a coding system and as per regulations provided by legislations available for such type of SW. The collection of the e-waste is conducted herein using municipal depots and collection points (including pick-up points) or by EEE producers and retailers. Treatment facilities are responsible in this scenario for manual disassembly, condition/shredding and recycling in an environmentally sound matter.

- Scenario 2 (*direct disposal and treatment*): This scenario is predominant in regions and countries where shortcomings in collection and documentation occur due to a number of reasons, namely deficits in funds. E-waste is typically disposed of with no segregation alongside MSW and gets incinerated directly or landfilled despite negative economic and environmental implications.
- Scenario 3 (*unofficial/illegal collection*): This scenario involves the illegal collection and unofficial documentation of collected e-waste due to insufficient legislations or waste scavenging activities (Al-Salem et al., 2015), which might lead to various economic losses or illegal exportation of waste.
- Scenario 4 (*developing world e-waste management*): This scenario is predominant in developing world countries (WTO, 2022). E-waste in this scenario is collected informally by waste brokers and scrappers where no regulations govern such activities. Basic and rudimentary treatment takes place where metal components are typically sought after.

Improper segregation of e-waste including components of ferrous and non-ferrous metals nature, leads to vast accumulation of various regulated substances in urban environments as depicted prior in the aforementioned scenarios. To overcome such problems, a sequential step-wise cycle is followed to comply with the proper handling and management of e-waste (Islam et al., 2020):

- Step 1: This step involves segregation, processing and refining of e-waste which is used to prepare a raw material feedstock. Fees such as advanced disposal fees (ADF) and advanced recycling fees (ARF) should also be included.
- Step 2: The segregation and physical separation leads to a feedstock material appropriate for treatment where it is essential to condition the e-waste component for treatment and recovery processes in the next step.
- Step 3: The recovery of valuable metals and other products occurs in this final step, in accordance with regulations and laws of the country.

E-waste segregation and separation methods are essential to have an effective recycling scheme that will satisfy the requirements for each component quality, recover high value content such as precious metals and satisfy legislations for e-waste management (Tansel, 2017). Segregation methods involve fractionation and separation based on size reduction and physical treatment for sorting. However, at this stage of the work; it is essential to state that segregation and recovery facilities must comply with a number of regulations set out by various governing bodies, namely when intended to be commissioned on the European continent. The first of these regulations is set out by the WEEE Directive 2012/19/EU (EC, 2012), which sets out the recovery and recycling rates aforementioned in the previous section. Transboundary and movement restrictions on e-waste and derived materials are set out by the European Commission and the Basel Convention (BC) (EC, 2006; BC, 2014; Bruch et al., 2022). Finally, quality restrictions have to be met for all components derived from e-waste (EC, 2017a, 2017b).

Comminution techniques are normally carried out for e-waste as one of the most common separation methods. It aims at size reduction using mechanical/physical treatment methods to control the product's particle size distribution (Bruch et al., 2022). Disassemblement of e-waste is carried out in operations using rotor chain crushers without shear or cutting tools to ensure safe handling of hazardous components (Hoggerl, 2015; Linnenkoper and Reintjes, 2017; Salhofer et al., 2016). Hammer or impact milling processes are then used to adjust the mean particle size produced. Other techniques based on shock wave fragmentation (EHF) and electrodynamic fragmentation have also been reported (Bokelmann et al., 2017; Pestalozzi et al., 2018; Bruch et al., 2022). Such techniques are typically used on printed circuit boards (PCBs). Chemical sorting techniques are another common separation technology that are well established and can be of great benefit, namely for small particle sizes (Dalrymple et al., 2007; Wang and Xu, 2014; Zhang and Xu, 2016). These techniques will typically involve sieving, hydrocyclones separation, flotation separation methods, electrostatic sorting, magnetic sorting and eddy current separation (Al-Salem et al., 2009, 2019; Bruch et al., 2022). E-plastics are commonly segregated and separated using such technologies. ABS is separated post charging with friction using triboelectrostatic separation (Wu et al., 2013; Li et al., 2015; Bruch et al., 2022). LDPE, HDPE, PET PVC, PP and mixtures of such e-plastics, can also be separated in the same manner depending on size and polymer type (Silveira et al., 2018). E-plastics are also separated and sorted from e-waste using cyclones as previously reported by various authors in Cu recovery process (Pascoe, 2006; Peeters et al., 2014) or segregation from high chlorine (Cl) content e-waste using air-sifting (Yoshida et al., 2010). Sink-float techniques are also quite common for plastics separation (Al-Salem et al., 2009), and are also applied using dense media sorting for e-plastics (Gent et al., 2011; Menad et al., 2013; Peeters et al., 2014; Truc and Lee, 2017a, 2017b). Another type of direct chemical sorting technique is the hydrometallurgical process which is defined as the recovery of metals in post leaching solutions and is normally applied to recover Fe, Cu and Al from e-waste (Tuncuk et al., 2012; Al-Qassimi et al., 2018; Kentish and Stevens, 2001; Al-Salem et al., 2019). This process follows a sequential order of three stages that start with (1) leaching, followed by (2) purification; and finally, (3) recovery via electrolysis to capture desired metals (Brandl et al., 2001; Cerruti et al., 1998; Xu et al., 2007). The chemical hydrometallurgical processes have been well established but notable for having a high impact on the environment due to extensive use of solvents (Hadi et al., 2015; Iannicelli-Zubiani et al., 2017). Further success was proven for this type of process in sorting high purity polymer recovery from e-waste and separation from BFRs using ionic liquids (Lateef et al., 2008). Cu amongst other metals, have been documented to be effectively extracted by electrolysis whilst optimising the electrical current density for desired efficiency (Zhang et al., 2017; Yang et al., 2018; Choubey et al., 2021). The process of cementation is also carried out (post leaching under a metal stoichiometric ratio) to recover metals as well (Mahapatra et al., 2019). Recovery of metals such as Cu and Ni and 95% for Zn could also be achieved by chemical precipitation of leachates (Verma and Hait, 2019).

Sorting techniques that remove metals from e-waste by utilising magnetic separation with or without a combination with mechanical separation, are also quite common and have been extensively reported in past literature (Cui and Forssberg, 2003; Veit et al., 2005, 2006). Table S4 summarises advantages/disadvantages of various mechanical and physical separation methods comparatively to each other. Magnetic separation is typically used to separate ferrous from non-ferrous particles (typically after crushing) (Zhang and Xu, 2016). A two-step system employing crushing and corona electrostatic separation (CES), to recover metallic and non-metallic materials is a prime example of such (Huang et al., 2009; Li et al., 2007; Li and Xu, 2010). As a standalone processes, eddy current separation and electrostatic separation have achieved high recovery efficiency for various metals separation such as Fe, Ni, Co (Zhang et al., 1999; Settimo et al., 2004; Zeng et al., 2012; Habib et al., 2013; Jujun et al., 2014; Menad et al., 2013). CES utilises the concept of selective sorting of charged or polarised bodies in an electric field (Wu et al., 2008). Applying CES has proven effective on PCBs since the differences in properties of metallic and non-metallic items (e.g., density and electrical conductivity, etc.) provide an excellent environment for its application. Particle sizes between 0.6 and 1.2 mm are most feasible for separation after crushing, screening and drying processes take place to strip metals from base plates (Li et al., 2007;

Merafhe, 2011). Li et al. (2017) studied and optimised eddy current separation for PCBs and concluded that velocity of belt ($v = 1.18$ m s-1) and rotating speed of magnet ($w = 3000$ rpm) alongside the thickness of metal layer ($Rp = 8.44$ mm) are the controlling parameters and cannot deviate for highly efficient separation processes.

Electrochemical processes are also considered to be a major technology that encompasses various techniques for e-waste separation namely for the ferrous part. A typical setup for such includes two cathodes, one anode and an acid bath in an electrolytic cell separation reactor to leach over 97% of Cu and 93% Au, respectively (Fogarasi et al., 2013, 2014; Kim et al., 2011a, 2011b; Lister et al., 2014). Cu could be recovered from e-waste using an ammonia-based arrangement as well (Sun et al., 2016), which can be done electrochemically using ammonium carbonate salts to carefully control the electrodeposition conditions to achieve 80–90% depending on the ammonia salts and high purity copper (99.9 wt%). Furthermore, sophisticated remote sensing and scanning equipment are also reported to be effective for sorting e-waste which can include colour cameras, 3D-scanners, Fourier Transform IR spectroscopy (FTIR), infrared (IR) and ultraviolet–visible (UV–Vis) spectroscopy. These techniques are applied for metallic and non-metallic separation as described previously in Bruch et al. (2022).

2.4. Recycling rates and e-waste global management scenarios

Recycling e-waste is not as straightforward as it might seem, where various parameters must be considered namely economic value, quality of recycled product and limits of hazardous substances in the recyclates. A prime example is the European Union's RoHS limit on BFRs where it should not exceed 0.1% of polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) (Schut, 2007). BFRs presents a prime challenge in e-waste recycling (Forti et al., 2020). This leads to the incineration of such goods which is associated with release of environmental pollutants such as dioxins or furans. This legislation took effect in 2006 and is mandatory still, even though newer EEE are manufactured with non-halogen FRs but older equipment is still in circulation after the European ban on PBDEs and PBBs (EC, 2011). One possible effective route to maintain such limits is the use of HNO_3, H_2SO_4, HNO_3, H_2O_2 and HBF_4 baths for microwave digestion of PCs and TVs (Jia et al., 2022; Ernst et al., 2000). Various recovery quotas for recycling e-waste exist the world over. The EU, Korea and Japan impose a recovery rate for recycling e-waste (i.e., brown and white goods) that reaches 85% (Zoeteman et al., 2010). Such high mandatory quotas are quite understandable when put in context of generation rates previously shown in Fig. 3 and material flow estimates of e-waste on a global scale. Between the years 1997 and 2007, the US alone discarded 500 million PCs; whilst on the other hand, Japan discarded 610 million PCs in 2010 alone and China discards 5 million PCs and 10 million TV sets on an annual basis (Kiddee et al., 2013). Such serious recycling quotas resulted in making Europe the top collector and recycler of e-waste with a 42% recycling rate (Shittu et al., 2021). The UK recycling rates vary between 4 and 50% of e-waste depending on the size of the item and its source (Tanskanen, 2013).

E-waste is also a transboundary issue that is both legally (under Basel Convention trade act regulations) and illegally exported and moved around various countries. Demand for cheaper goods on the African continent makes transporting used EEE products from developing European countries a matter of growing concern. The Basel Convention (BC, 2014) signatory countries are expected to restrict the movement of hazardous waste across borders. Furthermore, e-waste is sometimes exported under the guise of used EEE (Shittu et al., 2021). This makes controlling such transport a very laborious matter that is seldom taken seriously. Using global positioning systems (GPS), Hopson and Pucket (2016) have confirmed that e-waste enters Asia from the EU and the US regularly. Nigeria for example imports e-waste under the pretence of using EEE where 19% of it fails basic functionality requirements (Ogungbuyi et al., 2012).

The four scenarios previously depicted in section 2.3. Could be further explored globally. A generic flow of e-waste is shown in Fig. 6 which indicates how it might end up in various environmental sinks and can cross borders between countries. The main options for the e-waste management include (i) landfilling/incineration, (ii) exporting, (iii) material recycling/recovery, or (iv) direct use. Fig. 6 also summarises routes of treatment and contribution of e-waste to global SW. The reader is referred to Zoeteman et al. (2010), Forti et al. (2020) and Islam et al. (2020) for a detailed assessment of e-waste global generation rates and exports.

Various arguments exist in literature, namely after imposing EU directive pertaining e-waste, that such European legislations are not effective but in fact encourage unsound environmental solutions and open loop problems (Hammond and Beullens, 2007; Huisman et al., 2006; Krikke and Zuidwijk, 2008; Zoeteman et al., 2010). The EU Directive for transboundary e-waste movement (SwedWatch, 2009) and the Basel Convention Act (BC, 2014) might reduce such activities but will for sure not omit them. To start having legal transport activities conducted under OECD laws and to also start transporting EEE for production, high level recovery options must be encouraged at the regional and national levels (Fig. 6).

2.5. Environmental and health impact

EEE are constructed and manufactured from various chemicals and items that possess a plethora of substances of chemical nature with certain environmental effects and health impact (Jaiswala et al., 2015). E-Waste is typically comprised of the following components/substances which are reported on weight average to provide the reader with a generic idea of how chemical compounds are essential in its manufacturing (Widmer et al., 2005): metals (ferrous and non-ferrous, 60.2%), plastics (15.21%), screens (11.87%), metal/plastic mixtures (4.97%), chemical pollutants (2.7%), polychlorinated biphenyls (1.71%) and cables (1.97%). BFRs are a prime example of such toxic compounds found in e-waste which makes up about 30 wt% of e-plastics (Charitopoulou et al., 2021, 2022). They are essential as a FR to reduce flammability and delay combustion (Buekens and Yang, 2014; Benedetti et al., 2017). Table S5 summarises the major toxic substances found in e-waste and cites their major health impacts documented in literature. In the 1990s, e-waste toxic effect and impact on urban environment and health was recognised which sparked interest in regulating its disposal and management (Kiddee et al., 2013).

Cadmium (Cd) is another major metal substance that is quite common in e-plastics filled with FRs (Islam et al., 2020). It might leach to groundwater or get mixed with soil when disposed of improperly leading to adverse health effects by reaching to the food chain or human exposure. Cathode ray tubes, a major part of e-waste, might also get mixed with acidic waters and dissolves large amounts of Pb (Sthiannopkao and Wong, 2013; Guo et al., 2018). Nnorom and Osibanjo (2008a) reported the pollution caused from improper e-waste management at the City of Guiyu (Ghana) causing heavy metal levels of water and sediment to rise to unprecedented levels. These levels reached as high as 230 mg kg^{-1} for Pb in sediment samples and 24 mg L^{-1} for water; and Ni levels were reported to be 181 mg kg^{-1} in sediment samples (Wong et al., 2007; Hicks et al., 2005). Table S6 shows a selection of the world's major e-waste management plants and pollution reported in literature associated with their activities. E-plastics, CRT funnel glass, batteries and PCBs; are all associated with phosphor coatings of cathode ray tube, which is a hazardous material and can easily pollute the environment when not managed properly (Nnorom and Osibanjo, 2008a). As e-waste incineration is considered to be one of the easiest management solutions, harmful gases associated with such can lead to contaminated water and foods affecting residents of nearby areas (Ewa et al., 2018; Caravanos et al., 2011). This was evident in the case of Agbogbloshie (Ghana) e-waste recycling/separation site where employees and residents showed elevated metal levels in the blood and urine (Sepúlveda et al.,

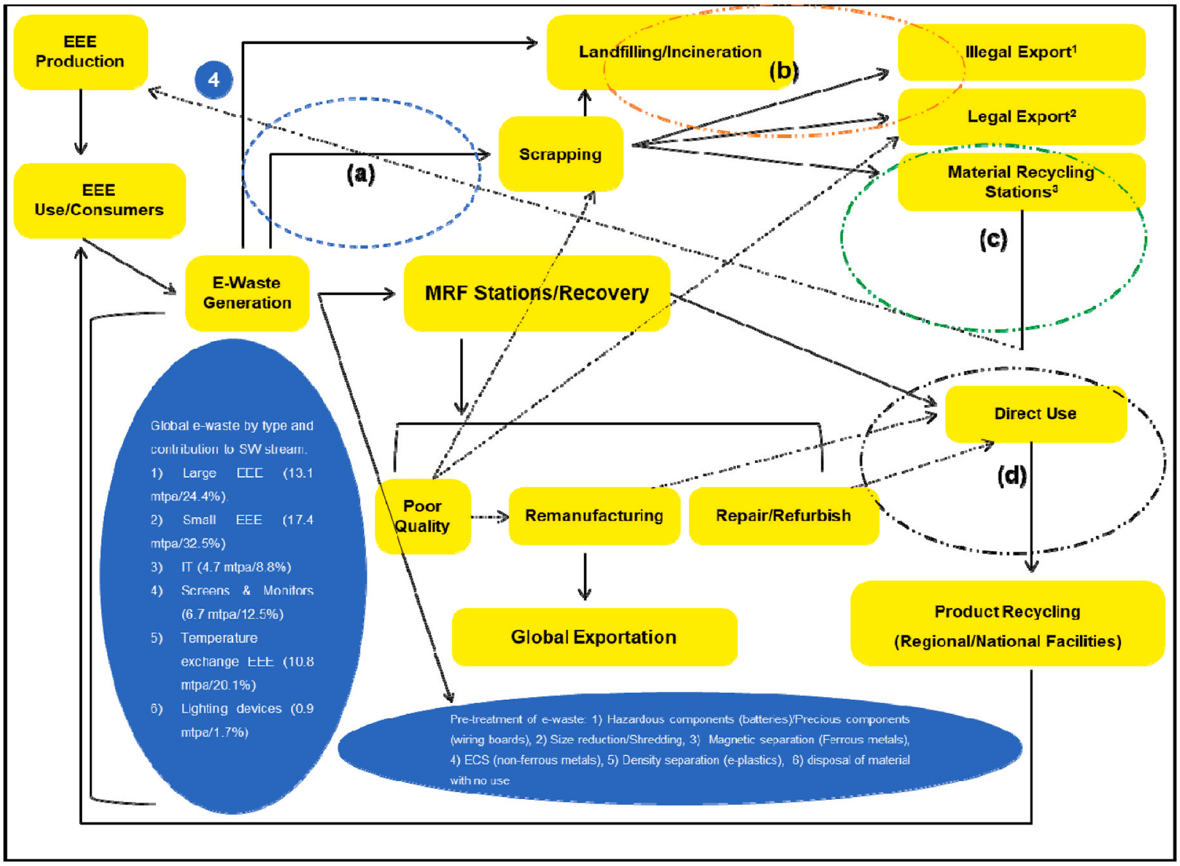

Fig. 6. 1. Illegal exports typically conducted to transport e-waste to China, India or on the African Continent, 2. Legal exports conducted under the Basel Convention to Organisation for Economic Co-operation and Development (OECD) countries under trade act, 3. The end of cycle here is to transport product for EEE production, i.e., start of the initial cycle/stage, 4. Dotted lines indicate the end of life/termination stage. Dashed circles indicate global e-waste management scenarios/material flow (a) do nothing - developing world countries, (b) exporting and dumping, (c) global material recycling and low-level recovery, (d) high level recovery on a regional basis. Adapted from: Ramprasad et al. (2022), Tanskanen (2013), Zoeteman et al. (2010).

2010; Caravanos et al., 2011). Crude '*backyard*' recycling of e-plastics which involves burning or leaching it with strong acids to retrieve precious metals and reduce its volume, has been associated with environmental pollution in various developing countries and leads to adverse environmental effects (Nnorom and Osibanjo, 2008b). As previously mentioned, PCs contain a large proportion of PWBs which contain some 8% of Pb by weight equivalent to about 4 kg (Li et al., 2006; Powel, 2002). This makes PCs a major source of Pb in the MSW stream when not managed and disposed of properly. CRTs also contain other toxic compounds such as lead oxide, alkaline/alkaline earth and zinc borate (Lee et al., 2000). A metric tonne of scrap PCs contain 17 kg of gold ore (Li et al., 2004). Furthermore, other metals could also be recovered from PWBs which contain Cu (10.9%), Fe (7.7%), Ni (2.5%) and Ag (0.00818%). Plastics are also present in the following typical amounts: 25% of CHO Polymers such as polyesters, phenol–formaldehyde, 5% halogenated polymers such PVC, traces of PTFE, poly-bromo compounds, and 1% nitrogen containing polymers such as nylon and polyurethane (Oh et al., 2003). Nevertheless, such elements in e-waste are important resources to control over-mining and exploiting natural resources, and their potential as valuable products on the market, recovering them and managing them through strict regulations is a must to have a safer environment on a global scale. Various regions around the world have either inadequate or no legislations and regulations to regulate e-waste and its impact. Poor regulations on the disposal of e-waste were proven to have adverse effects on the environment in developing world countries specially when open land disposal and recycling were conducted (Puckett and Smith, 2002). Evidence from various cities around the world show that poor recycling measures led to direct environmental poisoning in places such as Guiyu and Taizhou in China, Gauteng in South Africa, New Delhi in India, Accra in Ghana and Karachi in Pakistan (Kiddee et al., 2013). In addition, crude backyard burning has been reported in various parts of the world and linked to heavy metals release (e.g., Pb, Cd, Ni, Cr, Hg and As) and emission of organic pollutants (e.g., PAHs, polychlorinated biphenyls, BFRs) formed during the combustion process itself. Reported soil/water/air pollution cases from around the world leading of elevated levels of regulated chemicals and metals, are well documented for PBDEs, PAHs, PCDD/Fs, As, Cd, Cr, Cu, F, Fe, Hg, Mn, Ni, Pb and Zn (Wang et al., 2005; Chen et al., 2009; Muenhor et al., 2010; Ha et al., 2009; Deng et al., 2006; Kiddee et al., 2013).

Simulated landfill leachate for a number of e-waste components, namely mobile phones, have shown toxic components as detailed by Kiddee et al. (2013). These results showed the following detected levels (mg L^{-1}): Ag (0–0.010), As (0.056–0.067), Ba (1.46–2.88), Cd (0.0006–0.006), Cr (0.04–0.13), Hg (0–0.010), Pb (38.2–147.0) and Se (0.073–0.12). E-waste components fall under the regulations of the Resource Conservation and Recovery Act (RCRA) which stipulates the toxicity of certain chemicals/metals as per the following (mg L^{-1}) (Townsend et al., 2005): 5 for As, 100 for Ba, 1 for Cd, 5 for Cr, 5 for Pb, 0.2 for Hg, 1 for Se and 5 for Ag. There exists an interlinked connection that is well established between improper e-waste management and pollution to environmental sinks (Fig. 7). Manufacturing EEE goods will utilise resources that require mining of various precious metals such as Au and Co; which on the other hand led to utilisation of land, energy and water (Rajesh et al., 2022). This is also linked with the addition of chemicals that will pollute the atmosphere directly by emitting harmful

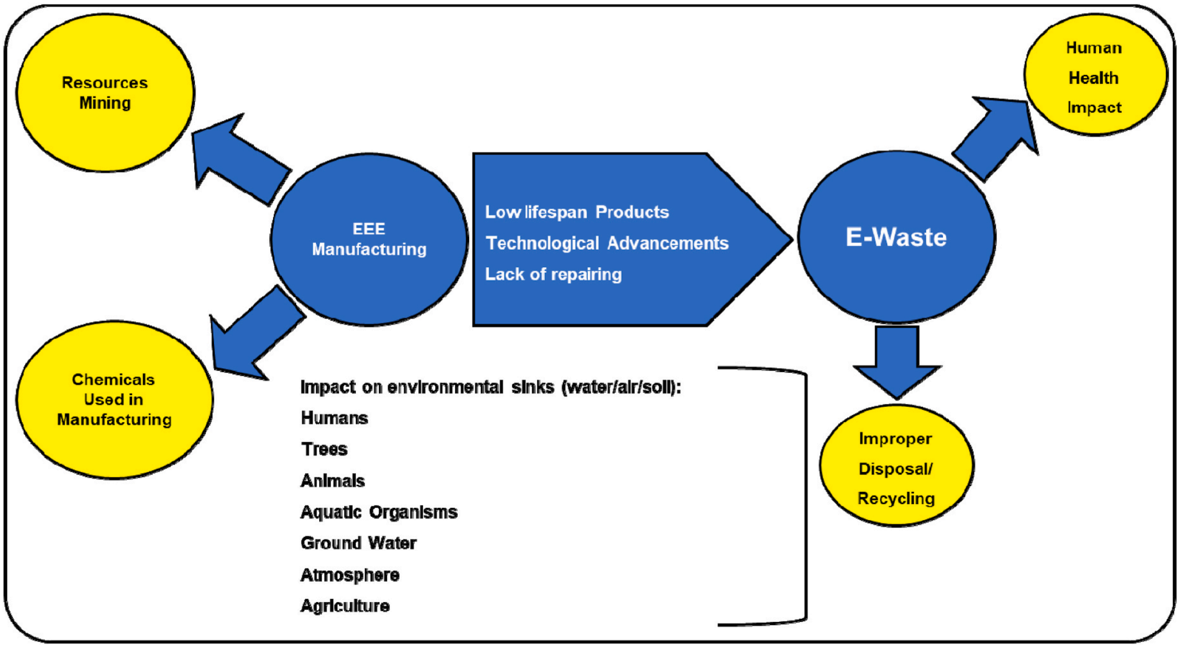

Fig. 7. Schematic representation of back-to-back pollution caused by e-waste. Adapted from Rajesh et al. (2022).

gases. All EEE products will have limited lifespan due to a number of reasons such as lack of technological repair or faulty instruments (Fig. 7).

3. An overview of e-waste management regulations

3.1. Development of regulations from the waste management hierarchy in Europe

It is quite imperative to understand and regulate each type of SW, in order to minimise its burden on the environment. E-waste could end up in a variety of scenarios in environmental sinks, e.g., air, water or soil. It could be disposed of by incineration, landfill, acid bath/leaching, dismantling or exportation to other countries depending on regulated substances laws and regulations that govern borders between countries. Various e-waste components and types have been documented to be exported from developed countries to China, India and Pakistan; and other world developing countries as well (Rajesh et al., 2022; Kiddee et al., 2020; Ismail and Hanafiah, 2021). The developed world is also moving towards the concepts of urban future and circular economy (see Table 1). These are moving us away from the classical linear economy model which relies typically on the stage of: take, make and dispose. This is clearly noticed when comparing the world's resources extraction rate in 2015 to 1900, which was 13 folds higher increasing from 7 Gtonnes to 89 Gtonnes and the associated global SW which rose from 0.3 Mtonnes per day to 3.5 Mtonnes per day between 1900 and 2010 (Zhang et al., 2022). The concept of circular economy (CE) will aim at closing such a loop in the industrial management of the waste. CE will apply the original concept of the three Rs (reduce-reuse-recycle) in preventing the generation of the waste and turn it into a resource rather than a burden. In more practical terms, e-waste is part of the general waste management hierarchy that the European Union (EU) has taken serious measures to regulate. Major advances were taken throughout Europe where technical approaches with regulations that can govern such a problem in an environmental context were established. Moreover, it is now well established that the EU's Waste Directive of 2008 (EC, 2008) is a milestone the world over for managing waste. The European experience can be a good starting point to analyse directives and regulations that govern e-waste, which started by applying the politician Lnsik's Ladder concept back in 1979 to the council's directives. The first directive which actually dates back before Lansik's Ladder was in 1975 namely by issuing directive no. 442/EEC which focused on reducing waste quantities in general, and applying various recycling techniques to manage the accumulation of waste downstream after realising its environmental burdens (Fig. 8). The directive of 1975 didn't give preferences to management methods, but did regulate the waste in a generic manner. Unlike Lanisk's Ladder, which developed later on to be the waste management hierarchy and gave preferences to manage the generated waste, directives in Europe didn't do so until the latter stages of the early 1990s to give preferences of disposal. The EU directive of the year 1991 (91/156/EEC) (EC, 1991) took a more holistic approach and actually named preferable scenarios for recovery and disposal (Fig. 8). This evolved into the Directive 08/98 EC (EC, 2008) which is more commonly referred to as the EU's Waste Directive of 2008 or the EU Waste Framework. Till 2013, when the Bartl hierarchy was first introduced, various directives and hierarchical methodologies were established for the management of SW. More specifically, PSW management has been ranked according to treatment preferences from primary to quaternary treatment methods which also encompass the e-plastics component. Primary recycling of plastics involves in-house techniques, whilst secondary ones will encompass physical/mechanical treatment. Tertiary recycling includes biodegradation and thermolysis and quaternary energy recovery (least preferable), are considered the top of the ladder in preference (Al-Salem et al., 2009, 2017; Hopewell et al., 2009; Mastellone, 1999). Food waste and construction and demolition waste, have their own hierarchies which developed over time as the US EPA Food Waste Hierarchy and the Delft Hierarchy, respectively (Zhang et al., 2022). In the year 2018 and through the amendment of the Waste Framework, requirements were strengthened in Directive 08/851 by defining the concepts of prevention, recovery and end-of-waste-criteria. Further details are shown in Fig. 8 below. The e-waste related definitions were given above in Table 1 of this communication which reflect the most recent standardised terms.

E-waste management within a European context could be viewed from two different angles, EU countries and non-EU countries. Large amounts of e-waste are generated annually from the EU, recently estimated as 12 Mtonnes in 2019 (Forti et al., 2020). Therefore, enforcing regulations to control and regulate e-waste, especially hazardous

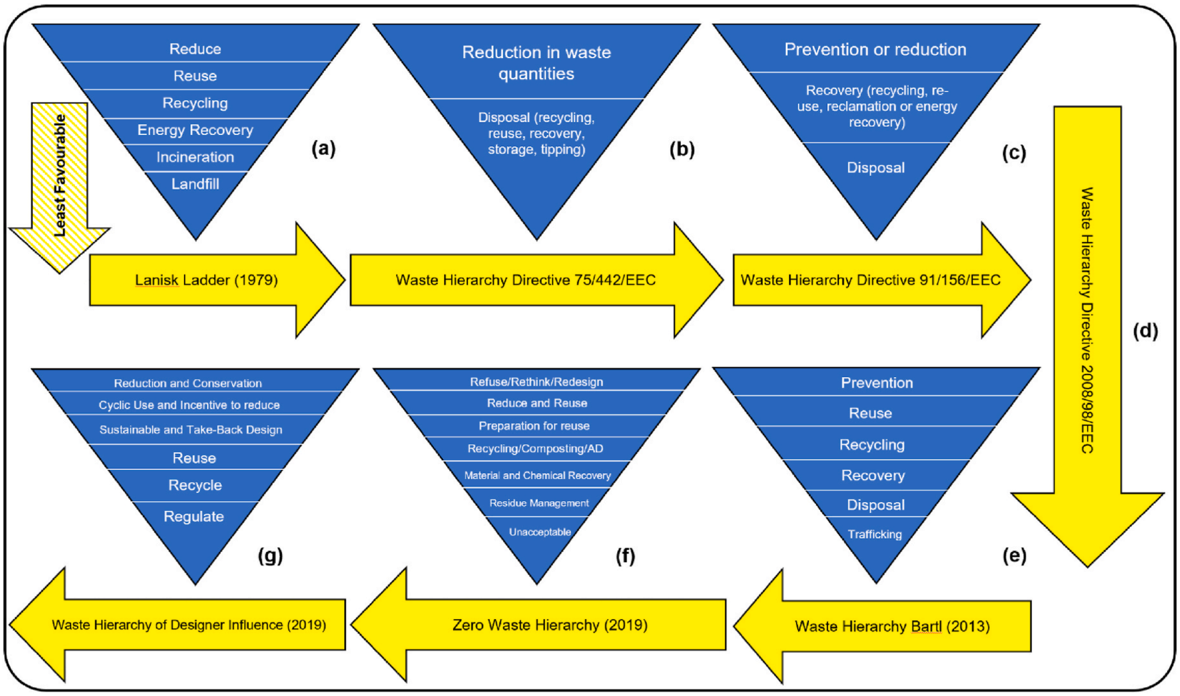

Fig. 8. Main Stages of the Waste Management Hierarchy Development Through Time Showing (a) The First Concept of Lanisk in 1979, (b) The European Directive of 1975, (c) The European Directives of 1991, (d) The European Directive of 2008 (ladder not shown) which depicts a similar concept as to the 1991 hierarchy but separates prevention stage as non-waste and the rest of stages as waste stages that require intervention, (f) Zero Waste Management Concept, and (g) The Designer Influence Concept. Source: Recycling.com (2019), EC (1991, 2008), Bartl (2013), Hendricks and Janssen (2001), Ceryes et al. (2021), Zero Waste Hierarchy (2019), Cole et al. (2019), Gharfalkar et al. (2015), Zhang et al. (2022).

substances within this type of waste is needed. The EC directives are established and enforced by the EU as legislative instruments for e-waste management. The first e-waste directive in Europe was the 2002/96/EC (EC, 2002), which implemented the *extended producer responsibility* (EPR) principle as one of the tools to manage e-waste making producers collect end of life EEE from consumers (Shittu et al., 2021). Fig. S4 and Table S5 summarise the main tools applied for e-waste management and review the recent findings including life cycle assessment (LCA), material flow analysis (MFA), multi criteria analysis (MCA) and the principle of extended producer responsibility (EPR). The Directives sets a minimum of 4 kg per person per year as a collection rate. It was later amended by Directive (2012/19/EU (EC, 2019a) which clarified various terms and definitions and enforced recycling rates (see Section 2.2. and Table 1). At present, each member state is required to annually collect 45% EEE put on market with a collection rate of 65% (see Table S1 for calculation method). This is based on Directive 2012/19/EU which came into force in 2014. On the other hand, Directive 2002/95/EC (Restriction on Hazardous Substances - RoHS Directive) started to be implemented in 2004 which was referred to earlier in this communication as a regulatory mandate for toxic substances of POPs and metals type in EEE products (EC, 2003b). It was later reformulated as Directive 2011/65/EU to expand regulations to more types of EEE products and components in 2017 (EU, 2017). As of 2019, 71% of the world's population is covered with legislation pertaining e-waste management. However, in many countries; such policies and regulations are not law binding which is the root cause of the e-waste accumulation and its environmental impacts (Forti et al., 2020). Furthermore, in countries with law binding legislations; collection rates vary considerably when it comes to targets. A prime example is Europe, where Malta has a 12% collection rate and Estonia has 82% (above the 65% target) (Forti et al., 2020). Another important milestone in the European experience is the recently revised POPs regulation 2019/1021/EU (EC, 2019b) that controls FRs concentration namely PBDEs, HBB, HBCD, SCCPs with a limit of threshold of 1000 mg kg^{-1}. Table S7 summarises the main strategies implemented in various EU countries (and UK). It is evident that a generic strategy that can be implemented across the continent is a must whereby all countries can meet specified targets. In the current state, the enforcement of e-waste management laws is also lacking which is clear from the variation in collection and recycling rates.

3.2. *Extended producer responsibility (EPR) and sustainability in e-waste management*

The EPR scheme, which is considered as one of the major e-waste management strategies in the world especially in the EU (see Fig. S4), is a take back system that is now recognised as a circular economy (CE) cornerstone for MSW (OECD, 2001). Within the chain of EEE management, EPR manages to promote downstream collection and recycling, (Favot et al., 2022). EPR is also recognised as a polluter-payer scheme which identifies the root causes of the pollution problems and manages the flow of the pollution based on the fact that each sector holds its responsibility. It is a responsibility approach rather than a liability one that aims at identifying the sector responsible for the initiative and what is the most effective approach (cheapest cost avoider) (Massarutto, 2014). Favot et al. (2022) elaborated on the fact that such compliance schemes start with creating legal or de-facto monopolies to develop a recycling market with time. This approach is proven to be effective with time and reduces the negative value of recyclables too (e.g., with time the value of the recycled material due to EPR will increase and be positive). Economic studies are also available for a number of case studies discussing EPR (Ahlers et al., 2021; Busuttil et al., 2016; Dimitropoulos et al., 2021). Another fact worth mentioning is that a similar approach is also taken by the UK where a cap-and-trade scheme is adopted. However, such an approach was criticised for its costs with time (Vaudey and Glachant, 2007).

EPR also aids in CE and sustainability to a great extent. The fact that EPR can motivate the upstream in managing their produced e-waste and have green initiatives that can handle them, is also something that can be easily envisaged. For examples, companies can easily manage their produced EEE and components that pollute the environment, such as high-lead content in the CRT funnel glass, batteries, printed circuit boards (PCB), capacitors, mercury-containing parts, and plastics containing flame-retardant bromine, etc. This is achieved when they handle the products once again from the waste sector/consumers. For every PC discarded, 2 kg of Pb could be extracted, which makes it lucrative to extract 340,000 tonnes of lead from the obsolete PCs in the US annually (Nnorom and Osibanjo, 2009a). Therefore, take back schemes are promoted as a prime solution that can rid the environment from toxins such FRs, Pb, Hg, Cd and Cr (VI), with relative ease.

3.3. A short note on the Basel Convention (BC)

The Basel Convention (BC) on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal is a multilateral treaty which opened for signatory back 1989 and took effect in 1992, has 187 countries in its roster controlling and monitoring the movement of hazardous waste (Forti et al., 2020). The BC affirms the fact that e-waste which contains hazardous elements should not be traded between countries unless strict cross-border notification and clarification is undertaken. The BC pays special emphasis to waste transport to developing world countries The BC also permits trade for EEE aimed at reusing, hence causing piracy and misinformation across countries from SW dealers. The only exception given for waste transboundary movement is when an agreement of treatment between countries is established (Shittu et al., 2021). The BC has made it possible to reduce waste movement to West Africa which led to the Bamako West-African Convention. The effect of the BC, Bamako and Stockholm convention made it possible to regulate the hazardous components of waste and later spilled into various e-waste management schemes around the world, including African nations, Asian and North/South American countries which are summarised in Table S8 and key Statistics are shown prior in Table S1. Table S9 reviews the world's main e-waste management schemes.

4. Circular economy (CE) and E-waste

The concept of Circular Economy (CE) goes hand in hand with optimal waste management strategies, which was also touched upon and defined in both Sections 1 and 3, due to the interlinked and connection CE has with the topics discussed above. As of March 2019, all of the actions of the original 2014 EU action plan for CE, were either delivered or being implemented (EC CE, 2020). This shows how serious developed world countries, namely the EU, are in nullifying linear economies and starting to consider waste as a sustainable feedstock for the future. E-waste contains valuable resources and components including 69 elements from the periodic table of elements (Forti et al., 2020). These contain precious metals, such as Au, Ag, Cu, Pt, etc.; and critical raw feedstock materials, such as cobalt, palladium, indium, germanium, bismuth, and antimony. The value of these materials is estimated to be billion $57 for 25 Mtonnes with prices increasing (see Table S2). E-waste also contains non-critical materials such as Al and Fe. Therefore, such materials are essential to reduce the pressure on natural resources (mining) and e-waste can certainly provide a sustainable raw feedstock for it. The recent Global E-Waste Monitory report (Forti et al., 2020) indicates that only 17.4% of e-waste is collected and recycled (even documented) which leaves plenty of room to speculate on the unexplored economic losses CE can provide when e-waste is actually fully utilised properly. This leaves an estimated potential of $10 billion worth of raw materials available for recovery, with a potential of 4 Mtonnes of raw materials that would become available when utilised in a CE approach. The associated environmental benefits from recycling Al, Fe and Cu alone managed to off-set 15 Mtonnes of $CO_{2\text{-eq}}$ back in 2019 alone. Au is also abundant in EEE devices, estimated to be 280 gm per tonne of e-waste; and quite large proportions are available in mobile phones and PCs. Deubzer (2007) estimated that if Au amongst other metals is recycled properly from e-waste, less than 5% of material losses are to be gained by separation methods alone.

Recycling and recovering metals and valuable chemicals from e-waste is also a challenging matter due to the presence of toxins. Recent studies show that e-plastics reclaimed from e-waste is a challenging material to deal with due to their level of toxicity (Barouta et al., 2022; Crippa et al., 2019; Dahlbo et al., 2018; Delva et al., 2018). This is clearly noted in various countries where they are taking measures for eco-design of EEE to allow easier downstream recovery of the e-waste through recycling procedures (Tables S3 and S5). Such requirements for eco-design are restricted to the WFD, 10 ppm POP limit and CELENEC specifications (Barouta et al., 2022), which are typically used in the plastics identification (not chemical limits) by XRF techniques or near IR (Wagner and Schlummer, 2020). The reader is referred to the stated references for a detailed review on the recovery of metals and valuable chemicals including fuels from e-waste (Anholeti et al., 2022; Madhav et al., 2022; Li et al., 2017; Al-Salem et al., 2009, 2017; Charitopoulou et al., 2022). E-plastics could be valorised after separation using a number of techniques that could yield high added value to the overall recovery chain. As e-waste is generally treated separately from MSW, it is also essential to treat plastics and metal containing parts on their own to avoid potential cross contamination with toxic substances (Das et al., 2021). The major technologies for treating e-plastics and metal containing parts were previously reviewed and discussed for their potential value elsewhere (Das et al., 2021; Islam et al., 2020). E-plastics also represent an economic challenge when recycling. About 71 Mtonnes of e-plastics containing BFRs were generated in 2019 including PCBs, connectors and wirings (Herat, 2008). The presence of such toxins promotes the easier route of incineration under controlled conditions to avoid furans and dioxins emissions. The EU has also banned the use of PBDEs and PBBs due to their health implications (EC, 2011). Other heavy metals and chemicals present in e-waste such as Hg, Cd, Pb, CFCs and HCFCs also present a challenge on a technical and economic basis for recyclers.

Currently, more than 1.3 Mtonnes of e-plastics are collected in the EU and about 1 Mtonne is sent to recycling facilities resulting in over half this amounts as available materials suitable to sustain a CE (Haarman et al., 2020). This of course doesn't exclude the fact that various types of recovered plastics are to be excluded from CE initiatives due to aforementioned challenges (Ügdüler et al., 2020). It is also encouraged to establish civil engineering applications (asphalt and concrete road) for e-plastics to increase their applications as recylates (Barouta et al., 2022). On the other hand, demand for metals such as Cu, Fe and Al is growing where it was estimated to be 39 Mtonnes in 2019 (Forti et al., 2020). Currently, e-waste can provide (in an ideal scenario on a global basis) about 25 mtonnes of these metals. This shows that EEE production growth is also a matter that requires regulations in order to reduce their demand with designs that are more environmentally friendly and have longevity in use. A similar case could be put forward for Hg which is a toxic element that could enter the food chain if not dealt with properly (see Table S1). A small fraction of old EEE devices still exist with a Br content that exceeds the 8% BFR limit of RoHS. This makes an argument put forward by producers to increase the Br limit to 6000 ppm to have more recyclable e-plastics suitable to be handled within CE approach since what is being dealt with is not with existing regulations which will also respect the industry's capabilities (Jandric et al., 2020).

5. Implications on the state of Kuwait in-light of European and world experiences

This section discusses the implications of the current situation for the particular case of the State of Kuwait, in view of recent statistics and SW management scenario. Kuwait presents a specific challenge where no waste management infrastructure exists with no clear future plans are put in place for such. This section will focus on the potential gains from management of e-waste, in-light of the technologies and regulations review conducted in this work.

5.1. Country description and rationale

Kuwait is part of the Gulf Council Countries (GCC) which face a challenge in managing their SW fraction due to climatic conditions and ever-growing population and energy demands. This region of the world is noted to have a large per capita waste generation rate with high standards of living, putting pressure on their urban environment (Alghazo and Ouda, 2016). The World Bank dataset puts matter in context and is depicted in Table S10 for the GCC. Kuwait is noted to produce a high MSW per capita rate exceeding 1.55 kg per day, with a total e-waste generation per capita rate of 17.2 kg per year. No e-waste management policies exist in Kuwait (Forti et al., 2020) and a large dependence between local gross product demand and SW generation has been established due to consumer behaviour (Al-Salem et al., 2018). The typical life cycle of a mobile phone for example in Kuwait is only two years, indicating a high e-waste generation rate and accumulation due to the EEE imports and population behaviour (Al-Anzi et al., 2017). Kuwait is noted to produce 3000 tonnes per annum of e-waste in the form of mobiles alone. The number of mobiles per 100 persons in Kuwait was estimated previously as 88.5 (Abou Elseoud, 2008).

Kuwait has a total land area of 17,818 km^2 of which landfill sites at present occupy 45.5 km^2 and are expected to increase to 60 km^2 by 2025 (Alghazo and Ouda, 2016). The MSW mainly constitutes of organics (50%) and PSW (18%), and the majority of Kuwait's waste can actually be recycled (76%) which can reduce the pressure on landfill sites if SW is manged properly (Alsulaili et al., 2014). To date, there is no information about the composition of e-waste in Kuwait or the GCC. It is also estimated that Kuwait will produce 111,000 tonnes of e-waste in the year 2040 compared to the current 67,000 tonnes produced (Alghazo et al., 2018).

Kuwait has no official infrastructure to date to support any waste management schemes and no official policy to govern SW namely e-waste. A recent study showed that the landfill sites have heavy metal concentrations exceeding Canadian and Australian limits (Al-Salem et al., 2020) making it hard to rehabilitate the sites if no intervention is considered immediately. The management of SW falls under a number of Government based entities namely the Kuwait Environment Public Authority (KEPA), Ministry of Public Works, Pubic Authority of Industry (PAI), Public Authority of Communication and Ministry of Health (MoH). It is therefore imperative that waste management coordination exists with a clear vision for the future to how SW is managed in Kuwait and how can products from recycling serve as a pillar of local economy.

5.2. Data and design of work

Kuwait presents quite a particular case that is worth researching and investigating. It has an oil-based economy with unlimited economical resources, yet has no SW infrastructure that can ease burdens on the environment or be integrated with current industrial activities. Kuwait relies heavily on imports as well, where all EEE devices are imported. According to the recent OEC report (OEC, 2020), Kuwait's top imports are automobiles (billion $2.3), medicine (million $820) and broadcasting devices and equipment (million $680). Kuwait's top export is crude oil and derivatives (billion $27.6) with a per capita import equal to $6.7 thousand. Kuwait's EEE was recently estimated at billion $1.2 (Kuwait Press, 2021). To effectively conduct this case study which aims at assessing the benefits of recovery and recycling of a fraction of the e-waste in Kuwait, data collection by way of Government statistics from Central Bureau of Statistics (CBS) and governmental channels. This was achieved post the technologies review and Kuwait/GCC review conducted initially (Fig. 2). Based on the surveys conducted, the flow of EEE in Kuwait and appropriate e-waste was assessed for reclamation. There is no baseline study in Kuwait for e-waste, which this work represents a first of its kind. An initial MFA analysis following the methodology of Sajid et al. (2019) was conducted based on the flowchart depicted in Fig. S5 and the MFA model shown in Fig. S6.

5.2.1. E-waste flow analysis and model applied

The technical information gathered from the data collection stage and literature survey showed that Kuwait has a major problem in SW accumulation. There exists various methods and models used for e-waste flow characterisation and assessment, each with its own application domain and limitations (Fig. S4). It is best to use MFA in the case at hand due to the fact that it can quantify each waste stream and is also versatile to the use. MFA is also based on the conservation of matter and mass balance, where material flowing in equals the material out of a process/stream in a defined boundary. It is estimated that e-waste (with no accumulation or backlog) in Kuwait is generated at a rate of 67,000 tpa, and the imports of broadcasting EEE generate 19,428 tonnes after 3 years of service. Applying the assumption that each EEE of the broadcasting devices will have a typical polyethylene (PE), glass and iron components applicable for recycling gives the following respective amounts of 1676 tonnes, 11,074 tonnes and 1943 tonnes (Goosey, 2012). The MFA was accordingly adjusted to the scenario herein based on the economic reports and data available at hand (Fig. S6).

5.2.2. E-waste handling and potential recycling

The handling of SW in general and e-waste in particular, is conducted and operated totally by the governmental sector in Kuwait. This is an advantage in this particular case as the costs of manpower/operation could easily be subsidised in the country and supported by various sectors. After reviewing economic factors and current prices of potential recovered plastics, iron and glass from broadcasting devices in Kuwait as e-waste, shows a total revenue of $399,729 per annum after considering prices and amount of recyclable e-waste components (D'Adamo et al., 2019; SMB, 2022; PST, 2022; LR, 2022). This revenue will open the prospect of ventures for other e-waste and fuel recovery options as well as environmental benefits. Kuwait is predominantly invested in the oil and gas ventures, the development of a waste management strategy and infrastructure with appropriate EPR measures or governmental supported initiatives should be on the top of the list in future visions. This should be implemented with the philosophy of a circular economy mind-set.

6. Conclusion

E-waste has become a growing concern to both decision makers and takers alike, in the fact that it has been growing in numbers to large proportions of solid waste. Recent estimates put e-waste generation at a rate of about 54 million tonnes per annum with figures reaching some 75 million tonnes by the year 2030. In this manuscript, the state-of-the-art technologies and techniques for segregation, recovery and recycling of e-waste with a special focus on the valorisation aspects of e-plastics and e-metals are critically reviewed. A history and insight into environmental aspects and regulation/legislations are presented including those that could be adopted in the near future for e-waste management. In a more focused manner, the case of the State of Kuwait was studied after reviewing other countries experiences. As an oil dependent nation that is lacking in waste management infrastructure, Kuwait has a plethora of chances to design modern waste valorisation platforms and implement technologies that could reduce environmental burdens. To that extend, Kuwait could also benefit from schemes such as extend producer responsibility where residents could benefit from take back systems. Material flow analysis was implemented to study the effectiveness of e-waste valorisation in Kuwait namely a prime component of it. According to recent reports, Kuwait's top imports are automobiles (billion $2.3), medicine (million $820) and broadcasting devices and equipment (million $680). Kuwait's top export is crude oil and derivatives (billion $27.6) with a per capita import equal to $6.7 thousand. Kuwait's EEE was recently estimated at billion $1.2. It is estimated that e-waste (with no accumulation or backlog) in Kuwait is generated at a rate of 67,000 tpa, and the imports of broadcasting EEE generate 19,428 tonnes after 3 years of service. Applying the assumption that each EEE of the broadcasting devices will have a typical polyethylene (PE), glass and iron components applicable for recycling gives the following respective amounts of 1676 tonnes, 11,074 tonnes and 1943 tonnes. This accumulates as about $400,000 of annual profits if economic factors are to be considered based on the e-waste management scheme proposed for these amounts alone. This shows that e-waste management could be a gateway for a proper circular economy scheme within Kuwait and neighbouring countries that rely solely on oil and gas ventures with large waste accumulation rates. It is also envisaged that with such work, the ground could be laid out for developing national industries that could diversify the income and reduce reliance on oil based industries. This on the other hand can reduce environmental stressors and burdens; and create local jobs and industries. Shifting from typical linear economy to a circular one is also a matter that will require serious efforts from decision making entities in Kuwait. Therefore, the work on waste components such as e-waste which contain large amounts of precious metals and valuable products; is definitely a good starting point that could change the shape of the local economy with time.

Authors credit statement

S.M. Al–S.; Conceptualization, Data Analysis, Initial and Final Draft Preparation, G.A.L; Initial and Final Draft Preparation, M.S.E., Final Draft Review, M. van H.; Final Draft Review, A.C.; Final Draft Review, R. D.; Initial and Final Draft Preparation, J.B., Final Draft Review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116181.

References

Abou Elseoud, N., 2008. Chapter 8, Waste Management Report of the Arab Forum for Environmental and Development. Arab Environment Future Challenges.

Ahlers, J., Hemkhaus, M., Hibler, S., Hannak, J., 2021. Analysis of Extended Producer Responsibility Schemes: assessing the performance of selected schemes in European and EU countries with a focus on WEEE, waste packaging and waste batteries. Available at: https://erp-recycling.org/wp-content/uploads/2021/07/adelphi_study_Analysis_of_EPR_Schemes_July_2021.pdf. (Accessed 14 June 2022).

Al-Anzi, B.S., Al-Burait, A., Thomas, A., Ong, C.S., 2017. Assessment and modeling of E-waste generation based on growth rate from different telecom companies in the State of Kuwait. Environ. Sci. Pollut. Res.

Al-Qassimi, M., Sultan, H., Al-Salem, S.M., 2018. Futuristic overview of waste from electronics & electrical equipment (WEEE). In: Al-Salem, S.M. (Ed.), The State of Kuwait. Kuwait: Kuwait Institute for Scientific Research (KISR) Book of Proceedings, pp. 13–33.

Al-Salem, S.M., 2019. Chap 1: introduction. In: Plastics to Energy: Fuel, Chemicals, and Sustainability Implications. Elsevier, pp. 3–20.

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Mange 29 (10), 2625–2643.

Al-Salem, S.M., Papageorgiou, L.G., Lettieri, P., 2014a. Techno-economic assessment of thermo-chemical treatment (TCT) units in the Greater London area. Chem. Eng. J. 248, 253–263.

Al-Salem, S.M., Evangelisti, S., Lettieri, P., 2014b. Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area. Chem. Eng. J. 244, 391–402.

Al-Salem, S.M., Abraham, G., Al-Qabandi, O.A., Dashti, A.M., 2015. Investigating the effect of accelerated weathering on the mechanical and physical properties of high content plastic solid waste (PSW) blends with virgin linear low density polyethylene (LLDPE). Polym. Test. 46, 116–121.

Al-Salem, S.M., Antelava, A., Constantinou, A., et al., 2017. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). J Environ Mange 197, 177–198.

Al-Salem, S.M., Al-Nasser, A., Al-Dhafeeri, A.T., 2018. Multi-variable regression analysis for the solid waste generation in the State of Kuwait. Process Saf. Environ. Protect. 119, 172–180.

Al-Salem, S.M., Constantinou, A., Leeke, G.A., Hafeez, S., Safdar, T., Karam, H.J., Al-Qassimi, M., Al-Dhafeeri, A.T., Manos, G., Arena, U., 2019. A review of the valorisation and management of industrial spent catalyst waste in the context of sustainable practice: the case of the state of Kuwait in parallel to European industry. Waste Mange Res 37 (11), 1127–1141.

Al-Salem, S.M., Zeitoun, R., Dutta, A., Al-Nasser, A., Al-Wadi, M.H., Al-Dhafeeri, A.T., Karam, H.J., Asiri, F., Biswas, A., 2020. Baseline soil characterisation of active landfill sites for future restoration and development in the state of Kuwait. Int J Environ Sci Tech 17 (11), 4407–4418.

Alassali, A., Barouta, D., Tirion, H., Moldt, Y., Kuchta, K., 2020a. Towards a high quality recycling of plastics from waste electrical and electronic equipment through separation of contaminated fractions. J. Hazard Mater. 387, 121741.

Alassali, A., Aboud, N., Kuchta, K., Jaeger, P., Zeinolebadi, A., 2020b. Assessment of supercritical CO_2 extraction as a method for plastic waste decontamination. Polymers 12, 1347.

Alassali, A., Calmano, W., Gidarakos, E., Kuchta, K., 2020c. The degree and source of plastic recyclates contamination with polycyclic aromatic hydrocarbons. RSC Adv. 10, 44989–44996.

Alghazo, J.M., Ouda, O.K.M., 2016. Electronic waste management and security in GCC countries: a growing challenge. In: 2nd ICIEM 2016, International Conference on Integrated Environmental Management for Sustainable Development.

Alghazo, J., Ouda, O.K.M., El Hassan, A., 2018. E-waste environmental and information security threat: GCC countries vulnerabilities. Euro-Mediterranean J Environ Integr. 3, 13.

Alsulaili, A., AlSager, B., Albanwan, H., Almeer, A., AlEssa, L., 2014. An integrated solid waste management system in Kuwait. In: 5th International Conference on Environmental Science and Technology, vol. 69. IACSIT Press, Singapore (12).

Altarawneh, M., Saeed, A., Al-Harahsheh, M., Dlugogorski, B.Z., 2019. Thermal decomposition of brominated flame retardants (BFRs): products and mechanisms. Prog. Energy Combust. Sci. 70, 212–259.

Aminoff, A., Sundqvist-Andberg, H., 2021. Constraints leading to system-level lock-ins - the case of electronic waste management in the circular economy. J. Clean. Prod. 322, 129029.

Anholeti, M.S., de Oliveira, A.R.H., da Cruz, J.C., Luciano, V.A., Nascimento, M.A., Puiatti, G.A., de Carvalho Teixeira, A.P., Lopes, R.P., 2022. Zn/ZnO heterostructures photocatalyst obtained by sustainable processes from alkaline batteries waste: synthesis, characterization and application. Mater. Chem. Phys. 284, 126058.

Baldé, C.P., et al., 2015. Global E-Waste Monitor - 2014. United Nations University and IAS-SCYCLE, Bonn, Germany.

Barouta, D., Alassali, A., Picuno, C., Bruno, M., Syranidou, E., Fiore, S., Kuchta, K., 2022. E-plastics in a circular economy: a comprehensive regulatory review. J. Clean. Prod. 355, 131711.

Bartl, A., 2013. Ways and entanglements of the waste hierarchy (presentation). Available at: https://www.vt.tuwien.ac.at/fileadmin/t/vt/Mech_VT/FB_Mech_VT_Faser_Abfallhierarchie.pdf. (Accessed 9 June 2022).

BC, 2014. UNEP and Basel convention, Basel convention on the control of transboundary movements of hazardous wastes and their disposal. Available at: www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf. (Accessed 30 May 2022).

Beccagutti, B., Cafiero, L., Pietrantonio, M., Pucciarmati, S., Tuffi, R., Vecchio Ciprioti, S., 2016. Characterization of some real mixed plastics from WEEE: a focus on chlorine and bromine determination by different analytical methods. Sustainability 8, 1107.

Beigl, P., et al., 2017. E-waste – from collection to secondary resource. In: Sixteenth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy, 2 - 6 October 2017. CISA Publisher, Italy.

Benedetti, M., Cafiero, L., De Angelis, D., Dell'Era, A., Pasquali, M., Stendardo, S., Tuffi, R., Vecchio Ciprioti, S., 2017. Pyrolysis of WEEE plastics using catalysts produced from fly ash of coal gasification. Front. Environ. Sci. Eng. 11 (5), 11.

Bokelmann, K., Hartfeil, T., Kunkel, K., et al., 2017. Neue Methoden zur Wertstoffgewinnung aus primaren und sekundaren Rohstoffquellen. In: Thome-Kozmiensky, K.J., Goldmann, D. (Eds.), Recycling and Raw Materials [Recycling und Rohstoffe], vol. 10. Thome-Kozmiensky Verlag GmbH, Nietwerder, Germany, pp. 427–437.

Boulding, K.E., 1966. The economy of the coming spaceship earth. In: Daly, H., Freeman, W.H. (Eds.), Economics, Ecology, Ethics: Essay towards a Steady State Economy. San Francisco, 1980.

Brandl, H., Bosshard, R., Wegmann, M., 2001. Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59, 319–326.

Bruch, J., Bokelmann, K., Grimes, S.M., 2022. Process development options for electronic waste fractionation to achieve maximum material value recovery. Waste Mange Res 40 (1), 54–65.

Buekens, A., Yang, J., 2014. Recycling of WEEE plastics: a review. J. Mater. Cycles Waste Manag. 16 (3), 415–434.

Burstall, M., 1997. Recycling end-of-life equipment. In: Hoyle, W., Karsa, D.R. (Eds.), Chemical Aspects of Plastics Recycling; Ch8. The Royal Society of Chemistry, UK, ISBN 0854047123, pp. pp41–49.

Busuttil, C., Gies, G., Valiante, U., 2016. Competition in Select Extended Producer Responsibility Programs (Vancouver).
Cafiero, L., De Angelis, D., Di Dio, M., Di Lorenzo, P., Pietrantonio, M., Pucciarmati, S., Terzi, R., Tuccinardi, L., Tuffi, R., Ubertini, A., 2021. Characterization of WEEE plastics and their potential valorisation through the production of 3D printing filaments. J. Environ. Chem. Eng. 9, 105532.
Caravanos, Jack, et al., 2011. Assessing worker and environmental chemical exposure risks at an e-waste recycling and disposal site in Accra, Ghana. J Health Pollut 1.1, 16–25.
Carneiro, O., Silva, A., Gomes, R., 2015. Fused deposition modeling with polypropylene. Mater. Des. 83, 768–776.
Cerruti, C., Curutchet, G., Donati, E., 1998. Bio-dissolution of spent nickel–cadmium batteries using Thiobacillus ferrooxidans. J. Biotechnol. 62, 209–219.
Ceryes, C.A., Antonacci, C.C., Harvey, S.A., Spiker, M.L., Bickers, A., Neff, R.A., 2021. Maybe it's still good?" A qualitative study of factors influencing food waste and application of the E.P.a. food recovery hierarchy in U.S. supermarkets. Appetite 161, 105111.
Charitopoulou, M.A., Kalogiannis, K.G., Lappas, A.A., Achilias, D.S., 2021. Novel trends in the thermo-chemical recycling of plastics from WEEE containing brominated flame retardants. Environ. Sci. Pollut. Control Ser. 28, 59190–59213.
Charitopoulou, M.A., Stefanidis, S.D., Lappas, A.A., Achilias, D.S., 2022. Catalytic pyrolysis of polymers with brominated flame-retardants originating in waste electric and electronic equipment (WEEE) using various catalysts. Sus Chem Pharma 26, 100612.
Chen, D., Bi, X., Zhao, J., Chen, L., Tan, J., Mai, B., Sheng, G., Fu, J., Wong, M., 2009. Pollution characterization and diurnal variation of PBDEs in the atmosphere of an e-waste dismantling region. Environ. Pollut. 157, 1051–1057.
Choubey, S., Goswami, P., Gautam, S., 2021. Recovery of copper from Waste PCB boards using electrolysis. Mater. Today Proc. 42, 2656–2659.
Cole, C., Gnanapragasam, A., Cooper, T., Singh, J., 2019. An assessment of achievements of the WEEE directive in promoting movement up the waste hierarchy: experiences in the UK. Waste Manage. (Tucson, Ariz.) 87, 417–427.
Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff, A.C., Van Doorsselaer, K., Velis, C., Wagner, M., 2019. A Circular Economy for Plastics – Insights from Research and Innovation to Inform Policy and Funding Decisions. https://doi.org/10.2777/269031. European Commission. European Commission, Brussels, Belgium.
Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electric and electronic equipment: a review. J. Hazard Mater. 99, 243–263.
Dahlbo, H., Poliakova, V., Myllari, V., Sahimaa, O., Anderson, R., 2018. Recycling potential of post-consumer plastic packaging waste in Finland. Waste Manage. (Tucson, Ariz.) 71, 52–61.
Dalrymple, I., Wright, N., Kellner, R., et al., 2007. An integrated approach to electronic waste (WEEE) recycling. Circ. World 3, 52–58.
Das, P., Gabriel, J.P., Tay, C.Y., Lee, J.M., 2021. Value-added products from thermochemical treatments of contaminated e-waste plastics. Chemosphere 269, 129409.
Delva, L., Hubo, S., Cardon, L., Ragaert, K., 2018. On the role of flame retardants in mechanical recycling of solid plastic waste. Waste Manage. (Tucson, Ariz.) 82, 198–206.
Deng, W.J., Louie, P.K.K., Liu, W.K., Bi, X.H., Fu, J.M., Wong, M.H., 2006. Atmospheric levels and cytotoxicity of PAHs and heavy metals in TSP and PM2.5 at an electronic waste recycling site in southeast China. Atmos. Environ. 40, 6945–6955.
Deubzer, O., 2007. Explorative Study into the Sustainable Use and Substitution of Soldering Metals in Electronics.
Dimitrakakis, E., Janz, A., Bilitewski, B., Gidarakos, E., 2009a. Small WEEE: determining recyclables and hazardous substances in plastics. J. Hazard Mater. 161 (2–3), 913–919.
Dimitrakakis, E., Janz, A., Bilitewski, B., Gidarakos, E., 2009b. Determination of heavy metals and halogens in plastics from electric and electronic waste. Waste Manage. (Tucson, Ariz.) 29 (10), 2700–2706.
Dimitropoulos, A., Tijm, J., in'T Veld, D., 2021. Extended Producer Responsibility. Design, Functioning and Effects.
D'Adamo, I., Ferella, F., Rosa, P., 2019. Wasted liquid crystal displays as a source of value for e-waste treatment centers: a techno-economic analysis. Curr. Opin. Green Sustain. Chem. 19, 37–44.
EC, 1991. Council directive 91/156/EEC of 18 March 1991 amending directive 75/442/EEC on waste. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.1991.078.01.0032.01.ENG. (Accessed 9 June 2022).
EC, 2002. European Commission, Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment (WEEE) - Joint Declaration of the European Parliament, the Council and the Commission Relating to Article 9. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32002L0096. (Accessed 21 May 2022). Accessed on.
EC, 2003a. Directive 2003/108/EC of the European Parliament and of the Council of 8 December 2003 Amending Directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE). Available at: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32003L0108. (Accessed 22 May 2022).
EC, 2003b. European Union Directive 2002/95/EC. Official Journal of the European Union.
EC, 2006. European commission (2006) regulation (EC) No. 1013/2006 of the European parliament and of the council of 14 june 2006 on shipments of waste. Off. J. Eur. Union 190, 1–98.
EC, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098. (Accessed 18 May 2022). Accessed on.
EC, 2011. European parliament directive 2011/65/EU of the European parliament and of the council of 8 june 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. Off. J. Eur. Union 88–110.
EC, 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02012L0019-20180704. (Accessed 18 May 2022).
EC, 2015. First circular economy action plan. Available at: https://ec.europa.eu/environment/topics/circular-economy/first-circular-economy-action-plan_en#:~:text=In%202015%2C%20the%20European%20Commission,growth%20and%20generate%20new%20jobs. (Accessed 21 May 2022).
EC, 2017a. European commission, commission regulation (EU) 2017/227 of 9 February 2017 amending Annex XVII to regulation (EC) No. 1907/2006 of the European parliament and of the council concerning the registration, evaluation, authorisation and restriction of chemicals (REACH) as regards bis(pentabromophenyl)etherf. Off. J. Eur. Union 35, 6–9.
EC, 2017b. European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 List of Critical Raw Materials for the EU. COM/2017/0490 Final. European Commission, Brussels.
EC, 2019a. European commission report on the implementation of the circular economy action plan. Available at: https://doi.org/10.1259/arr.1905.0091. (Accessed 19 May 2022).
EC, 2019b. Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on Persistent Organic Pollutants (Text with EEA Relevance), pp. 45–77. PE/61/2019/REV/1OJ L 169, 25.6.2019.
EC, 2020. European commission, A new circular economy action plan. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1& format=PDF. (Accessed 19 May 2022).
EC CE, 2020. The EU's Circular Economy Action Plan. Setting the World's Largest Single Market on a Transition towards a Circular Economy.
Elliot, B., 2017. E-plastics explained. Available at: https://resource-recycling.com/e-scrap/2017/04/26/e-plastics-explained/. (Accessed 19 May 2022).
Ernst, T., Popp, R., van Eldik, R., 2000. Quantification of heavy metals for the recycling 421 of waste plastics from electrotechnical applications. Talanta 53, 347–357.
Esposito, L., Cafiero, L., De Angelis, D., Tuffi, R., Ciprioti, S.V., 2020. Valorization of the plastic residue from a WEEE treatment plant by pyrolysis. Waste Manag. 112, 1–10.
EU, 2017. European Union Restrictions on the use of certain hazardous substances in electrical and electronic equipment. Available at: http://eur-lex.europa.eu/summary/EN/uriserv:2004_4.
Euro Stats, 2022. Recycling - secondary material price indicator. . Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Recycling_%E2%80%93_secondary_material_price_indicator#:~:text=In%202020%2C%20average%20prices%20of,they%20dropped%2014%25%20on%20average. (last accessed on 29th May 2022).
Ewa, Z., Adriana, W., Katarzyna, S., Walery, Z., 2018. Health hazards resulting from the WEEE combustion at illegal e-waste yards in developing countries on the example of Agbogbloshie. J Health Edu Sport 8 (12), 363–369.
Favot, M., Grassetti, L., Massarutto, A., Veit, R., 2022. Regulation and competition in the extended producer responsibility models: results in the WEEE sector in Europe. Waste Mange 145, 60–71.
Fogarasi, S., Imre-Lucaci, F., Ilea, P., Imre-Lucaci, _A., 2013. The environmental assessment of two new copper recovery processes from waste printed circuit boards. J. Clean. Prod. 54, 264–269.
Fogarasi, S., Imre-Lucaci, F., Imre-Lucaci, A., Ilea, P., 2014. Copper recovery and gold enrichment from waste printed circuit boards by mediated electrochemical oxidation. J. Hazard Mater. 273, 215–221.
Forti, V., Baldé, C.P., Kuehr, R., Bel, G., 2020. The Global E-Waste Monitor 2020: Quantities, Flows and the Circular Economy Potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.
FRM, 2022. Flame Retardants Market by Type (Aluminum Trihydrate, Antimony Oxide, Brominated), Application (Epoxy, Polyolefin, Unsaturated Polyester), End-Use Industry (Building & Construction, Electronics & Appliances) and Region- Global Forecast to 2027, Flame Retardant Market (FRM) Report, Top Market Reports. Available at: https://www.marketsandmarkets.com/Market-Reports/flame-retardant-chemicals-market-686.html?gclid=EAIaIQobChMI3fywob6B-AIVUQKLCh212wWwEAAYASAAEgK7qvD_BwE. (Accessed 28 May 2022).
Fromme, H., Lahrz, T., Piloty, M., Gebhart, H., Oddoy, A., Rüden, H., 2004. Occurrence of phthalates and musk fragrances in indoor air and dust from apartments and kindergartens in Berlin (Germany). Indoor Air 14 (3), 188–195.
FRs, 2022. The flame retardants market, FLAME RETARDANTS-ONLINE report. Available at: https://www.flameretardants-online.com/flame-retardants/market. (Accessed 28 May 2022).
Gent, M.R., Menendez, M., Toraño, J., et al., 2011. Optimization of the recovery of plastics for recycling by density media separation cyclones. Resour. Conserv. Recycl. 55, 472–482.
Gharfalkar, M., Court, R., Campbell, C., Ali, Z., Hillier, G., 2015. Analysis of waste hierarchy in the European waste directive 2008/98/EC. Waste Manage. (Tucson, Ariz.) 39, 305–313.
Gómez, M., Peisino, L.E., Kreiker, J., Gaggino, R., Cappelletti, A.L., Martín, S.E., Uberman, P.M., Positieri, M., Raggiotti, B.B., 2020. Stabilization of hazardous

compounds from WEEE plastic: development of a novel core-shell recycled plastic aggregate for use in building materials. Construct. Build. Mater. 230, 116977.
Goosey, M., 2012. Waste Electrical and Electronic Equipment (WEEE) Handbook. Woodhead Publishing Series in Electronic and Optical Materials, pp. 123–144.
Gu, L., Ozbakkaloglu, T., 2016. Use of recycled plastics in concrete: a critical review. Waste Manage. (Tucson, Ariz.) 51, 19–42.
Guo, Q., Wang, E., Nie, Y., Shen, J., 2018. Profit or environment? A system dynamic model analysis of waste electrical and electronic equipment management system in China. J. Clean. Prod. 194, 34–42.
Ha, N.N., Agusa, T., Ramu, K., Tu, N.P.C., Murata, S., Bulbule, K.A., Parthasaraty, P., Takahashi, S., Subramanian, A., Tanabe, S., 2009. Contamination by trace elements at e-waste recycling sites in Bangalore, India. Chemosphere 76, 9–15.
Haarman, A., Magalini, F., Courtois, J., 2020. Study on the Impacts of Brominated Flame Retardants on the Recycling of WEEE Plastics in Europe.
Habib, M., Miles, N.J., Hall, P., 2013. Recovering metallic fractions from waste electrical and electronic equipment by a novel vibration system. Waste Mange 33, 722–729.
Hadi, P., Xu, M., Lin, C.S.K., et al., 2015. Waste printed circuit board recycling techniques and product utilization. J. Hazard Mater. 283, 234–243.
Hamade, R., Al Ayache, R., Ghanem, M.B., El Masri, S., Ammouri, A., 2020. Life cycle analysis of AA alkaline batteries. Procedia Manuf. 43, 415–422.
Hammond, D., Beullens, P., 2007. Closed-loop supply chain network equilibrium under legislation. Eur. J. Oper. Res. 183 (2), 895–908.
Hazra, A., Das, S., Ganguly, A., Das, P., Chatterjee, P., Murmu, N., Banerjee, P., 2019. Plasma Arc Technology: A Potential Solution toward Waste to Energy Conversion and of GHGs Mitigation. Waste Valor Recyc, pp. 203–217.
Hendriks, C.H.F., Janssen, G.M.T., 2001. Application of construction and demolition waste. Heron 46, 95–108.
Herat, S., 2007. Sustainable management of electronic waste (e-Waste). Clean 35 (4), 305–310.
Herat, S., 2008. Environmental impacts and use of brominated flame retardants in electrical and electronic equipment. Environmentalist 28 (4), 348–357.
Hicks, C., Dietmar, R., Eugster, M., 2005. The recycling and disposal of electronic waste in China—legislative and market response. Environ. Impact Assess. Rev. 25, 459–471.
Hoggerl, G., 2015. Aufbereitung von Elektroaltgeraten nach dem neuesten Stand der Technik. BHM Berg- und üttenmännische Monatshefte 160, 275–283.
Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. Philos. Trans Royal Soc. B 364 (1526), 2115–2126.
Hopson, E., Pucket, J., 2016. Scam Recycling: E-Dumping on Asia by US Recyclers. Basel Action Network, USA.
Hossain, M.S., Al-Hamadani, S.M.Z.F., Rahman, M.T., 2015. E-Waste: a challenge for sustainable development. J Health Pollut 5, 3–11.
Huang, K., Guo, J., Xu, Z., 2009. Recycling of waste printed circuit boards: a review of current technologies and treatment status in China. J. Hazard Mater. 164, 399–408.
Huisman, J., Stevels, A., Marinelli, T., Magalini, F., 2006. Where did WEEE go wrong in Europe? Practical and academic lessons for the US. In: Proceedings of the 2006. IEEE International Symposium on Electronics and the Environment. IEEE, pp. 83–88.
Iannicelli-Zubiani, E.M., Giani, M.I., Recanati, F., et al., 2017. Environmental impacts of a hydrometallurgical process for electronic waste treatment: a life cycle assessment case study. J. Clean. Prod. 140, 1204–1216.
Islam, A., Ahmed, T., Awual, M.R., Rahman, A., Sultana, M., Abd Aziz, A., Monir, M.U., Teo, S.H., Hasan, M., 2020. Advances in sustainable approaches to recover metals from e-waste-A review. J. Clean. Prod. 244, 118815.
Ismail, H., Hanafiah, M.M., 2021. Evaluation of e-waste management systems in Malaysia using life cycle assessment and material flow analysis. J. Clean. Prod. 308, 127358.
Jaiswala, A., Samuela, C., Patela, B.S., Kumar, M., 2015. Go Green with WEEE: eco-friendly approach for handling e- waste. Procedia Comput. Sci. 46, 1317–1324.
Jandric, A., Part, F., Fink, N., Cocco, V., Mouillard, F., Huber-Humer, M., Salhofer, S., Zafiu, C., 2020. Investigation of the heterogeneity of bromine in plastic components as an indicator for brominated flame retardants in waste electrical and electronic equipment with regard to recyclability. J. Hazard Mater. 390.
Jia, C., Das, P., Zeng, Q., Gabriel, J.-C.P., Tay, C.Y., Lee, J.-M., 2022. Chemosphere. https://doi.org/10.1016/j.chemosphere.2022.134878, 2022 (in press) Activated recovery of PVC from contaminated waste extension cord-cable using a weak acid.
Jirang, C., Roven, J., 2011. Waste - a Handbook for Management. Elsevier, Academic Press, pp. 281–296.
Jujun, R., Yiming, Q., Zhenming, X., 2014. Environment-friendly technology for recovering nonferrous metals from e-waste: eddy current separation. Resour. Conserv. Recycl. 87, 109–116.
Kaza, S., Shrikanth, S., Chaudhary, S., 2021. More Growth, Less Garbage. Urban Development Series. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/35998 License: CC BY 3.0 IGO. (Accessed 18 May 2022). Accessed on.
Kentish, S.E., Stevens, G.W., 2001. Innovations in separation technology for the recycling and re-use of liquid waste streams. Chem. Eng. J. 84, 149–159.
Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33, 1237–1250.
Kiddee, P., Pradhan, J.K., Mandal, S., Biswas, J.K., Sarkar, B., 2020. An overview of treatment technologies of e-waste. In: Handb. Electron. Waste Manag. .. INC, pp. 1–18. https://doi.org/10.1016/B978-0-12-817030-4.00022-X (last on accessed 9 June 2022).
Kim, E.-y., Kim, M.-s., Lee, J.-c., Jeong, J., Pandey, B.D., 2011a. Leaching kinetics of copper from waste printed circuit boards by electro-generated chlorine in HCl solution. Hydrometallurgy 107, 124–132.
Kim, E.-y., Kim, M.-s., Lee, J.-c., Pandey, B.D., 2011b. Selective recovery of gold from waste mobile phone PCBs by hydrometallurgical process. J. Hazard Mater. 198, 206–215.
Krikke, H.R., Zuidwijk, 2008. Disposition Choices Based on Energy Footprints Instead of Recovery Quota, Applying Pareto Frontiers to Analyze the Effectiveness of Extended Producer Responsibility. CentER discussion paper, 2008-74, submitted to POM;. http://center.uvt.nl/pub/dp2008.html.
Kuah, A.T.H., Wang, P., 2020. Circular economy and consumer acceptance: an exploratory study in East and Southeast Asia. J. Clean. Prod. 247, 119097.
Kumar, A., Gaur, D., Liu, Y., Sharma, D., 2022. Sustainable waste electrical and electronic equipment management guide in emerging economies context: a structural model approach. J. Clean. Prod. 336, 130391.
Kuwait Press, 2021. Available at: https://pressn.net/article/13225417?news. (Accessed 18 June 2022).
Lateef, H., Grimes, S.M., Morton, R., et al., 2008. Extraction of components of composite materials: ionic liquids in the extraction of flame retardants from plastics. J. Chem. Technol. Biotechnol. 83, 541–545.
Lau, N.C., Lim, L.P., Weinstein, E.G., Bartel, D.P., 2001. An abundant class of tiny RNAs with probable regulatory roles in Caenorhabditis elegans. Science 294, 858–862.
Lee, D., 2022. Production efficiency and economic benefit evaluation of biohydrogen produced using macroalgae as a biomass feedstock in Asian circular economies. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2021.10.138 (Article (in press).
Lee, C.-H., Chang, S.-L., Wang, K.-M., Wen, L.-C., 2000. Management of scrap computer recycling in Taiwan. J. Hazard Mater. A73, 209–220.
Lehmann, C., Cruz-Jesus, F., Oliveira, T., Damasio, B., 2022. Leveraging the circular economy: investment and innovation as drivers. J clean Product 360, 132146.
Leung, A.O.W., 2019. Environmental Contamination and Health Effects Due to E-Waste Recycling, Electronic Waste Management and Treatment Technology. Elsevier, pp. 335–362.
Li, J., Xu, Z.M., 2010. Environmentally friendly automatic line for recovering metal from waste printed circuit boards. Environ. Sci. Technol. 44, 1418–1423.
Li, J., Wen, X., Liu, T., Honda, S., 2004. Policies, Management, Technologies and Facilities for the Treatment of Electrical and Electronic Wastes in China. The China–Netherlands Seminar on Recycling of Electronic Wastes, Beijing. http://www.bcrc.cn/en/Backup/Meetings/China-Netherland/10.pdf, 2004.
Li, Y., Richardson, J.B., Walker, A.K., Youn, P.-C., 2006. TCLP heavy metal leaching of personal computer components. J. Environ. Eng. 132 (4), 497–504.
Li, J., Lu, H., Guo, J., Xu, Z., Zhou, Y., 2007. Recycle technology for recovering resources and products from waste printed circuit boards. Environ. Sci. Technol. 41, 1995–2000.
Li, J., Wu, G., Xu, Z., 2015. Tribo-charging properties of waste plastic granules in process of tribo-electrostatic separation. Waste Mange 35, 36–41.
Li, J., Jiang, Y., Xu, Z., 2017. Eddy current separation technology for recycling printed circuit boards from crushed cell phones. J. Clean. Prod. 1316–1323.
Linnenkoper, K., Reintjes, M., 2017. The wide world of shredders. Recycling Int 2, 26–35.
Lister, T.E., Wang, P.M., Anderko, A., 2014. Recovery of critical and value metals from mobile electronics enabled by electrochemical processing. Hydrometallurgy 149, 228–237.
LR, 2022. Let's recycle. Available at: https://www.letsrecycle.com/prices/glass/glass-prices-2021(last accessed on: 20 June 2022)./.
Luhar, S., Luhar, I., 2019. Potential application of E-wastes in construction industry: a review. Construct. Build. Mater. 203 (2019), 222–240.
Luthra, S., Mangla, S.K., Sarkis, J., Tseng, M.L., 2022. Resources melioration and the circular economy: sustainability potentials for mineral, mining and extraction sector in emerging economies. Resour. Pol. 77, 102652.
Madhav, A.V.S., Rajaraman, R., Harini, S., Kiliroor, C.C., 2022. Application of artificial intelligence to enhance collection of E-waste: a potential solution for household WEEE collection and segregation in India. Waste Manag. Res. 40 (7), 1047–1053.
Mahapatra, R.P., Srikant, S.S., Rao, R.B., Mohanty, B., 2019. Recovery of basic valuable metals and alloys from E-waste using microwave heating followed by leaching and cementation process. Sådhanå 44, 209 https://doi.org/10.1007/s12046-019-1193-ySadhana(0123456789( ).,-volV)F]T(30123456789( ).,-volV).
Maris, E., Botané, P., Wavrer, P., Froelich, D., 2015. Characterizing plastics originating from WEEE: a case study in France. Miner. Eng. 76, 28–37.
Martinho, G., Pires, A., Saraiva, L., Ribeiro, R., 2012. Composition of plastics from waste electrical and electronic equipment (WEEE) by direct sampling. Waste Manage. (Tucson, Ariz.) 32, 1213–1217.
Massarutto, A., 2014. The long and winding road to resource efficiency - an interdisciplinary perspective on extended producer responsibility. Resour. Conserv. Recycl. 85.
Mastellone, M.L., 1999. Thermal Treatments of Plastic Wastes by Means of Fluidized Bed Reactors. Department of Chemical Engineering, Second University of Naples, Italy. PhD dissertation.
Matthews, R.J., Marland, G., Fung, I., 1996. A $1^{\circ} \times 1^{\circ}$ distribution of carbon dioxide emissions from fossil fuel consumption and cement manufacture, 1950-1990. Global Biogeochem. Cycles 10, 419–429.
Menad, N., Guignot, S., van Houwelingen, J., 2013. New characterisation method of electrical and electronic equipment wastes (WEEE). Waste Mange 33, 706–713.
Merafhe, K., 2011. Real-time Monitoring for Corona-Electrostatic Separation in Recycling Waste Printed Circuit Boards, A Major Qualifying Project Proposal to Be Submitted to the Faculty of Worcester Polytechnic Institute in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science.
Muenhor, D., Harrad, S., Ali, N., Covaci, A., 2010. Brominated flame retardants (BFRs) in air and dust from electronic waste storage facilities in Thailand. Environ. Int. 36, 690–698.

Nagajothi, P.G., Felixkala, T., 2015. Electronic waste management: a review. Int. J. Appl. Eng. Res. 10, 133–138.
Nnorom, I.C., Osibanjo, O., 2008a. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour. Conserv. Recycl. 52, 843–858.
Nnorom, I.C., Osibanjo, O., 2008b. Electronic waste (e-waste): material flows and management practices in Nigeria. Waste Mange 28, 1472–1479.
Nnorom, I.C., Osibanjo, O., 2009. Toxicity characterization of waste mobile phone plastics. J. Hazard Mater. 161, 183–188.
OEC, 2020. Kuwait report. Available at: https://oec.world/en/profile/country/kwt. (Accessed 18 June 2022).
OECD, 2001. Extended Producer Responsibility. A Guidance Manual for Governments.
Ogungbuyi, O., et al., 2012. E-Waste Country Assessment: Nigeria. EMPA, B.C.U.
Oh, C.J., Lee, S.O., Yang, H.S., Ha, T.J., Kim, M.J., 2003. Selective leaching of valuable metals from waste printed circuit boards. J Air Waste Mange Assoc 53, 897–902.
Ongondo, F., Williams, I.D., 2011. Are WEEE in control? Rethinking strategies for managing waste electrical and electronic equipment. In: Kumar, S. (Ed.), Waste Management. Intech Open Access Publisher, Rijeka, Croatia.
Ongondo, F., Williams, I.D., Keynes, S., 2011a. Estimating the impact of the "digital switchover" on disposal of WEEE at household waste recycling centres in England. Waste Manage. (Tucson, Ariz.) 31 (4), 743–753.
Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011b. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manage. (Tucson, Ariz.) 31 (4), 714–730.
Otake, T., Yoshinaga, J., Yanagisawa, Y., 2001. Analysis of organic esters of plasticizer in indoor air by GC- MS and GC-FPD. Environ. Sci. Technol. 35 (15), 3099–3102.
Palmieri, R., Bonifazi, G., Serranti, S., 2014. Recycling-oriented characterization of plastic frames and printed circuit boards from mobile phones by electronic and chemical imaging. Waste Mange 34, 2120–2130.
Pan, X., Wong, C.W.Y., Li, C., 2022. Circular economy practices in the waste electrical and electronic equipment (WEEE) industry: a systematic review and future research agendas. J. Clean. Prod. 365, 132671.
Pascoe, R.D., 2006. Investigation of hydrocyclones for the separation of shredded fridge plastics. Waste Mange 26, 1126–1132.
Pedersen, Marius, 2019. E-waste collection and transport, Marius Pedersen a.s. Available at: https://www.mariuspedersen.cz/en/about-marius-pedersen/services/58.shtml. (Accessed 22 May 2022). Accessed on.
Peeters, J.R., Vanegas, P., Tange, L., Van Houwelingen, J., Duflou, J.R., 2014. Closed loop recycling of plastics containing Flame Retardants. Resour. Conserv. Recycl. 84, 35–43.
Perea, C.G., Restrepo Baena, O.J., Ihle, C.F., Estay, H., 2021. Copper leaching from wastes electrical and electronic equipment (WEEE) using alkaline monosodium glutamate: thermodynamics and dissolution tests. Cleaner Eng Technol. 5, 100312.
Pestalozzi, F., Eisert, S., Woidasky, J., 2018. Benchmark comparison of high voltage discharge separation of photovoltaic modules by electrohydraulic and electrodynamic fragmentation. Recycling 3, 13.
Powel, J., 2002. E-scrap news. Resource recycling magazine. E-Scrap future: recent key trends. In: Regional Electronics Conference, Louisville, Kentucky, USA August 29, 2002.
PST, 2022. Plastic trip. Available at: https://www.plasticsouptrip.com/post/97791290765/what-can-the-prices-of-plastics-teach-us. (Accessed 20 June 2022).
Puckett, J., Smith, T., 2002. In: Coalition, S.V.T. (Ed.), Exporting Harm the High-Tech Trashing of Asia.
Rajesh, R., Kanakadhurga, D., Prabaharan, N., 2022. Electronic waste: a critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environ Challenges 7, 100507.
Ramprasad, C., Gwenzi, W., Chaukura, N., Azelee, N.I.W., Rajapaksha, A.U., Naushad, M., Rangabhashiyam, S., 2022. Strategies and Options for the Sustainable Recovery of Rare Earth Elements.
Recycling.com, 2019. Original Waste Hierarchy of Ad Lansink [WWW Document]. Available at: https://www.recycling.com/downloads/waste-hierarchy-lansinks-ladder/. (Accessed 9 June 2022).
Rocha, T.B., Penteado, C.S.G., 2021. Life cycle assessment of a small WEEE reverse logistics system: case study in the Campinas Area, Brazil. J. Clean. Prod. 314, 128092.
Saikia, N., De Brito, J., 2012. Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. Construct. Build. Mater. 34, 385–401.
Sajid, M., Syed, J.H., Iqbal, M., Abbas, Z., Hussain, I., Baig, M.A., 2019. Assessing the generation, recycling and disposal practices of electronic/electrical-waste (E-Waste) from major cities in Pakistan. Waste Mange 84, 394–401.
Salhofer, S., Steuer, B., Ramusch, R., et al., 2016. WEEE management in Europe and China – a comparison. Waste Mange 57, 27–35.
Schlummer, M., Brandl, F., Mäurer, A., Van Eldik, R., 2005. Analysis of flame retardant additives in polymer fractions of waste of electric and electronic equipment (WEEE) by means of HPLC-UV/MS and GPC-HPLC-UV. J. Chromatogr. A 1064 (1), 39–51.
Schlummer, M., Mäurer, A., Leitner, T., Spruzina, W., 2006. Report: recycling of flameretarded plastics from waste electric and electronic equipment (WEEE). Waste Manag. Res. 24 (6), 573–583 (2006).
Schlummer, M., Gruber, L., Mäurer, A., Wolz, G., van Eldik, R., 2007. Characterisation of polymer fractions from waste electrical and electronic equipment (WEEE) and implications for waste management. Chemosphere 67 (9), 1866–1876.
Schut, J.H., 2007. Recycling E-Plastics New Material Stream Brings its Own Set of Problems, Brominated Flame Retardants Restrict its Use. Most Now Goes to China, but New Recycling Processes Promise to 'clean up' E-Waste. Available at: https://www.ptonline.com/articles/recycling-e-plastics-new-material-stream-brings-its-own-set-of-problems. (Accessed 1 June 2022).
Schwarzer, S., Bono, A.D., Giuliani, G., Kluser, S., Peduzzi, P., 2005. E-Waste, the Hidden Side of IT Equipment's Manufacturing and Use. United Nations Environment Programme (UNEP). Available at: https://www.semanticscholar.org/paper/E-waste%2C-the-hidden-side-of-IT-equipment%27s-and-use-Schwarzer-Bono/be902ef65fc39202b84b9997c487780640d4748f. (Accessed 23 May 2022).
Sengupta, D., Ilankoon, I.M.S.K., Kang, K.D., Chong, M.N., 2022. Circular economy and household e-waste management in India: integration of formal and informal sectors. Miner. Eng. 184, 107661.
Senthil Kumar, K., Baskar, K., 2018. Effect of temperature and thermal shock on concrete containing hazardous electronic waste. J. Hazard. Toxic Radiact. Waste 22 (2), 04017028.
Sepúlveda, Alejandra, et al., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipment during recycling: examples from China and India. Environ. Impact Assess. Rev. 30, 28–41.
Settimo, F., Bevilacqua, P., Remb, A.R., Eddy, 2004. Current separation of fine non-ferrous particles from bulk streams. Phys. Separ. Sci. Eng. 13, 15–23.
Shittu, O.S., Williams, I.D., Shaw, P.J., 2021. Global E-waste management: can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Mange 120, 549–563.
Siddique, R., Khatib, J., Kaur, I., 2008. Use of recycled plastic in concrete: a review. Waste Manage. (Tucson, Ariz.) 28 (10), 1835–1852.
Silveira, A.V.M., Cella, M., Tanabe, E.H., et al., 2018. Application of tribo-electrostatic separation in the recycling of plastic wastes. Process Saf. Environ. Protect. 114, 219–228.
Singh, N., Duan, H., Tang, Y., 2020. Toxicity evaluation of E-waste plastics and potential repercussions for human health. Environ. Int. 137, 105559.
Sivaramanan, S., 2013. E-waste management, disposal and its impacts on the environment. Univ. J. Environ. Res. Technol. 3, 531–537.
SMB, 2022. Scrap metal buyers we buy scrap metals nationwide. Available at: https://www.scrapmetalbuyers.com/current-prices. (Accessed 20 June 2022).
Statita, 2021a. Forecast Number of Mobile Devices Worldwide from 2020 to 2025 (In Billions). Available at: https://www.statista.com/statistics/245501/multiple-mobile-device-ownership-worldwide/#:~:text=In%202021%2C%20the%20number%20of,billion%20in%20the%20previous%20year. (Accessed 18 May 2022).
Statita, 2021b. Generation of Electronic Waste Worldwide in 2019. by region. Available at: https://www.statista.com/statistics/499952/ewaste-generation-worldwide-by-major-country/. (Accessed 18 May 2022).
Statita, 2022. Global E-Waste Generation by Major Country 2019. Available at: https://www.statista.com/statistics/499921/ewaste-generation-worldwide-by-region/. (Accessed 18 May 2022).
Stenvall, E., Tostar, S., Boldizar, A., Foreman, M.R., Möller, K., 2013. An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste Manage. (Tucson, Ariz.) 33 (4), 915–922.
Sthiannopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci. Total Environ. 463, 1147–1153.
Sun, Z., Xiao, Y., Sietsma, J., Agterhuis, H., Yang, Y., 2016. Complex electronic waste treatment – an effective process to selectively recover copper with solutions containing different ammonium salts. Waste Manag. 57, 140–148.
SwedWatch, 2009. Out of Control, E-Waste Trade Flows from the EU to Developing Countries. www.sedwatch.org.
Tange, L., Slijkhuis, C., 2009. The classification of WEEE plastic scrap in view of PBB's &PBDE's. Tech. rep.
Tanrıverdi, S., 2021. E-Waste and its Types, Waste advantages magazine. Available at: https://wasteadvantagemag.com/e-waste-and-its-types/. (Accessed 23 May 2022).
Tansel, B., 2017. From electronic consumer products to e-wastes. Global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45.
Tanskanen, P., 2013. Management and recycling of electronic waste. Acta Mater. 61, 1001–1011.
Townsend, T.G., Vann, K., Mutha, S., Pearson, B., Jang, Y.-C., Musson, S., Jordan, A., 2005. RCRA toxicity characterization of electronic wastes. Hazard. Waste Consult. 23, 16–18.
Truc, N.T.T., Lee, B.-K., 2017a. Combining ZnO/microwave treatment for changing wettability of WEEE styrene plastics (ABS and HIPS) and their selective separation by froth flotation. Appl. Surf. Sci. 420, 746–752.
Truc, N.T.T., Lee, B.-K., 2017b. Selective separation of ABS/PC containing BFRs from ABSs mixture of WEEE by developing hydrophilicity with ZnO coating under microwave treatment. J. Hazard Mater. 329, 84–91.
Tuncuk, A., Stazi, V., Akcil, A., et al., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25, 28–37.
Ügdüler, S., Geem, K.M. Van, Roosen, M., Delbeke, E.I.P., Meester, S. De, 2020. Challenges and Opportunities of Solvent-Based Additive Extraction Methods for Plastic Recycling, vol. 104, pp. 148–182. https://doi.org/10.1016/j.wasman.2020.01.003.
UK, G.O.V., 2022. Waste and environmental impact, Classify different types of waste. Available at: https://www.gov.uk/how-to-classify-different-types-of-waste/electronic-and-electrical-equipment. (Accessed 22 May 2022). Accessed on.
Vaudey, A.D., Glachant, M., 2007. Les Packaging Recovery Notes (PRN) Sont-Ils Economiquement Efficaces? No. hal-03175092f), Lyon.
Veit, H.M., Dihl, T.R., Salami, A.P., et al., 2005. Utilisation of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste Mange 25, 67–74.
Veit, H.M., Bernardes, A.M., Ferreira, J.Z., et al., 2006. Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy. J. Hazard Mater. 137, 1704–1709.
Verma, A., Hait, S., 2019. Chelating extraction of metals from e-waste using diethylene triamine pentaacetic acid. Process Saf. Environ. Protect. 121, 1–11.

Wäger, P.A., Schluep, M., Müller, E., Gloor, R., 2012. RoHS regulated substances in mixed plastics from waste electrical and electronic equipment. Environ. Sci. Technol. 46, 628–635.
Wagner, S., Schlummer, M., 2020. Legacy additives in a circular economy of plastics: current dilemma, policy analysis, and emerging countermeasures. Resour. Conserv. Recycl. 158, 104800.
Wang, R., Xu, Z., 2014. Recycling of non-metallic fractions from waste electrical and electronic equipment (WEEE): a review. Waste Mange 34, 1455–1469.
Wang, D., Cai, Z., Jiang, G., Leung, A., Wong, M.H., Wong, W.K., 2005. Determination of polybrominated diphenyl ethers in soil and sediment from an electronic waste recycling facility. Chemosphere 60, 810–816.
Wang, M., You, X., Li, X., Liu, G., 2018. Watch more, waste more? A stock-driven dynamic material flow analysis of metals and plastics in TV sets in China. J. Clean. Prod. 187, 730–739.
Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Boni, H., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25 (5), 436–458.
Williams, I.D., 2016. Global metal reuse, and formal and informal recycling from electronics and other high-tech wastes. In: Izatt, R.M. (Ed.), Metal Sustainability: Global Challenges, Consequences, and Prospects. Wiley, Oxford, U.K, pp. 23–51.
Wong, C.S.C., Wu, S.C., Duzgoren-Aydin, N.S., Aydin, A., Wong, M.H., 2007. Trace metal contamination of sediments in an e-waste processing village in China. Environ. Pollut. 145 (2), 434–442.
WTO, 2022. World trade organisation classification. Available at: https://www.wto.org/english/-tratop_e/devel_e/d1who_e.htm. (Accessed 30 May 2022).
Wu, J., Li, J., Xu, Z.M., 2008. Electrostatic separation for recovering metals and nonmetals from waste printed circuit board: problems and improvements. Environ. Sci. Technol. 42, 5272–5276.
Wu, G., Li, J., Xu, Z., 2013. Triboelectrostatic separation for granular plastic waste recycling: a review. Waste Mange 33, 585–597.
Xu, K., Deng, T., Liu, J., et al., 2007. Study on the recovery of gallium from phosphorous flue dust by leaching with spent sulfuric acid solution and precipitation. Hydrometallurgy 86, 172–177.
Yang, D., Chu, Y., Wang, J., Chen, M., Shu, J., Xiu, F., Xu, Z., Sun, S., Chen, S., 2018. Completely separating metals and nonmetals from waste printed circuit boards by slurry electrolysis. Separ. Purif. Technol. 205, 302–307.
Yoshida, F., Yoshida, H., 2013. E-Waste management in Japan: a focus on appliance recycling. In: Proceedings of the 8th International Conference on Waste Management and Technology 2013, vol. 10, pp. 23–25.
Yoshida, M., Nakatsukasa, S., Nanba, M., et al., 2010. Decrease of Cl contents in waste plastics using a gas-solid fluidized bed separator. Adv. Powder Technol. 21, 69–74.
Zeng, X.L., Zheng, L.X., Xie, H.H., Lu, B., Xia, K., Chao, K.M., Li, W.D., Yang, J.X., Lin, S. Y., Li, J.H., 2012. Current status and future perspective of waste printed circuit boards recycling. Procedia Environ Sci 16, 590–597.
Zero Waste Europe, 2019. A Zero waste hierarchy for Europe. Available at: https://zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/. (Accessed 9 June 2022).
Zhang, L., Xu, Z., 2016. A review of current progress of recycling technologies for metals from waste electrical and electronic equipment. J. Clean. Prod. 127, 19–36.
Zhang, S., Rem, P.C., Forssberg, E., 1999. The investigation on separability of particles smaller than 5mm by eddy current separation technology – part I: rotating type eddy current separators. Mag Elec Seper 9, 233–251. E.
Zhang, S., Li, Y., Wang, R., Xu, Z., Wang, B., Chen, S., Chen, M., 2017. Superfine copper powders recycled from concentrated metal scraps of waste printed circuit boards by slurry electrolysis. J. Clean. Prod. 152, 1–6.
Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., Tukker, A., 2022. An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Sci. Total Environ. 803, 149892.
Zoeteman, B.C.J., Krikke, H.R., Venselaar, J., 2010. Handling WEEE waste flows: on the effectiveness of producer responsibility in a globalizing world. Int. J. Adv. Manuf. Technol. 47, 415–436.