RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Sustainability*, 2025, **3**, 1039

2002–2022: 20 years of e-waste regulation in the European Union and the worldwide trends in legislation and innovation technologies for a circular economy†

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Waste Electrical and Electronic Equipment (WEEE or e-waste) has emerged as a formidable global waste stream, reflecting the mounting demand for technology in our interconnected world. Over the past two decades, besides a world facing a rapid digital, e-mobility, and green energy transition, there has been a growing recognition across the globe, among both society and industries, regarding the hazards and opportunities linked to e-waste management. This collective consciousness has driven the adoption of best practices, including the implementation of circular economy (CE) models, fostering environmentally sustainable production and recycling processes. With a rate of around the 72% of the global population (81 countries) reached by specific regulations by 2023, this review explores the evolving landscape of international legislation and emerging technologies designed for e-waste prevention and valorization, emphasizing low-environmental impact and sustainability. Despite a prolific scientific community (papers published on e-waste grew over 1000 times in the period 2002–2022) and the rise in good practices in different countries, the modest increase of innovation patents (rate of around 50% increase) and the limited number of industrially established innovation processes demonstrates that while the advancing technologies are promising, they remain in an early, embryonic stage. This paper offers a concise review of life cycle assessments from existing literature to underpin the technological advancements discussed. These assessments provide insights into the reduced environmental footprint of various innovative processes aimed at enhancing the circular economy and incorporating them into the emerging concept of safe- and sustainable-by-design. Meanwhile, global e-waste production rose from an estimated 34 Mt in 2010 to 62 Mt in 2022, while documented proper collection and recycling only increased from 8 Mt to 13.8 Mt over the same period. This shows that e-waste generation is growing nearly five times faster than formal recycling. Furthermore, if waste management activities remain at 2022 levels, a projected economic (benefit − costs) deficit of 40 billion USD is expected by 2030. It is time for communities to reverse the trend by expanding good practices and implementing technology-economic-environment sustainable and efficient circular economy models.

Received 4th September 2024
Accepted 6th November 2024

DOI: 10.1039/d4su00548a

rsc.li/rscsus

Sustainability spotlight

As EEE global consumption increases by 2.5 Mt annually, with a production growth ≥5% p.a. makes waste EEE the fastest growing waste stream in the world. Since the early 2000s, governmental directives have focused on WEEE management for its environmental ramifications, endorsing eco-friendly practices. This includes preserving natural reserves of raw materials through material recycling within a circular economy framework, in line with the United Nations 2030 Agenda. As the EU directives on WEEE mark their 20th anniversary, the authors aim to highlight the efforts taken in legislating, designing and advocating for highly efficient, environmentally conscious processes capable of both seizing the opportunities and facing the challenges related to WEEE recycling.

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† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d4su00548a

1. Introduction

Electrical and Electronic Equipment (EEE) are integral to our daily life. In recent decades it has largely contributed to improving the quality of life, providing different benefits and opportunities in a variety of sectors: from energy, transport, health, and security, to school/education. Population growth and consumer demand are driving manufacturing and fueling raw material consumption, resulting in countries having to face an increasing accumulation of e-waste. On the other hand, Waste Electrical and Electronic Equipment (WEEE or e-waste) has emerged as a formidable global waste stream, reflecting the voracious and often insatiable demand for technology in our interconnected world. A shift of paradigm from the unsustainable linear economic model to a circular approach is therefore essential to reduce the pressure on our limited natural resources and limit the environmental impact of waste landfills. As a consequence, governments are being compelled to confront mounting environmental challenges associated with WEEE management, resulting in specific regulations aimed at curtailing landfill use, transforming waste into valuable resources, and enhancing the overall sustainability of the value chain. Among them, EU directives have played a pivotal role in driving the "green" revolution in e-waste recycling.

This work highlights the progress made in e-waste recycling over the last 20 years, with a focus on sustainable approaches to safeguard human health and the environment. It also explores how to improve e-waste minimization and management at the global level to advance the Sustainable Development Goals of United Nations – Agenda 2030. The narrative places a particular focus on multidisciplinary approaches in materials recycling, incorporating principles of green chemistry and green engineering that maximize process efficiency while minimizing environmental impact.

The review draws on:

• Data from Global E-Waste Monitor by the United Nations Institute for Training and Research (UNITAR) and International Telecommunication Union (ITU) under the Global E-waste Statistics Partnership (GESP);[1]

• Data from the International Renewable Energy Agency (IRENA) related to photovoltaic technologies;[2]

• Scientific as well as patent databases (such as SCOPUS[3] and Orbit[4]);

• Regional information about policy, good practices and industrial technologies provided by the IUPAC members – Division VI Chemistry and the Environment Division, involved in writing this manuscript;

• Technologies proposed at relevant industry fairs.

This review discusses the evolution of industrial and societal awareness and responsibility around the world, with specific reference to: (i) the development over time of the e-waste concept, from an environmental issue to a valuable resource of secondary raw materials in the framework of the circular economy (CE); (ii) the development of regulations and policy in different countries, focusing on the responsibilities and the request for innovation in products design (eco-design for effective end-of-life, EoL, management) and sustainability in treatments (green processes); (iii) the ways new production and recycling processes have been developed to promote a more sustainable life cycle of EEE, supported by life cycle assessment (LCA); and (iv) how countries have implemented the suggestions and encouragements of the regulations in recent decades through specific initiatives and achieving target goals.

2. The birth of urban mines: where e-waste management meets the criticality of materials

Population growth and consumer demand are two key factors driving manufacturing and fuelling the consumption of raw materials. Resource extraction using classical mining is labour- and energy-intensive and generates wastes that endanger human health and the environment. To preserve our limited natural resources, the unsustainable linear economic model should be replaced by a circular approach.

The term 'urban mining' emerged in the scientific literature in the mid-1980s,[5,6] and refers to the processes of reclaiming valuable materials, energy and elements from waste generated in an urban environment. The resources recovered can be reincorporated into the manufacturing processes to stimulate a low-carbon CE and enhance the recycling of waste material. In 1988, Professor Hideo Nanjo of the Research Institute of Mineral Dressing and Metallurgy at Tohoku University pioneeringly introduced the concept of urban mines related to information and eco-innovation technologies, as "areas of industrial products concentrated on the surface", highlighted in particular the high quantity and quality of rare metals they contained compared to primary resources.[7,8] Although almost unheeded at that time, Professor Nanjo pointed out the fact, now evident to us, that industrial products held an abundance of metals that often surpassed the grades found in raw ores. Furthermore, the quantity of already mined metal resources surpassed the known reserves. In this context, he proposed a new model of supply chain resources where, besides primary production, refined metals are readily reused without the energy-intensive processes required for smelting and refining crude ores.[9] Since the 1980s, the concept of urban mines has gained traction, evolving into the 'artificial deposit concept' by Shiratori and Nakamura,[10] followed by better defining current concepts, terminology and challenges.[11]

Discarded EoL or obsolete electronic and electrical equipment becomes e-waste. The first issues related to the management of this specific category of waste date back to the mid-1970s, when they were recognized as hazardous waste and their dumping became illegal under the Resource Conservation and Recovery Act (RCRA) in the United States.[12] Due to the continuously growing accumulations of EoL devices, in Europe the landfill of e-waste, named Waste from Electrical and Electronic Equipment – WEEE, was regulated from 2002 (Directive 2002/96/EC on WEEE)[9] as part of the framework of the general waste management directives addressed to preserving the environment and natural sources. The EU regulation strategy gave a new vision to managing e-waste, emphasizing circularity. This encompassed initiatives such as reuse, sustainable urban mining, and eco-design, alongside establishing rigorous responsibilities for producers and polluters to develop ambitious targets for collection and valorization. According to the Global E-waste Monitor 2024 (GEM2024),[13] the world generated 62 Mt of e-waste in 2022 with an average growth of 2.3 Mt per year since 2010. Further estimates predict the achievement of 82 Mt of WEEE by 2030.[14] Urban mining is an important strategy in e-waste management for the reduction in resource exploitation. As an example, Van Eygen *et al.* carried out a LCA on the recycling of desktop and laptop computers in Belgium in 2013 and found that compared to landfilling, urban mining reduced resource consumption for desktops and laptops by 80 and 87%, respectively.[15]

The complex nature of e-waste reflects the heterogeneity of their sources: up to 69 elements from the periodic table can be found in a piece of electronic or electrical equipment. The e-waste stream comprises a mix of metals (among them are valuable elements such as gold, silver, copper, platinum, palladium, ruthenium, rhodium, iridium, and osmium; and noncritical metals, such as aluminium and iron), metalloids, raw materials in critical supply (*e.g.*, cobalt, palladium, silicon, indium, germanium, bismuth, and antimony), rare earth elements (REEs, *e.g.*, neodymium, yttrium and dysprosium), glass, and plastics that contain flame retardants and other additives.[16] Many valuable commodities are found in high purity and quality in e-waste. The concept of a "Critical Raw Material" (CRMs), established in 2010 by an ad hoc working group of the European Commission, links the supply shortage of materials with their industrial interest. Throughout the centuries, humanity has progressively utilized a larger portion of known elements to drive technological advancements, particularly focusing on metals. Presently, a diverse array of vital technologies spanning various industries, including chips, batteries, medical imaging, and defense equipment, heavily rely on the distinctive physical properties of specific CRMs. The demand for CRMs is anticipated to surge in the upcoming years. As an example, based on the Digital Report 2024,[17] in January 2024 approximately 5.61 billion individuals were recorded as internet users, while 5.15 billion individuals were reported as mobile phone users. This respectively accounts for approximately 66 and 69% of the global population.[18] Additionally, the COVID-19 pandemic and subsequent lockdowns and work-from-home situations have led to a surge in consumer demand for electronics, particularly in the internet technology sector. Consequently, this has contributed to a worrisome increase in e-waste generation, posing a significant global concern.[16,19] Furthermore, as the world moves towards achieving "net-zero" emissions and embraces the digital age, which both heavily rely on materials, there is uncertainty regarding whether the supply of CRMs will be able to meet the projected demands.[20] Several economic analyses have highlighted the significance of e-waste as an urban mine for CRMs. On one hand, the demand for technological production drives the criticality of materials, leading to shifts in CRM selection over the years.[21] On the other hand Hi-Tech goods serve as the best primary alternative source for these materials compared to primary minerals. Metals that can be recovered from the global e-waste generated in 2022 are estimated to be USD 91 billion.

Despite the potential of e-waste as an urban mine is already well established, the valorization of EoL equipment is still a challenge. In the scientific community and commercial sector, much research is focused on ways to improve the efficiency and sustainability of e-waste urban mining, including mechanical methods, metallurgy, pyrometallurgy, hydrometallurgy, and biohydrometallurgy.

In this framework, the present review aims to critically evaluate the industrial, social, and innovation evolution during the past 20 years concerning the treatment and valorization of e-waste within and outside the EU, with a further focus on criticalities and perspectives.

3. Worldwide and European Union regulations evolution

3.1. Global legal and policy frameworks on waste electrical and electronic equipment

Many intergovernmental organizations (IOs) such as the United Nations Environment Programme, Organization for Economic Cooperation and Development (OECD), World Bank, World Customs Organisations as well as regional governing bodies *e.g.* the European Union (EU) have developed legal and policy frameworks that are relevant to the topic of e-waste. This effort is still widening, involving an increasing number of countries and populations over the years. As reported by the GEM2024,[14] in 2017 over 50% (estimated 66%) of the whole worldwide population was covered in some extent by policy and/or regulations on e-waste management. For comparison, in 2019, regulations regarding this matter covered 78 countries, slightly increased to 81 by 2023, covering around 72% of the global population. In contrast, only 61 countries, representing 44% of the population, were actively engaged in 2014. These regulations relate to topics of (hazardous) waste management, specific e-waste legislation, legislation on product standards and policies focused on the CE. Today, most of the regulated countries (67 over 81) had a legal instrument addressing the environmental policy principle of extended producer responsibility (EPR) which requires a network for a separate collection of e-waste, appropriate management systems and infrastructures, as well as monitoring and tracking tools. Table 1 illustrates several international and regional conventions and agreements that have significantly impacted policy on WEEE. We list the years they were adopted, the number of parties, the goals and the key strengths and challenges. Global conventions are the main legal instruments to protect the environment, including from harms that result from e-waste, and they set collective norms and provisions that are legally binding. Yet, they share the challenge of implementation into regional, national and sometimes state-level legislation, which results in varying interpretations and levels of commitment.[26]

The evaluation of the implementation also varies across the different conventions, with some focusing on legal and

Table 1 International agreements with relevance to e-waste

Year of adoption (entry into force)	Convention	Parties	General goal	Goals of relevance to e-waste	Strengths (S) & challenges (C)
1989 (1992)	Basel convention	191	Controlling transboundary movements of hazardous wastes and their disposal	Addressing the increasing cross border trade in (hazardous) waste resulting from the tightening of waste treatment legislation and increasing waste treatment costs in various industrialized countries	S: regulating legal types of waste trade. C: failed in illegal waste trade prevention and control[22]
1994 (2019)	Basel ban amendment (decision III/1)	103		Banning the export of hazardous waste intended for disposal, recovery, or recycling from Annex VII countries (EU, OECD and Lichtenstein) to non-Annex VII countries	C: countries willing to keep trading in recyclables did not sign the ban amendment
1987 (1989)	Montreal protocol	197	Limiting the production and consumption of substances that deplete the ozone layer	It restricts production and use and regulates the correct disposal of waste CFCs used in cooling systems	S: successful international convention ratified by 197 parties. Reduced production and consumption of ODS and halted the depletion of the ozone layer
1998 (2004)	Rotterdam convention	165	Sharing responsibilities in trading hazardous chemicals and pesticides	Regulating the trade in toxic substances – not toxic waste, among them substances are used in the electrical parts of EEE as well as in the plastic casings, as that is covered by the Basel convention	S: contributes to transparency of international trade and allows parties to refuse imports, yet illegal trade happens in parallel to legal trade,[23] making irrelevant the subjective distinction between WEEE and UEEE (waste *vs.* used EEE)
2001 (2004)	Stockholm convention	186	Eliminating or restricting the production and use of persistent organic pollutants (POPs)	Among POPs, it applies to polychlorinated biphenyls (PCBs) used in transformers of electrical devices	S: successful in identifying new POPs. C: very difficult to get sufficient support for timely national implementation[24]
2013 (2017)	Minamata convention	147	Protecting human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds	Regulating the mining and use of mercury in products such as UEEE/WEEE and processes (including artisanal gold mining based on the use of liquid mercury)	S: provisions on phasing down or out mercury use barely on the agenda before mercury poisoning. C: a safe gold mining remains a formidable challenge[25]

regulatory changes, while others focus on technical aspects of measuring pollution. In the next section, we further examine a couple of regions to explain the particular foci of these legal and policy frameworks as well as discuss some of the challenges in more detail.

3.1.1. European Union. All European countries have legislation and/or policies that are relevant to WEEE.[14] In 2002, the European Union enforced its first specific WEEE directive (Directive 2002/96/EC),[27] which was followed by updates in 2012 (Directive 2012/19/EU)[28] and 2018 (Directive 2018/849).[29,30] The WEEE directive aims for more sustainable production and consumption of EEE, increased resource efficiency and re-use of secondary raw materials and contributing to a CE. Member states are required to extend as much as possible the life-cycle of EEE, then separately collect and properly recycle and treat WEEE (with set targets for each) and to fight illegal waste exports. The WEEE directive implements the Basel convention but leaves less room for interpretation. For instance, the requirement of demonstrating proof of testing of equipment (functionality) and ensuring correct packaging for transport of UEEE. By being able to define shipments of (U)EEE as possible e-waste, the WEEE directive provides a better basis for crime control by its member states than the Basel convention. However, once again, there is room for interpretation as to what precisely constitutes appropriate packaging, labelling and transportation. As a result, some member states implement stricter controls on e-waste trafficking, while others use more flexible operational procedures and strategies to monitor waste shipments. Because of this divergence in interpretations, participants in the trade can effectively 'shop jurisdictions' and legally exploit these regulatory asymmetries.[31] The most important changes of the 2012 directive are the focus on the idea of a CE and an open scope, rather than a closed scope, regarding the products it covered. Furthermore, the new directive demands higher targets from the Member States (MS). However, these higher standards in some cases were balanced out by new, less strict product classifications.[29] The directive is based on two guiding principles: the extended producer responsibility (EPR) and the polluter pays principle (PPP). Producers are responsible for take-back schemes for and recycling of their products. The 2018 directive changes the reporting requirement from three yearly to yearly and added a possibility to use economic incentives. The European Commission is currently working on an evaluation of the directive (European Commission, n.d.). Despite the aim to harmonize the approach across Europe, the interpretation and implementation vary, causing an imbalance for multinational manufacturers in their time spent on abiding by specific regulations per country, *versus* compliance to the general 'spirit' of the directive.[29] Furthermore, differences in enforcement remain between countries regarding collection rates.[14]

Indirectly, other European legislation also impacts e-waste. Take for instance the Regulation on Hazardous Substances (RoHS) that requires manufacturers to phase out the use of the most hazardous components in the production of any product, including electronics.[32]

3.1.2. Northern America. In the USA, regulations on WEEE are implemented on a state instead of federal level. 25 states have specific legislation on e-waste.[33] The focus on state-level governance could accelerate the legislation process and therefore open the door to more innovative policies. However, it has led to similar problems for multi-state manufacturers as the national differences in legislation within the EU. Furthermore, regulation on a federal level would receive more stable funding and be more effective in regard to tackling the issue of transboundary movements of e-waste.[33]

Canada has no federal legislation on e-waste either. Their e-waste management system relies on the same EPR principle as the EU WEEE-directive. The private sector is the main responsible party for the recycling of e-waste, through provincial stewardship programs.[34]

3.1.3. Latin America. Several Latin American countries have modelled their WEEE legislation after the European WEEE directive, but several others (Argentina, Bolivia, Uruguay) have no specific WEEE legislation or have included it within their general waste legislation (Mexico). Chili, Brazil, Colombia and Paraguay have WEEE legislation, with Chili even including informal recycling within their WEEE management system.

3.1.4. Africa. The Bamako convention, which entered into force in 1998, is a response of African countries to the failures of the Basel convention to regulate export of hazardous waste to African countries, which several cases demonstrated. Not all African countries signed the convention.

Between 2013 and 2017, Africa was the continent with the least specific legislation on WEEE.[35] By 2020, still only thirteen African countries had implemented WEEE-management legislation or policies.[14] For instance, Algeria, Libya, Morocco and Tanzania do not have specific legislation on WEEE while report[14] states that 29 out of 46 countries in the Asia region do not have national e-waste legislation, while 17 have frameworks in place but have ineffective e-waste management and recycling systems. E-waste legislation in Australia has been stepped up as part of the National Waste Policy Action Plan of 2019. An overall challenge for Africa is the large informal waste management sector and the imports of illegal (e-)waste.

3.1.5. Asia. According to the most recent UN Global E-waste Monitor,[14] of the 46 countries in the Asia region, 29 countries do not have national e-waste legislation. We list a couple of Asian countries with specific e-waste legislation:[36]

• China is both the largest producer of electronics and e-waste in the world and is a major importer of e-waste. Since 2000, the Chinese government has imposed a ban on the import of e-waste, but it is estimated that 8 million tons of e-waste per year enter illegally.[37,38] China has a Home Appliance Old for New Rebate Programme since 2011 but although the formal e-waste sector has grown it has limited capacity and reach.[39] Since 2012, EPR has been included in legislation.[37]

• Japan has the Home Appliance Recycling Law since 1998 and the Small E-waste Recycling Act.[39,40] The formal e-waste management sector, producers, retailers and consumers share responsibilities for recycling.[39] On the other side, Japan has not addressed the export of e-waste in criminal law.

• India has specific legislation on e-waste since 2011, which implemented EPR.[37] The E-Waste (Management) Rules (2016 & 2022)[41,42] targets traders, producers, online traders and Producer Responsibility Organizations (PROs). In major cities, e-waste recycling is an emerging market.[43]

• Korea: EPR was implemented in 2003 and required producers to meet target rates for collecting and recycling e-waste, with a penalty that is more expensive than recycling the products.[40] In addition, in 2008 the Eco-Assurance System was implemented and updated regularly since, aimed at reducing and recycling e-waste, to reduce the carbon footprint.

• Singapore has a Resource Sustainability Act since 2019 that focuses, among other things, on e-waste, with an EPR framework. Producers with more than 300 m^2 are obliged to set up their own collection points for e-waste on their premises and are obliged to offer a free collection service for consumers for old goods. The government has appointed a German company to oversee company compliance and e-waste collection.[44] In addition to these legislative initiatives, the National Environmental Agency, which monitors and regulates waste management, has also established the National Voluntary Partnership Program for e-waste recycling, in order to create more awareness among consumers together with producers and retailers.[37]

• Taiwan does not have specific e-waste legislation but is praised for its recycling legislation (the '4-in-1 recycling program'), which makes four parties responsible: the local community, the recycling industry, the local government and the recycling fund (paid for by retailers and producers).[37]

Two overall challenges for this region, similar to several African countries, are the informal waste management sector which makes it difficult to assess recycling activities and rates, and the illegal imports of (e-waste).[37,40,45]

3.1.6. Oceania. In Australia, the 2009 National Waste Policy and 2011 The Product Stewardship Act are relevant for e-waste.[37]

The government also wants to introduce mandatory product stewardship (shared responsibility for reducing public health and environmental impacts of products) to reduce waste from small electronic products and solar energy systems. A public consultation phase on this subject was completed in 2023.[46]

In New Zealand, the 1991 Resource Management Act and a Product Stewardship Act similar to that of Australia exist. In July 2020, the government declared e-waste (with five other product categories) as a priority product. This allowed it to implement regulated product stewardship for e-waste, placing the responsibility for EoL products on producers, importers and retailers instead of consumers, local communities and nature.[47]

3.2. Implementation: efficiency and challenges

The above overview makes clear that several regions and countries are focusing on e-waste. 81 out of 193 countries have some policy that focuses on e-waste (dated 2022).[14,48] These initiatives combine a focus on waste as well as CE. It contains legislation that focuses on trade in UEEE/WEEE and on national treatment and recycling. Legislation on e-waste trade has proven to be a complex and even controversial topic. The legal framework provides a basis but leaves room for interpretation. An effort to mitigate the differences in the interpretation of legislation should be pursued. Moreover, legislation on WEEE from a waste management perspective alone does not manage to eliminate discarded electrical and electronic products from causing environmental and human harm.[49] It is promising to focus on CE principles, but it will also need to contain a focus on less consumption altogether. The stagnation in global e-waste collection and recycling rates is likely worsened by the fact that only 46 countries have set targets for collection rates, and only 36 have set targets for recycling rates. Overall, we see many regions and countries struggle in differentiating valuable and hazardous components within WEEE, many countries do not have sufficient infrastructure in place to collect and recycle, and specifically small WEEE ends up in regular waste streams being landfilled or incinerated, and the costs of re-use of secondary raw materials remains high. Besides, in many Asian, African, Latin-American countries, and even European and North American countries albeit to a lesser extent, part of the e-waste management happens informally, with lacking reporting, but also lower standards for environmental and human safety.

4. E-waste recycling processes

4.1. General approach for formal and informal recycling

Very heterogeneous composition and technology of e-waste heavily affect the valorization approach and the stages of treatments. It should be noted that the weight fractions of materials contained in different categories of e-waste vary significantly. According to the reported data[14] and following the WEEE classification by Directive 2012/19/EU, in 2022 the largest amount of e-waste generated globally was represented by small equipment which accounted for 20.4 Mt (32.9% of the total 62 Mt e-waste generated), followed by large equipment (15.1 Mt, excluding photovoltaic panels, 24.3%), temperature exchange equipment (13.3 Mt, 21.4%), screens and monitors (5.9 Mt, 9.5%), small IT and telecommunication equipment (4.9 Mt, 7.9%), lamps (0.9 Mt, 1.7%), and, finally, photovoltaic panels (0.6 Mt, 1.0%). The percentage along the time of the different classes of WEEE has slightly evolved in the last 20 years as shown in Fig. 1, and it is expected to become more significant in the next few years for waste streams like PVP (estimated to grow up to 2.4 Mt by 2023). Despite an average indication of the global e-waste stream (Fig. 2), the material composition and, consequently, the recyclable potential are specific for each class of appliances, as detailed in Table 2 for a representative selection of waste belonging to the cited reference categories of WEEE.

Metals represent the most abundant and, even better, valuable and profitable fraction of the e-waste stream. Among them, copper, gold and iron recovery payback have the highest value both in economic and environmental terms. As shown in Table 2, almost all electronic devices, with only a few exceptions, are equipped with at least one electronic circuit board (PCB). The qualitative and quantitative metallic composition of PCBs makes them one of the most intriguing and rich sources of secondary raw materials (see Fig. 3). Recovering these metals poses a real challenge, but this would feed their supply chain and consequently reduce the environmental impacts related to their extraction from traditional mines.[56–58]

The material composition heavily affects both recycling treatments and the economic appeal of materials recovery for the different e-waste categories.

Despite the awareness of the ever-growing flow of e-waste all over the world, a precise estimation of the quantities produced annually is not easy to assess. Besides the reduced availability of data, the reasons for this phenomenon must be sought mainly in the existence of waste flows that follow illegal routes both within regulated countries, that bypass the official supply chain, and, even more, within those without reference legislation, concerning exports to emerging economy countries. Several reports show that about 80% of the total e-waste generated globally is transported or shipped, often illegally, to developing countries.[59] Approximately 70% of exported e-waste finds its way to China.[60] Significant quantities also make their way to India, Pakistan, Vietnam, the Philippines, Malaysia, Nigeria, and Ghana, and there are indications of potential e-waste flows to Mexico and Brazil as well.[61] As an example, about 70% of the e-waste processed in India comes from abroad[16,62] despite the import of e-waste being prohibited under the Basel convention. In many developing countries, including Ghana, the informal sector plays a dominant role in the e-waste system. In comparison to the highly automated processes employed in well-developed formal recycling sectors, the informal sector relies on extensive manual dismantling and crude recycling techniques. Notable examples of such crude methods involve:[63,64]

(a) Physically dismantling electronic components using simple tools such as hammers, chisels, screwdrivers, and bare hands to separate different materials.

(b) Removing components from PCBs by heating them over coal-fired grills.

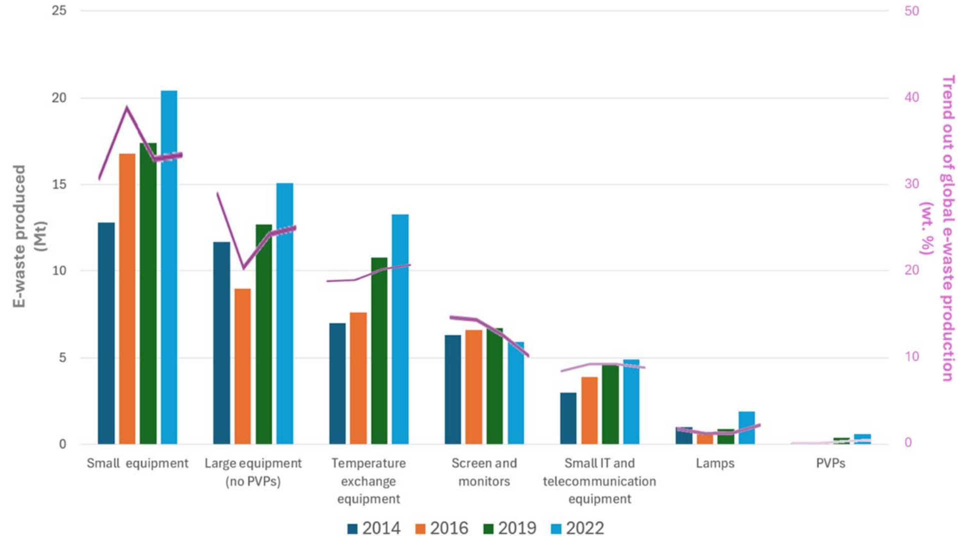

Fig. 1 E-waste produced yearly by category (histograms, left hand axis) and trend of percentage of the category in relation to the annual global e-waste production (curves, right hand axis).

(c) Stripping metals in open-pit acid baths to recover valuable metals like gold.

(d) Chipping and melting plastics without proper ventilation.

(e) Burning cables to recover copper and burning unwanted materials in open air.

(f) Disposing of unsalvageable materials in fields and riverbanks.

As shown, a series of manual disassembling and component selection procedures followed by open incineration and acid leaching for recovering copper, gold and other valued metals are typically employed. Leftovers are, then, disposed of along with municipal solid waste in open fields and water bodies, resulting in pollution of soil, air and groundwater by persistent organic pollutants (POPs, such as flame retardants and dioxins/furans, but also toxicant-laden dust and particulates) together with heavy metals like lead and cadmium.[63,65,66] During these

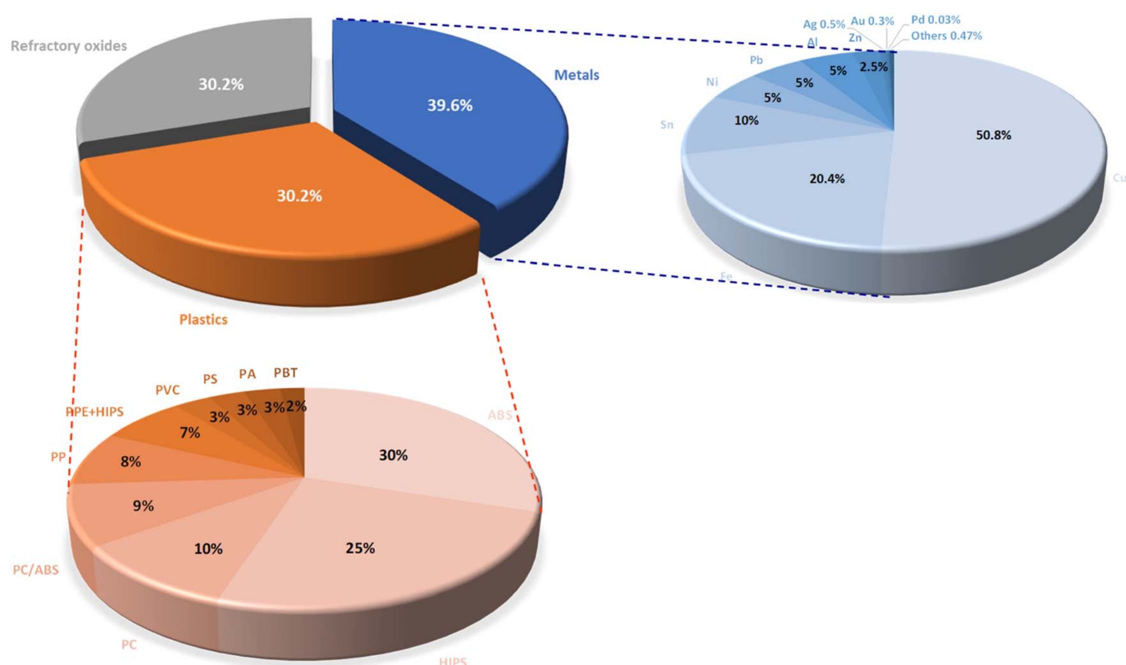

Fig. 2 Typical composition of WEEE (data from ref. 50 and 51). Adapted from ref. 52. ABS = acrylonitrile-butadiene-styrene; HIPS = high impact polystyrene; PC = polycarbonate; PP = polypropylene; PPE = polyphenylene ether; PVC = polyvinyl chloride; PS = polystyrene; PA = polyamide (nylon); PBT = polybutylene terephthalate.

Table 2 Material composition of a selection of EoL EEE listed by categories as in EU directives 2012/19/EU[53]

WEEE category	Equipment	Contained components/materials, %: Ferrous material	Aluminum	Copper cable and material/non-ferrous metals	Plastic	PCB	Glass	Battery
Temperature Exchange Equipment	Refrigerator	47.6	1.3	3.4	43.7	0.5		
	Air conditioner	45.9	9.3	17.8	17.7	2.7		
Screens and Monitors	CRT TV	12.7	0.4	3.9	17.9	8.7	51.2[a]	
	PDP TV	33.6	15.1	1.2	10.1			
	LCD TV	43.0	3.8	0.8	31.8	11.6		
	Notebook PC	19.5	2.4	1.0	25.8	13.7		14.4
Lamps	Fluorescent lamps and tubes	1.0		3	10		81	
Large Equipment	Washing machine	51.7	2.0	3.1	35.3	1.7		
	Stereo system	41.4	1.7	1.7	18.9	11.1		
Small Equipment	Video recorder	52.6	4.5	2.0	24.1	15.8		
	DVD player/recorder	62.5	—	3.6	15.3	14.0		
	Radio cassette recorder	35.1	0.5	3.2	46.9	10.4		
	Facsimile	33.3	1.7	6.1	49.1	12.2		
	Digital camera	5.2	4.3	0.3	31.8	20.2		
	Camcorder	5.0		2.9	29.0	17.7		
	Portable CD player	0.8		0.4	72.3	10.1		
	Portable MD player	16.1	6.5	3.0	26.3	15.7		
	Video game	19.9	2.3	1.6	47.8	20.6		
Small IT and Telecommunication Equipment	Telephone			10.3	53.2	12.6		
	Printer	35.5	0.2	3.2	45.8	7.4		
	Mobile phone	0.8		0.3	37.6	30.3		20.4
	Desktop PC	47.2		0.9	2.8	9.4		

[a] 21.2% CRT glass; 30% non-CRT glass.

processes, reusable parts are directly re-addressed to the market, while non-reusable components are further "recycled". This allows revenue to be generated from both component reuse and material recycling.[67] These treatments largely exploit non-skilled manual labor with negligible consideration for potential hazards to the environment or health for keeping low costs.

Equipment well preserved, assembled and packaged, does not constitute a concern or a risk, which instead springs forth, both from an environmental point of view and for human health, when it becomes WEEE, even more so if their EoL is not managed in compliance with the protection of the environment and workers. It motivates the need for effective collection and treatment methods.[68] When considering recycling technologies, it is essential to address the appropriate management and treatment of these harmful components to avoid any adverse environmental or health consequences. Additionally, the generation and utilization of toxic/hazardous substances during e-waste processing, such as mercury-gold amalgam or combined dioxins resulting from improper incineration, should be carefully considered in the design of innovative technologies for materials valorization.

Formal e-waste recycling processes may be divided into three main steps, which are (i) collection, (ii) dismantling and pre-processing, and (iii) end-processing for the final recovery of valuable components. In general, the aim of the whole recycling chain may be viewed under an environmental and an economical plan. The purpose of the former is to eliminate the adverse effects of hazardous components of e-waste and to provide materials valorization in an environmentally sound

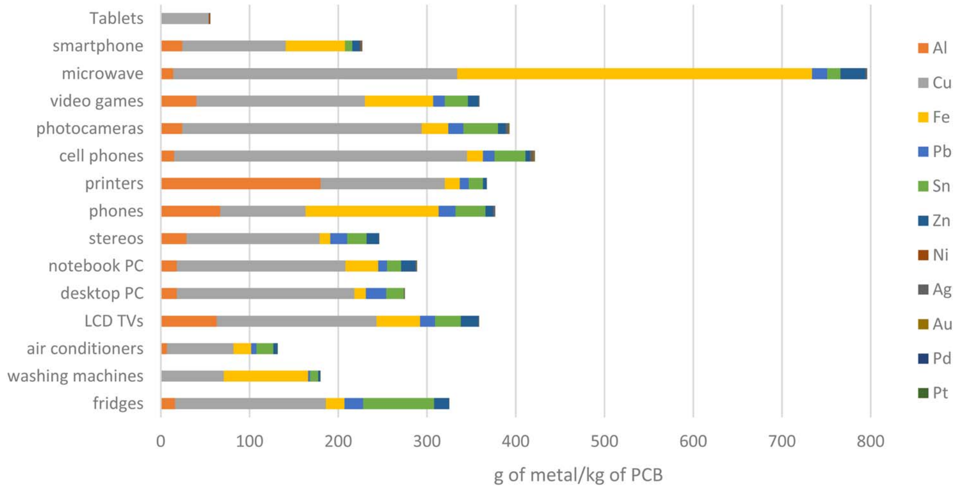

Fig. 3 Average metal composition in the most common electronic circuit boards.[53–55]

manner. At the same time, recycling must achieve an economically sound recovery of valuable components and material fractions.

The second and third steps of the abovementioned recycling process, namely, methods and technologies used for their treatment, will be discussed in the following sections.

4.2. Typical industrial dismantling and physical–mechanical processing of e-waste

The purpose of this step is to liberate the material values and address them to adequate subsequent final treatment processes. Mechanical treatments applied on the e-waste stream typically involve the comminution and separation techniques summarized in Fig. 4.

It is worth noting that the complexity of the e-waste stream requires specific measures for preventing pollution and making further recycling phases accessible. Specifically, hazardous substances have to be removed beforehand and stored or treated safely, while valuable components/materials need to be taken out for reuse or to be directed to efficient recovery processes. This includes the removal of batteries, capacitors, magnets, as well as cooling gases, phosphors, *etc.*, before further mechanical pre-treatments. The batteries, for example, can be sent to dedicated facilities for the recovery/inertization of cobalt, nickel, lithium and copper, as well as magnets and phosphors may be valorized by REEs recovery.

Fig. 4(a–e) summarize the typical dismantling and pre-processing treatments required for the most representative and peculiar e-waste types.

4.2.1. Cooling and freezing appliances. In the temperature exchange equipment WEEE category, the main feature of dismantling and treatment of cooling and freezing appliances is the presence of a refrigeration circuit, which contains ozone-depleting substances (mainly chlorofluorocarbons and hydrochlorofluorocarbons). The handling of such waste requires de-gassing procedures. De-gassing activities are carried out semi- or fully-automatically.[69] A typical treatment line, complete with the output of the pre-treatment phase, is summarized in Fig. 4a, and involves the following phases:

(1) The incoming material is manually sorted and reclaimed: gas, oil and dangerous components are removed and sent to a dedicated treatment.

(2) The reclaimed material undergoes a first stage of size reduction, carried out in a closed environment to guarantee the complete capture of the gases.

(3) The output material undergoes further shredding to allow the subsequent mechanical separations.

(4) Separation of the polyurethane foam, which is pelletized before being sent to external suppliers for further treatment.

(5) The residual material undergoes consecutive magnetic and eddy current separations to intercept the ferrous and the non-ferrous metals.

4.2.2. Screens, monitors, and TVs. The main peculiarity of this e-waste is the presence of cathode ray tubes (CRT) which contain hazardous substances. The dismantling process of such e-waste type aims to recover valuable components or fractions, *e.g.* electron gun, PCB, *etc.* The main purpose of pre-processing of CRT is the separation of different types of glass used (the funnel contains lead and other metals) and the removal of coatings from the front panel. Different technologies are used to separate the funnel from the panel glass (hot wire cutting, thermal shock, laser cutting, diamond wire/saw, or water jet) as well as to remove coatings (plastic media blasting, water circulation, fluidized bed cleaning system).[70] An alternative approach includes manual removal of the CRT from the TVs and monitors, shredding and then mechanical recovery of the fractions (including the coating). After the shredding, the glass is mechanically separated from the other material streams (*e.g.* metals, plastics, circuit board and cable). A typical treatment line of screens containing CRT tubes, complete with the output of the pre-treatment phase, is summarized in Fig. 4b, and involves the following phases:

(1) CRTs are sorted and disassembled by hand, to separate the casings, CRT panel, and capacitors.

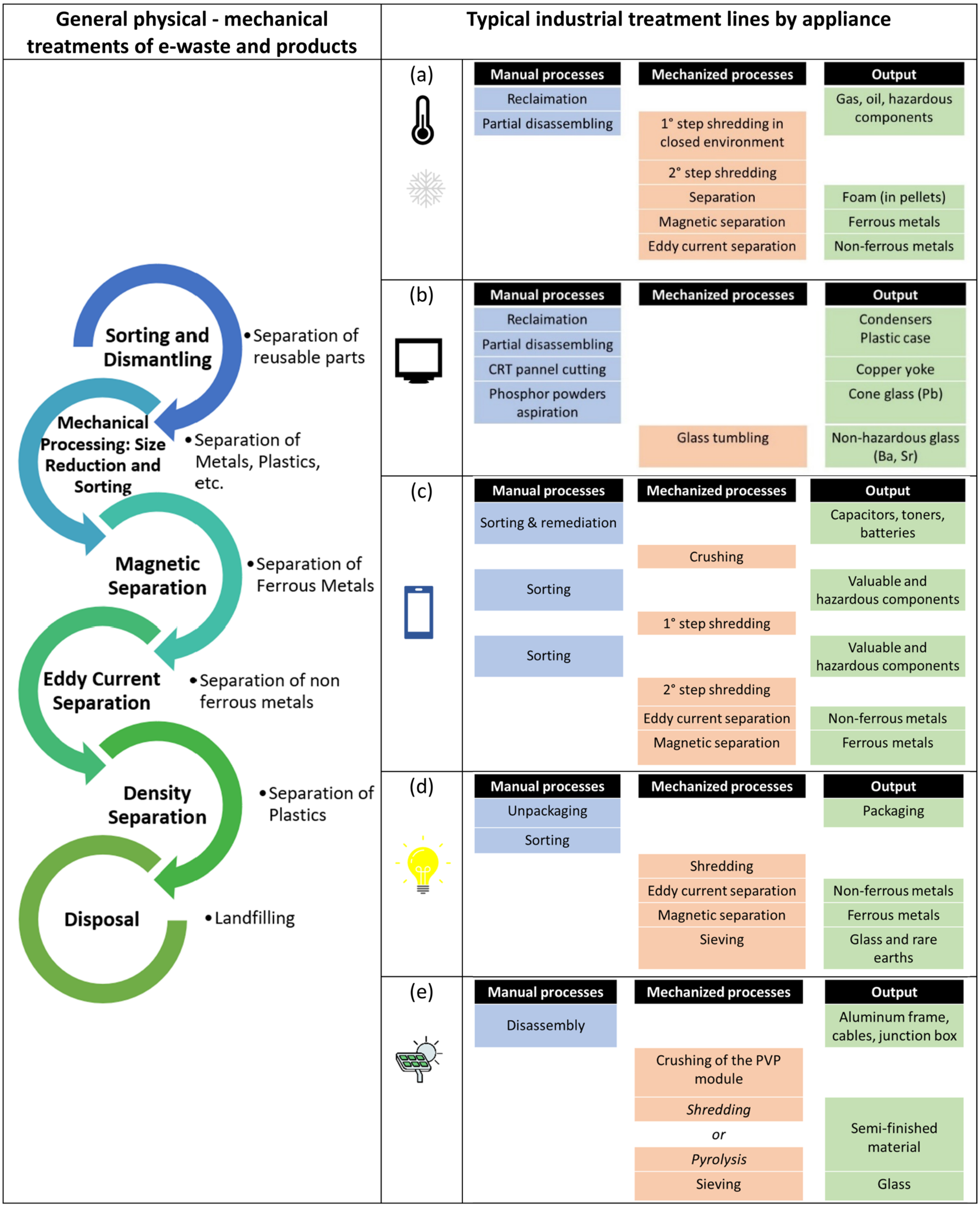

Fig. 4 Typical general physical–mechanical processing scheme for e-waste and description of industrial treatments and outputs of plants for specific appliances: (a) cooling and freezing appliances; (b) CRT monitors; (c) IT and telecommunication equipment; (d) lighting devices; (e) photovoltaic panels.[52]

(2) CRT panels are treated by separating the tube into two parts: the non-hazardous glass containing barium and strontium (70% by weight), from the front of the display, and the hazardous glass with lead (30% by weight), from the cone.

(3) After cutting the glass at the joint, the parts are separated and the interior is vacuum cleaned to extract the phosphors.

(4) The non-hazardous glass is fed into the glass refining unit, where it undergoes a tumbling process to achieve a uniform grain and polish.

In recent years, Liquid Crystal Displays (LCD) have become the dominant display devices, effectively replacing CRT. With an ever-growing demand, the annual production of LCD has reached billions, raising concerns about LCD waste generation. LCD has less environmental impact than CRT, even if the harmful nature of liquid crystals, indium, and other heavy metals present in LCD panels led many countries to classify EoL LCD as hazardous waste.[71] Although current treatment technologies can dismantle LCD into various components and recycle them based on their materials, there is currently no suitable model for effectively treating the whole LCD panels.

4.2.3. Information technology (IT) and telecommunications equipment. Equipment in the small IT and telecommunication equipment category has external dimension less than 50 cm, and the large equipment (any external dimension is more than 50 cm) or screens, monitors, and equipment containing screens have a surface greater than 100 cm^2. These items are typically represented by the EoL mobile phones, GPS, pocket calculators, routers, personal computers, printers, telephones.

The pre-processing stage is mainly focused on the separation of hazardous components as well as environmentally and economically relevant fractions (*e.g.* PCB, containing precious metals, copper, tin, *etc.*). E-waste fractions containing private or confidential data are destroyed by shredding or controlled smelting processes. Reusable parts are reclaimed for a new turn of application.

After dismantling, automated pre-processing of IT and telecommunications equipment typically exploits multistage shredding, which enabled the material size to be reduced to less than 20 mm, then physical selective metal separations for recovering metals and non-metallic fractions as summarized in Fig. 4c.[72] A typical configuration for a physical–mechanical treatment industrial plant for IT and telecommunication equipment involves the following phases:

(1) Upon arrival, the material is sorted and cleaned (removal of hazardous substances, materials, and components, such as ink cartridges, polychlorinated biphenyls containing capacitors, mercury-containing switchers, NiCd, NiMH Li-ion and Li-polymer batteries; removal and recovery of valuable or reusable components like hard drives or fractions like PCBs).

(2) A first mechanical treatment tears the casings in order to access the internal components.

(3) The processed material undergoes a manual selection of the valuable and hazardous components that have emerged.

(4) The remaining material is sent to a shredding machine, followed by a second manual sorting cycle.

(5) The last shredding reduces the material to a size of a few centimeters.

(6) The shredded material is then subjected to eddy currents to select non-ferrous metals.

(7) The remaining material is subjected to magnetic separation to select ferrous metals.

While strongly recommended, mechanical pre-processing of e-waste is not always essential, especially when chemical or thermal recovery methods are planned. Small, highly complex electronic devices such as mobile phones, MP3 players, *etc.* can (after removal of the battery) also be treated directly by an end-processor to recover the exposed metals.[70]

4.2.4. Lamps. Fluorescent lamps, discharge lamps and LED represent another EoL product whose pre-processing treatments need special care before final processing. Fluorescent lamps have to be categorized (tubes, compact fluorescent lamps CFL, crushed lamps) to separate hazardous and non-hazardous components such as Hg, ferrous and non-ferrous items, Al, fluorescent powders, valuable fractions, glass, plastics, *etc.*[73] Entire dismantling is a dry process involving several steps such as sorting and feeding with wheelie-bin turning devices for CFL and crushed lamps, horizontal feeding for fluorescent tubes and lamps. Fig. 4d summarizes a typical configuration for a pre-treatment industrial plant for lamps, which involves the following industrial phases:

(1) The lamps are unpacked manually and divided into two categories: tubes and bulbs.

(2) The selected lamps are shredded.

(3) Non-ferrous metals are separated by eddy currents.

(4) Ferrous metals are separated by magnetic current.

(5) The remaining material, consisting of glass and dust with a high content of REEs, is sieved to separate the glass and dust.

4.2.5. Photovoltaic panels (PVP). Listed in the large equipment WEEE category, PVP represents a large and continuously growing waste stream. As reported by IRENA,[74] the photovoltaic energy production in 2022 covered 35.8% of the global renewable energy supply, concerning the wind (10.2%) and the hydroelectric (18%) energies. This technology, established on the market in the 80s, guarantees long lifetimes, from 20 to 25–30 years, mainly limited by the exposure of photovoltaic modules to atmospheric phenomena. At the end of 2016, global PV waste reached 250 000 tonnes, while an increase to 5.5–6 million tonnes is expected by 2050. PVP are classified based on their structure and the semiconductor material used. They consist of several modules that can be embedded in a common structure thus forming a panel, *i.e.* a rigid structure fixed to the ground or a building. There are several known technologies for photovoltaic (PV) panels continuing to evolve. The main types of PV panel technologies disseminated on the market involve crystalline silicon (c-Si) (in 2021, 95% market share) and thin-film (in 2021, 5% market share) technologies.[75] In the same year, mono-crystalline silicon (Mono-Si) technology drove the market production with an 84% share of total c-Si production (the remaining 16% being represented by poly-crystalline silicon – poly-Si – modules). Mono-Si panels embed a cell based on a silicon single crystal structure. They are known for high efficiency if compared to other technologies and sleek appearance. Poly-Si panels, instead, are based on a cell with a silicon multiple crystal structure. They are generally less expensive and slightly less efficient with respect to mono-Si panels. As a potential alternative, based on cells made from various materials like amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), thin-film solar cells cover a small slice of the global PV-market with a market share not exceeding an average 5% in the last decade.[75] With respect to c-Si panels, thin-film solar cells are lighter, more flexible, and less expensive to manufacture but tend to have a lower efficiency. However, they have their niche in applications where flexibility or low weight is essential. Several technologies approaching the market for wide or niche applications are summarized in Table S1.†

As mentioned above, crystalline silicon technology is the most widespread photovoltaic technology on the market in recent decades and the one that is providing the largest amount of waste in the last and next years. It involves also bifacial solar panels (capturing sunlight from both sides, improving overall energy production by reflecting sunlight onto the rear side of the panel), as well as PERC technology (Passivated Emitter Rear Cells add a passivation layer on the rear side of the solar cell to increase efficiency by reducing electron recombination losses). The multilayered structure of PVPs (see Fig. S1†) makes challenging the demanufacturing and materials recovery operations.

As summarized in Fig. 4e, the most common approach for materials enhancement from PVP involves the following phases:

(1) Upon arrival, the material is disassembled (removal of the aluminum frame, cables, junction box). The module is size comminuted.

(2) The obtained material can be: shredded for favoring physical or chemical treatments for metals recovery, thermally treated to remove polymeric layers freeing the cell from the glass.

(3) Finally, glass is separated by sieving and the semi-finished material is addressed for further refinement.

Based on the above, for all waste streams, manual (or semi-automatic) disassembly and sorting may be considered as a preferable first-step treatment. Indeed, it allows for a preliminary selection and recovery of valued materials, as well as eases and makes more effective the following recovery phases. As an example of industrial practices, Table S2.† summarizes the average mechanical pre-treatment output from industrial plants by e-waste category in Italy in 2016. The fast evolution of mechanical technologies is driving a positive trend in metals recovering from WEEE, as discussed in Section 5.3.1.1. On the other hand, despite the crucial enhancement of the efficiency of leaching and recovery phases, mechanical comminution and separation phases have high capital costs, are time-consuming, and often are not as selective as desired for the efficient recovery of precious metals that are present in low amount (the loss of precious metals may reach 20 wt%). For these reasons, the degree and typology of pre-treatments should be very carefully assessed.

It is also worth noting that mechanical–physical comminution/separation technologies are the easiest to be industrially upgraded. This is the reason why most treatment plants pursue materials recovery by physical techniques avoiding further thermal/chemical refining processes.[76]

4.3. Conventional urban mining processes

Conventional methods of e-waste recycling have been mainly inherited by ores treatments and involve thermal, physico-chemical and chemical processes. Nevertheless, e-waste comprises an intricate system characterized by the presence of a wide array of organic compounds and metals. Consequently, the techniques and technologies used to recycle metals from it differ significantly from those employed in mineral separation processes.

4.3.1. Recycling of metal contained in e-waste. The final recovery of metals from pre-treated fractions takes place in three main directions. Ferrous fractions are directed to steel plants for the recovery of iron. Aluminum fractions are going to aluminum smelters, while copper/lead fractions, circuit boards and other precious metals containing fractions are going to *e.g.* integrated metal smelters, which recover precious metals, copper and other non-ferrous metals while isolating the hazardous substances.[77]

Pyrometallurgy has been successfully applied to industry. Its principle involves metals enrichment by smelting and converting, refining and other processes to remove the non-metallic material from e-waste.[78,79] Table 3 summarizes different typical industrial thermal approaches for metal valorization from e-waste.

While pyrometallurgical processes can efficiently recover metals from e-waste, they also come with environmental challenges, including the release of potentially harmful emissions and the generation of hazardous byproducts. As a result, these methods often require strict environmental controls and emission management to minimize their environmental impact. Additionally, they are less selective than some other methods, meaning they may not be suitable for recovering all valuable metals found in e-waste.[78] The hydraulic shaking bed separation was widely used for recycling metals in waste PCBs in the past. Crude copper particles can be obtained by this process. However, this process generates huge amounts of wastewater and residues.[80] In addition, it is difficult to recover other metals except for copper, and nonmetal materials cannot be recycled.

Conventional hydrometallurgical processes are associated with the use of acid or alkaline solutions to leach materials contained in crushed e-waste.[81]

Hydrometallurgical processes for metal recovery from e-waste are based on the use of chemical solutions to dissolve and separate metals from electronic waste materials. Fig. 5 summarizes the steps of a typical hydrometallurgical process.

Among the different phases, leaching represents a key step for an efficient and selective metal recovery. Typical leaching agents for base ($E^\circ < 0$) and noble ($E^\circ > 0$) metals are summarized in Table 4.[82,83]

Hydrometallurgical processes offer several advantages, including the ability to selectively recover specific metals and minimize environmental emissions compared to pyrometallurgical methods. However, they require the management of chemical reagents and waste products, and the choice of reagents and process conditions must be carefully tailored to the e-waste composition and target metals. Proper disposal and treatment of the residual waste and chemicals generated during hydrometallurgical processes are critical to minimize environmental impact.

Table 3 Main industrial thermal approaches for e-waste metal fraction valorization[79]

Thermal treatment	Description
Incineration	E-waste is burned at high temperatures in controlled environment to break down organic materials and combustible components, leaving behind ashes that contain metal residues
Smelting	The ashes or shredded e-waste are melted in furnaces at very high temperatures. This process separates metals from non-metallic materials, as metals have lower melting points. Valuable metals like copper, lead, and precious metals can be collected in the molten form
Cupellation	This process is used specifically for recovering precious metals like gold and silver. The metal-rich material is heated in a cupel (a porous container) with a blast of air, which oxidizes impurities and leaves behind the precious metals
Blast furnace	Similar to traditional metal smelting, a blast furnace can be used to extract metals from e-waste. It's particularly effective for recovering iron and steel components

4.3.2. Valorization of the non-metallic fraction of e-waste. Typical e-waste contains about 10–30 wt% of plastics. Recycling e-waste plastics can be challenging due to the presence of (i) a number of polymers in an electrical or electronics equipment as well as (ii) brominated flame retardants (BFRs) which may produce hazardous substances such as dioxins during recycling.[84] The highest amount of BFRs are usually found in screens (6000–13,000 ppm of bromine) followed by in small

Fig. 5 Main phases of a typical hydrometallurgical process for e-waste treatment.

Table 4 Typical leaching agents for base ($E°$ < 0) and noble ($E°$ > 0) metals

Leaching agent	Primary use in the dissolution of:	Description
Nitric acid (HNO_3)	Base metals (including REE) Ag, Pd, Cu, Hg	Nitric acid is commonly used in the leaching of e-waste to put into solution low reduction potential metals. Among them, Al, Cr and Fe, which can be dissolved in diluted HNO_3 aqueous solutions, are instead resistant to the pure acid due to passivation phenomena. Sn reacts with HNO_3 forming SnO_2(s). Noble metals, *i.e.* Ag, Pd, Cu, Hg, which are often found in electronic connectors and components, are also leached by nitric acid solutions. The oxidative leaching is accompanied by NO_x formation
Sulfuric acid (H_2SO_4)	Base metals (including REE) Cu	Sulfuric acid is employed for leaching base metals like Zn, Fe, Co, Pb, Al, from e-waste materials. Also, Cu slowly dissolves in hot H_2SO_4. It facilitates the dissolution of these metals from printed circuit boards and wiring. The oxidative leaching is accompanied by SO_x formation
Aqua regia (HNO_3 : HCl 1 : 3)	Noble metals (except for Rh, Ir, Ru, Ag)	It is a powerful leaching mixture used to extract precious metals, including gold and platinum, from e-waste. It is particularly effective in breaking down components like CPU pins and gold-plated connectors. Differently from Au, metals like Ag, Pd and Ru are easily passivated by the presence of chloride ions, preventing meaningful leaching of bulky metals. The reactivity depends upon the reaction conditions (*i.e.* temperature, degree of comminution, mechanical abrasion during the reaction)
Ammonia (NH_3)	Co, Ni Cu, Ag	Largely employed complexing agent, has a great affinity towards Cu. With higher reduction potential metals, *i.e.* Cu and Ag, its action can be empowered by adding oxidants such as H_2O_2, $(NH_4)_2S_2O_8$, or others
Cyanides (CN^-)	Fe, Zn Au, Ag, Cu, PGM	Cyanide solutions are used in e-waste treatment, especially for gold recovery, under strictly alkaline conditions in the presence of oxygen
Ammonium Persulfate ($(NH_4)_2S_2O_8$)	Ni, Zn, Fe, Co Cu	Ammonium persulfate solutions are used for leaching copper and base metals from e-waste. It acts as an oxidizing agent, aiding in the dissolution of copper traces on printed circuit boards. Its action can be assisted by the presence of ammonia or acids. It is also exploited to detach gold layers from PCB surface by removing the underlying metal layers
Hydrochloric acid (HCl)	Base metals	Due to the great affinity of chloride ion to coordinate metals and to the high solubility of most of its salts and complexes, HCl is largely used as a base metal leaching agent. Furthermore, the combination with appropriate oxidizing species provides leaching mixtures able to dissolve even noble metals (see aqua-regia description as an example)
Hydroxides (OH^-)	Al, W, Mo, Nb, Ta, Hf, Zr	A selection of metals shows a predominant affinity towards alkaline solutions

equipment (2000–7000 ppm). A number of mandatory regulations have been developed for the recycling of WEEE plastics such as to ensure the ability to dismantle plastic parts with commonly available or no tools, and plastic markings.[85,86] The processing of plastics containing the BFRs is generally regulated by the UNEP (United Nations Environment Programme) Stockholm convention that "the recycling or final disposal of articles containing BFRs or POPs covered under the convention is to be carried out in an environmentally sound manner and should not lead to recovery of the BFRs or POPs for reuse". The EU POP regulation prescribes the methods of treatment materials containing POPs above a certain limit also called the low POP content limit (LPCL).[87] The current LPCL value for hexabromobiphenyl (hexaBB), and hexabromocyclododecane (HBCD) are 50, and 500 ppm respectively. For commercial pentabromodiphenyl (PBDE), the current LPCL threshold is 500 ppm. It is noteworthy, that the LPCL thresholds have been lowered in the reviews in 2023 and there are plans for further reduction of these thresholds in 2025 and 2027.[88]

The non-metallic fraction is very difficult to valorize and its presence may hamper the recycling of the valued metal fraction. For these reasons, plastics-containing scraps are mostly treated by incineration or landfill, in particular in the informal recycling sector. From an industrial point of view, the enhancement in the form of energy is the way of election for plastics treatment which avoids disposal.[89] However, the content of BFRs might trigger serious environmental pollution when valorization processes require high-temperature thermal treatments.[90] Indeed, the uncontrolled combustion of organic matter may cause the emission of toxic components such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls, and polychlorinated dioxins (PCDs) as BFRs degradation products. In this context, pyrolysis has been proposed as a more controlled thermal combustion carried out in the absence of oxygen, which enables materials to be decomposed into smaller molecules potentially of interest as fuels or as precursors for the petrochemical industry.[91] As compared to incineration and landfilling, pyrolysis seems to be a compromise candidate, since it saved most resources lowering emissions and providing marketable products.

5. Innovation towards sustainability in e-waste recycling

5.1. Trends in research and innovation products concerning e-waste valorization

The rising amount of WEEE alongside stringent global regulations, as well as the growing focus on raw material recovery and ecodesign, have captured the scientific community's attention. Consequently, there has been a noticeable increase in the number of papers being published on these subjects over time. Furthermore, numerous industrial and commercial activities operating in the e-waste management chain have been established worldwide in the last 20 years, and, with the help of eco-investments and incentives, power the technological innovation in waste valorization as demonstrated by the statistics in patents' submission. The ESI material† for this manuscript details the distribution of publications and patents by year, subject, and geography related to urban mining, ecodesign, and e-waste (see Section S2†). The study, covering data from 2002 until 2022, exploited the Scopus database for publications and the Orbit database for patents.[3] Table 5 summarizes collected data in 2002, 2012 and 2022 years, as a reference. The collected publications clearly reflect a growing interest among researchers and academics from multidisciplinary backgrounds and diverse audiences. Similarly, the positive trends in patent publication highlight the increasing attention of the industrial sector which views proper e-waste management not only as a market opportunity but also as a responsibility to governments, people and the planet.

However, it is important to highlight that publications and patents focusing on "urban mining" and "ecodesign" within the Electric and Electronic Equipment sector constitute only a minor portion of the overall research and innovation outputs in that domain. Specifically, they respectively represent around 26 and 8%, of publications, and around 14 and 6%, for patents. This means that there remains considerable space for innovation in design, processes and technologies within those areas of interest.

One of the main positive aspects of this virtuous cycle promoted and fed by targeted and inspired regulations is the increased awareness and sensitivity of civil society on these extremely important and topical issues. Today, everyone, individuals of all ages, including children, recognizes the importance of environmentally responsible management of e-waste, the need to conserve raw materials for future generations, and the key role each person plays within the broader framework of the CE, as well shown by web searching statistics (see ESI material, Section S2†).

5.2. Implementation of the eco-design approach

As for the European Environment Agency,[92] the term ecodesign is both a principle and an approach that defines the integration of environmental aspects into all stages of the product development process, by balancing ecological and economic requirements, striving for products which make the lowest possible environmental impact throughout the product life cycle. Ecodesign is one of the most fundamental pillars of the EU directives towards more responsible use of resources, as well as sustainable waste management. In that sense, ecodesign is heavily encouraged in WEEE directives as a suitable approach by producers in facing the challenges related to the producer's responsibility principle. Correspondingly, the ecodesign directive (Directive 2009/125/EC amending the 2005/32/EC) of the European Union establishes a framework to set mandatory ecological requirements for energy-using and energy-related products sold in all member states.[93]

In the last decade, a variety of new terms emerged besides ecodesign, primarily sustainable design (or design for sustainability, D4S) and circular design.[94] They all refer to similar approaches, but a slight difference can be found in their focus scopes. Specifically, sustainable design is addressed to minimize social, environmental and economic impacts of a production as much as possible.[95] Ecodesign is a sustainable design approach specifically focusing on reducing the environmental impact all along the life-cyle of the product. Within the ecodesign concept falls circular design, which is instead specifically addressed to produce no waste, correspondingly no pollution, keeping products and materials in use (shared, reused, repaired, recycled) in a closed-loop system.[96]

Table 5 Publications and patent data on urban mining, ecodesign, and e-waste topics for 2002, 2012 and 2022 publication year. See details in ESI material, Section S2

Database	Topic	Query	No. of papers/patents per year		
			2002	2012	2022
Scientific database for publications: Scopus	Urban mining	"Urban mining" or "Urban mine"	0	12	783
	E-waste	"Ewaste" or "e-waste" or "WEEE" or "Waste Electrical and Electronic Equipment"	61	1094	6759
	Ecodesign	"Ecodesign" or "Eco design" or "Eco-design"	78	757	2795
Patent database: Orbit	Urban mining	"Urban mining" or "Urban mine"	0	3	3
	E-waste	"Ewaste" or "e-waste" OR "WEEE" or "Waste Electrical and Electronic Equipment"	131	212	198
	Ecodesign	"Ecodesign" or "Eco design" or "Eco-design"	3	3	2

Fig. 6 graphically summarizes concepts, implications and strategies related to these three connected terms.

Benefits deriving from the existing ecodesign directive, which covers 31 product categories, are clearly achieved at business, consumer and environmental levels. As reported by the official website of the European Union, in 2021 the effects of the directive application resulted in a EUR 120 billion reduction in energy costs for EU consumers. Additionally, products subject to these measures exhibited a 10% decrease in annual energy consumption.[98]

Despite the recognized importance of implementing eco-designed processes, only a few reported cases directly refer to EEE (as mentioned in the Section 5.1), primarily involving Design FOR Recycling (creating a product that enables better and easier EoL-recycling) and/or Design FROM Recycling (creating a product built from recycled materials).[99] Nevertheless, growing efforts are being made in this direction and a series of suggestions for best practices in designing electronics have been processed and available for users. A not exhaustive list of sound practices for a successful design for electronic boards recycling strategy, is:[100]

(a) Use of smaller and more compact board design.
(b) Minimize the number of components.
(c) Minimize the number of fasteners or connectors.
(d) Minimize different types of plastics and metals.
(e) Minimize the use of plated or contaminated metals.
(f) Avoid the use of nuts and bolts.
(g) Minimize the use of adhesives.

Today, the main electronics producers claim an ecodesign plan. It typically involves: (i) an increasing use of renewable or recycled materials in manufacturing; (ii) the use of clean energy for production; (iii) lower environmental costs for shipping products; (iv) design of high energy efficiency electronics for lowering energy consumption by new products; (v) recycling strategies for EoL equipment.

Research and innovation projects within National or European programs play a crucial role in raising awareness on this topic in the social, industrial, and research & innovation context of member states. This heightened awareness is leading to the development and implementation of valuable tools and models. As an example, the RE-CET project (Redesigning Electronics in a Circular Economy Transition project, funded by

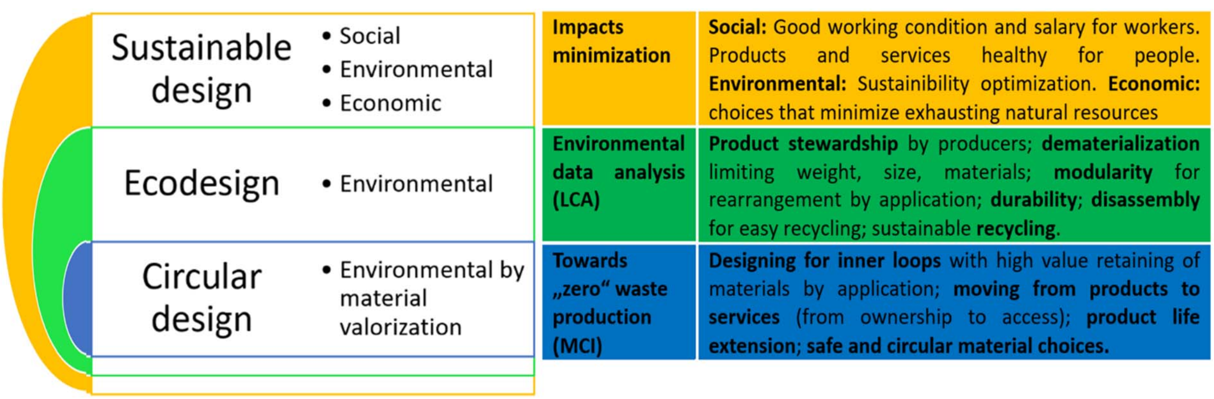

Fig. 6 Impacts, goals and strategies for Sustainable design, ecodesign and circular design. LCA: Life Cycle Assessment; MCI: Material Circularity Indicator.[97]

Rijkswaterstaat Environment, Dutch Government)[70,71] is addressed to increase the use of recycled plastics in electrical appliances such as vacuum cleaners through plastics standardization.[101]

In terms of education, several courses are available, often established or supported by universities or higher education institutions. Some of these courses provide a professional certification as in the case of the course "Designing Electronics for Recycling in a Circular Economy" delivered online by experts of the Delft University of Technology (DelftX), which grants the Professional Certificate in Sustainable Design of Electronics.[102] Recognized certifications can be also granted to companies and products which pursue ecodesign goals and meet sustainability requirements. In this framework, EPEAT® Ecolabel, the Electronic Product Environmental Assessment Tool operated by the Global Electronics Council®, identifies thousands of electronic products across the globe that meet EPEAT criteria addressed to assess priority sustainability impacts throughout the life cycle of electronics.

Several companies today offer consultancy services and products addressed to implement ecodesign principles in industrial processes/materials. Among them, Altair pretends to be a player specialized in designing sustainability into plastics value chains and offers engineering plastic solutions to produce innovative plastic parts.[103] Optimized plastic components, combined with efficient digital material modeling and performance prediction, pursue the lowest carbon footprint and waste prevention. In the same sector, IMA ZERO's No-Plastic Program (NOP) benefits from OPENLab, IMA Group's network of technological laboratories and testing areas, to find alternative materials to plastic, fostering plastic-free, compostable or biodegradable materials, recyclable and/or more sustainable plastic-based materials, including all laboratory phases, from design to engineering, of products and processes.[104] Software for simulation-driven solutions have been implemented and delivered covering several aspects of EEE design. One interesting example is represented by Cadence®'s PCB Design and Analysis Software for defining the best design for electronics recycling.[105]

5.3. Innovation in material recycling & enhancement processes

5.3.1. Innovative technologies to recover metals from e-waste. In recent years, on the basis of conventional thermal- and chemical-based technologies, some advanced recycling processes have been put forward and have gained considerable progress.[78] Specifically, actions addressed to implement green chemistry (GC) and green engineering (GE) principles (see Fig. 7), even better if combined, in completely new as well as in "revised" versions of well-known processes, demonstrated to be suitable in order to purse eco-sustainability goals at both "molecular" and industrial level.[108]

Metrics in GC focusing on the reduction or elimination of mass, energy usage, hazardous substances, and overall lifecycle environmental impacts have been integrated, serving as valuable tools for evaluating the sustainability of chemical processes at a molecular level. Conversely, LCA tools are designed to evaluate sustainability in industrial processes, aligning with the principles of GE.

Achieving fully sustainable processes necessitates a harmonized approach, wherein a "green" engineering design at the industrial level should not overlook the importance of "green" molecular-level methods, and *vice versa*. Integration and synergy between these two facets are crucial for a comprehensive and truly sustainable industrial framework.

5.3.1.1. Mechanical approach. In the framework of sustainable processes for metal recovery from WEEE, a variety of innovative mechanical methods have been developed in recent years, some of those already available on the market.[76] They typically involve a combination of advanced shredding, separation, and sorting technologies. These methods not only improve the efficiency of metal recovery processes but also contribute to the overall sustainability of electronic waste recycling.

Most cutting-edge techniques improve efficiency and energy demand by conventional equipment. Furthermore, high sensitivity separation techniques have been implemented for material recognition and recovery.

Table 6 elaborates the most recent progresses in mechanical technologies for metal recovery from WEEE.

A variety of technologies are presented each year at largely participating fairs and conferences in the e-waste recycling sector (*e.g.* International Electronic Recycling Conference, IERC; Waste Management Europe; Recycling Tech, Poland; EcoMondo, Italy; E-Waste World Conference & Expo Frankfurt, just to mention a few). Mechanical and digital technologies for sorting and separation are currently the ones with the greatest performance increase. They also limit emissions, use of chemical reactants as well as wastewater.

5.3.1.2. Thermal processes. In the framework of thermal processes, extensive studies and practices have been carried out on recycling metals from e-waste by vacuum metallurgy (VM). VM technologies involve the use of low-pressure environments to separate and refine metals exploiting the difference of vapor pressure of elemental metals at the same temperature.[109] These technologies offer advantages with respect to conventional pyrolytic processes, such as precise control over temperature and reduced atmospheric emissions and energy consumption. They are particularly useful for recovering metals with specific vaporization characteristics. Indeed, the vacuum environment (i) reduces the vapor pressure of materials during thermal decomposition, necessitating lower temperatures for evaporation; (ii) lowers the apparent activation energy of the non-metallic fraction, resulting in reduced energy requirements for the reactions; (iii) due to the sealed oxygen-free conditions, prevent the generation of secondary pollutants like PFDD/Fs, ensuring the production of high-purity products, as well as inhibits the oxidation of metals, enabling the direct recycling of precious metals in their metallic state. However, these processes can still be energy-intensive and require specialized equipment, making them suitable for certain applications and specific types of e-waste containing metals with distinct properties.

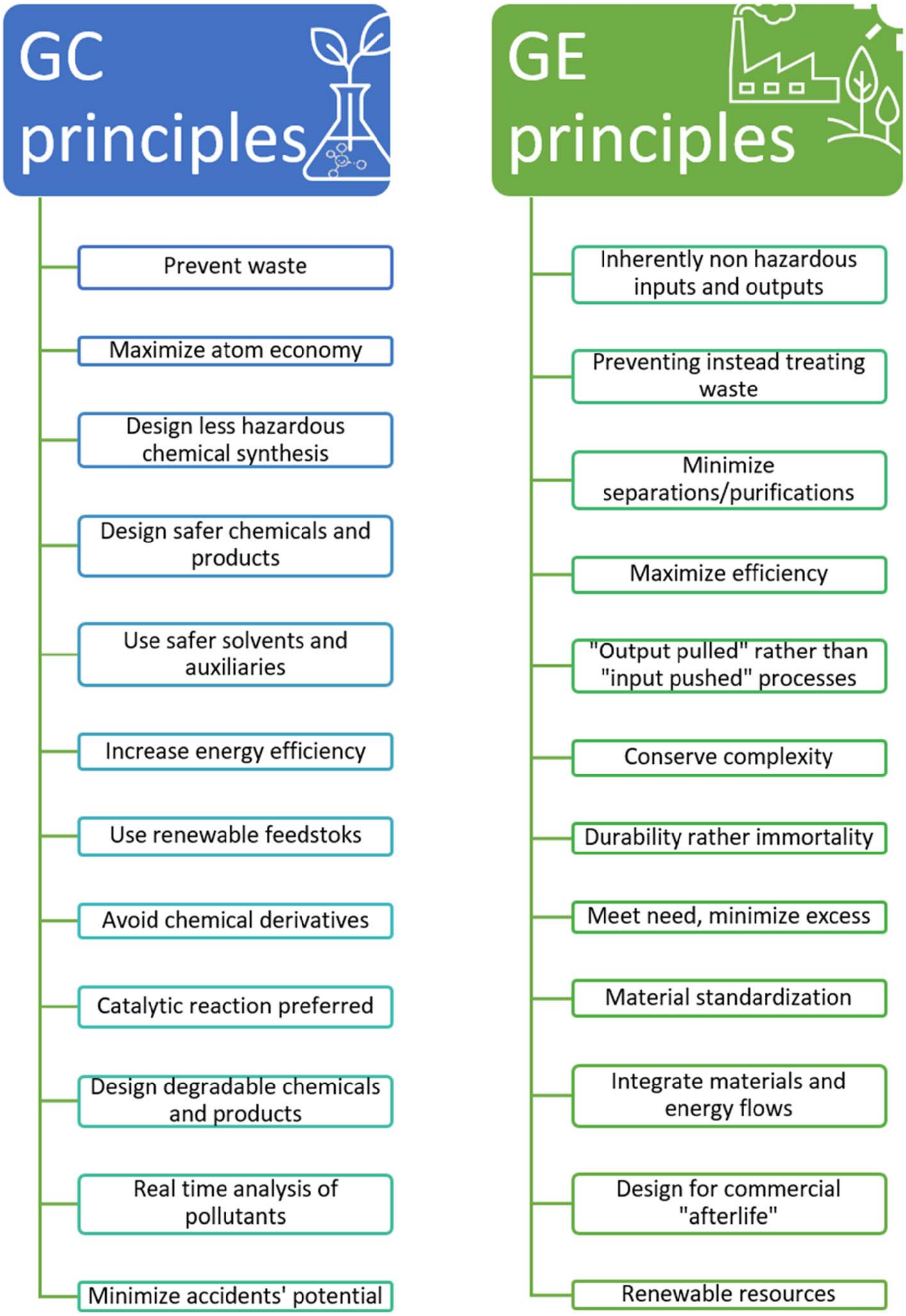

Fig. 7 A concise summary of the 12 principles of Green Chemistry (GC)[106] and Engineering (GE)[107] for the design of sustainable processes.

A variety of VM technologies are under study for metals recovery with interesting preliminary results. Among them Vacuum Pyrolysis (VP), Distillation (VD), and Reduction (VR), which share a controlled heating under reduced pressure but are applied to systems with different substrate/metal combinations and designed to exploit specific metal physical–chemical transformations.

In vacuum pyrolysis the controlled heating under a low-pressure environment causes organic components of e-waste to vaporize and be removed as gases, leaving behind metal-rich residues that need further treatments to recover the valuable metals.[78] Vacuum distillation allows for the separation and recovery of metals with high boiling points, such as gold and platinum, even more, when a huge vapor pressure gap occurs (as in the case of Cd and Zn). E-waste is heated in a vacuum to vaporize the metals at lower temperatures than would be required under normal atmospheric pressure, then the metal vapors are condensed, collected and purified for further processing. Vacuum reduction is used for the selective recovery of metals like tantalum and niobium from e-waste. The process involves reducing metal oxides in a low-pressure

Table 6 Advancements in mechanical treatments for metal recovery

Technology	Progresses & innovation
Mechanical shredding	Advanced shredding technologies ensure efficient and uniform size reduction, facilitating subsequent separation processes
Vibrating screens and air classifiers	High-frequency vibrating screens and advanced air classifiers improve accuracy in separating metal-bearing particles from other materials, enhancing the purity of recovered metals
Electrostatic separation	Advanced electrostatic separators use innovative designs and control systems to achieve higher separation efficiency and recover a wider range of metals
Magnetic separation	High-gradient magnetic separators and superconducting magnets improve the recovery of valuable magnetic materials, such as iron, nickel, and cobalt
Sensor-based sorting	Hyperspectral imaging, X-ray fluorescence (XRF), and near-infrared (NIR) technologies are integrated into sorting systems for accurate identification and separation of metal-bearing components
Robotic sorting systems	Advanced robotics, machine learning, and computer vision algorithms enable precise identification and sorting of different materials, optimizing the recovery process
Automated disassembly	Innovations in robotic arms and disassembly tools improve efficiency and reduce the risk of damage to valuable components during the disassembly process

environment, typically using hydrogen or other reducing agents. The reduced metals are then separated and purified.

These techniques have been satisfactorily applied on a variety of waste electronic devices as summarized in Table 7.

The potential of these technologies is high because they are able to preserve the benefits of the more conventional pyrolytic processes, such as effectiveness and efficiency, with a lower environmental impact due to the less harsh conditions required. Specifically, working under vacuum allows lower operating temperatures, with a consequent reduced energy consumption as well as lower rates of toxic by-products. On the other side, the main drawbacks are related to the still immature development degree of the technology, which also requires relatively high costs of investment.

As a further alternative to conventional highly energy-demanding thermal processes, recent studies report the enrichment behaviors of heavy and critical metals under microwave pyrolysis of spent PCBs. Thanks to their good microwave absorptivity, spent PCBs thermally treated under microwave irradiation in the presence of additives such as HBr, allowed a satisfactory metal enrichment for subsequent metal recovery treatments.[122,123]

5.3.1.3. Chemical processes. In the specific context of recovering metals through hydrometallurgy from WEEE, the synergy between effectiveness and sustainability in novel chemical processes can be realized by creatively leveraging profound knowledge of chemistry pertaining to various classes of metals and materials within complex, multicomponent wastes. This entails minimizing reliance on harmful reagents, solvents, and conditions, reducing the generation of byproducts and wastewater, and adopting energy-efficient processes.[108]

The efficiency of extracting metals from intricate materials like WEEE relies on the swift, selective formation of stable metal complexes. Thus, a critical aspect of process design is the judicious selection of ligands capable of forming stable complexes with the targeted metals. Consequently,

Table 7 Examples of application of VM technologies to e-waste for metal recovery. Vacuum Pyrolysis (VP), Distillation (VD), and Reduction (VR)

Waste device	Recovered metals	VM technology	Ref.
PCB	Solder + metal/non-metal residue	VP combined with vacuum centrifugal separation	110
	Cd and Zn, selectively	VP	78
LED	Ga + As	VP&D	111
CRT	Pb-nanopowder	VP	112
	Pb	VP&R	113
Li-ion batteries	Binders/Al foil/$LiCoO_2$ separation	VP	114
	Co + Li_2CO_3	VR (with C)	115 and 116
Ni–Cd batteries	Cd	VP&R	117
Glass diodes	Pd, Cu	VD & condensation	118
LCD	In	VR	119
	Glass, $InCl_3$, NH_4Cl	VP + VCS (vacuum chlorinated separation)	120
	$InCl_3$, C coating and energy	VP (with waste PVC)	121

sustainability in hydrometallurgy can be attained by optimizing various stages of the process, particularly in the leaching as well as in the concentration and separation phases.

Methods published in literature mainly aimed at reducing the environmental impact of processes. These methods utilize coordination chemistry knowledge to develop new, environmentally friendly formulations for conventional treatments or to identify and employ novel, low-impact chemical agents for metal extraction in mild conditions. Additional methods have also been explored such as solvometallurgy which refers to processes based on the use of non-aqueous solutions, where non-aqueous means solvent with a low or any water content.[124] The use of non-aqueous solvents can be a useful alternative to water when water may interfere with materials and/or recycling processes.[125] Furthermore, functional media may play a pivotal role in enhancing process efficiency and/or selectivity, offering a new design to the whole recovery process. A certain benefit in improving eco-friendly metal recovery efficiency and conditions has been found by using microwaves (or ultrasounds), bacteria (bioleaching/biosorption), attrition (mechanochemistry), and electricity (electrorefining/electrocatalysis) for assisting chemical processes. Among them, biometallurgy (or bio-hydrometallurgy) is gaining a renewed attention for the low environmental impact it potentially achieves. Therefore, the evolution of metal recovery methods by biometallurgy will be further described later in this section.

A variety of reviews have been published during the last 20 years, and also recently, that well summarize the great effort of the scientific community for their contribution towards recovery process sustainability. Specifically, a general overview on both conventional and innovative chemical approaches for metal recovery from e-waste is proposed in ref. 82 and 126–132, while ref. 133 (supercritical water – SCW – technology), [134–137] (bio-hydrometallurgy), [138] (bio-derived sorbents), [139] (solvometallurgy), [140] (electrochemistry), [141,142] (mechanochemistry), focus on the cited specific aspects. In this framework, Fig. 8 summarizes the most relevant innovative chemical approaches developed in the last two decades pursuing processes combining efficiency with sustainability. As a support, Table 8 presents a selection of literature cases developed on real electronic scraps with the view to support the cited innovative approaches with an adequate number of examples related to e-waste metal leaching, separation & concentration, and recovery phases improvement.

Despite the great effort of the scientific community for developing new more sustainable processes, as well as the interest and potential of the cited approaches, most of described applications for recycling of e-waste are still at a laboratory scale. Nevertheless, a considerable amount of time is needed for designing, testing and supporting under technical-economic and environmental assessment for a fruitful technology transfer.

Referring to biometallurgical processes, they can be used in mineral processing as an alternative technology for recovering metals from very low-grade ores and concentrates.[203] There are two main fields of biometallurgy for the recovery of metals, namely metal mobilization (*e.g.*, bioleaching) and metal immobilization (*e.g.* biosorption).[204] Bioleaching of e-waste is a process that uses microorganisms to extract valuable metals from electronic waste, such as circuit boards, computer chips, and mobile phones. The process involves the use of bacteria, fungi, or archaea that can oxidize or solubilize metals from the waste materials, releasing them into solution typically in the forms of metal complexes where they can be easily recovered. Various microorganisms have evolved specific mechanisms of mobilizing metals. For microorganisms that involve redox oxidation (*e.g.*, *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, *Leptospirillum ferrooxidans*, and *Sulfolobus* sp),[205–207] sulfur compounds, such as ferrous iron (Fe^{2+}) or elemental sulfur (S_8^0) was oxidised to generate ferric iron (Fe^{3+}) or sulfuric acid (H_2SO_4). These oxidants can then react with metal sulfide minerals, such as chalcopyrite ($CuFeS_2$), releasing metal ions into solution. Several bacterial and fungal strains (*e.g.*, *Acidithiobacillus caldus*, *Aspergillus niger* and *Penicillium simplicissimum*)[208–210] produce organic acids as metabolic byproducts that can low the pH of the leaching solution to promote the dissolution of metal ions from the solid matrix. Another group of cyanogenic bacteria (*e.g. Chromobacterium*

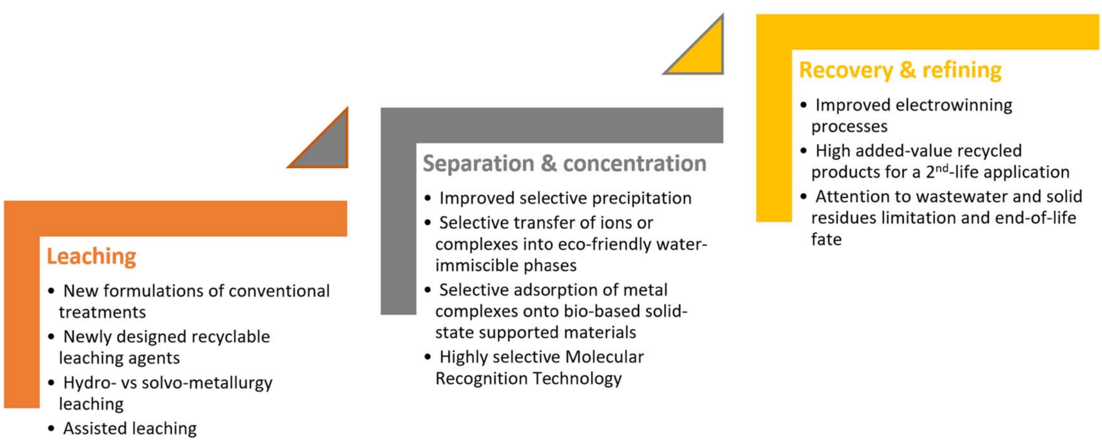

Fig. 8 Innovative chemical approaches for metal recovery of e-waste.

Table 8 Innovative literature-reported chemical approaches for metal leaching (L)/separation (S)/recovery (R) phases of e-waste[a]

Innovative phase	Action	E-waste	Metal target	Treatments/systems		Ref.
				Conventional	Alternative	
L	New formulations of conventional treatments	PCBs	Au, Cu	HNO_3 and HCl (aqua regia)	HCl/oxidant (Fe^{3+}, H_2O_2)	143 and 144
			Pd, Ag		NaCl/Cu^{2+}	145
		Ta-capacitors	Ta	Strong mineral acids	$FeCl_2$/heating	146
	Newly designed recyclable leaching agents	Shredded WEEE	Base metals/Cu/Au	Strong mineral acids	Dil. HCl/ammonia buffer solution, H_2O_2/S,S-donor chelating agent, I_2	147–149
		PCBs	Cu, Au, Ag, Co		Acidic/basic ILs	150
			Base metals/Cu, Ag/Au		Weak organic acid (citric acid)/ammonia buffer solution, $I_2(OH^-)$ (aq.)/I^-, I_2	56 and 151
			Base metals		Leaching mixtures based on organic acids	152–154
			Base metals/Cu, Ag/Au		$KI/H_2O_2/H^+$	57 and 151
		Semiconductor diodes	Ge		Weak organic acid	155
		Green lamp phosphors	Ce, Tb, La			156
	Hydro- *vs.* solvo-metallurgy leaching	PCBs	Au, Cu	Strong acids or thiourea in water	ILs or DESs as leaching media	157 and 158
			Cu	Strong mineral acids in	Supercritical CO_2	159
		Shredded WEEE	Base metals/Cu/Au	water	Aqueous HCl/ammonia buffer solution, H_2O_2; organic S,S-donor chelating agent, I_2	147
		Li-ion batteries	Li, Co		Py/$SOCl_2$ (organic aqua regia)	160
	Assisted leaching	PCBs	Au	Cyanide solutions	Bacteria/fungi	161
			Fe, Cu, Pd, Ag, Pt, Au	Cyanide solutions or strong mineral acids or		162–164
			Cu, Au	thiourea in oxidizing environment	Electricity	144, 165 and 166
			Cu, NMs	Strong mineral acids	Mechanochemistry	167 and 168
		CPU	Au	HNO_3 or other strong	Photocatalytic recycling	169
		Cell phones	Cu, Sn, Pb	mineral acids or cyanide	Electricity	143
			Cu, Sn, Ag, NMs	solutions	Ultrasounds using thiosulfate solution	170
		LCD	In		Mechanochemistry	171
		CRT funnel glass	Pb			141
		GaAs wafer	Ga, As		Electrocatalysis with iodine/ethaline	172
S	Improved selective precipitation	Smartphone	REEs	HF or H_2SO_4 or OH^- or $H_2C_2O_4$	REEs polymeric chelating/precipitating agents	173
		CPU	NMs	Sulfides	Selective precipitation	174
		Gold-bearing cable				175
	Selective transfer of ions or	PCBs	Au, Cu	Mixer-settlers-based	Ils or DESs as extraction media	157
	complexes into eco-friendly	PVP	Si-Ag, Cu	solvent extraction using		176
	water-immiscible phases	Shredded WEEE	Pd	VOCs or VOC containing	Cloud point extraction	177
		Hard-disk drive magnets	REEs	organic solvents		178
		Fluorescent lamps	Y, Eu		ILs or DESs as extraction media	179
	Selective adsorption of metal complexes onto high	PCBs	Au, Pt, Pd, Ag, Cu	Activated carbon	Porous porphyrin polymer	180
	selectivity and efficiency solid-state extractants	WEEE	Au		Light-activated polydopamine coated spheres	181
		Mobile phones	Au		Cross-linked polymer inclusion membrane (CL-PIM) incorporating the extractant	182

Table 8 (*Contd.*)

Innovative phase	Action	E-waste	Metal target	Treatments/systems: Conventional	Treatments/systems: Alternative	Ref.
					trihexyltetradecylphosphonium bis(2,4,4-trimethylpentyl) phosphinate (Cyphos® IL 104)	
		PCBs	Au, Cu	Activated carbon	Resins	166
			Au, Pd, Pt		3D printed mixture of polypropylene with 10 wt% of type-1 anion exchange resin	183
			Au		Ammonium thiosulfate (AT) and lactobacillus acidophilus (LA)	184
			Au		Starbon®	185 and 186
		Nd-based magnets	Nd	Ion exchange resins	*E. coli* cells in nonadsorptive (polyethylene glycol diacrylate) PEGDA hydrogel spheres	187
		ITO, LCD	In, Sn		Starbon®	185
		Li-ion batteries	Co		6-((2-(2-Hydroxy-1-naphthoyl) hydrazono)methyl)benzoic acid (HMBA) onto mesoporous silica monoliths	188
	Highly selective molecular recognition technology	WEEE	Base metals and PGMs	Activated carbon	SuperLIG®	189
R	Improved electrowinning processes	PCBs	NMs	HNO_3 or HCl electrowinning	Electrorefining	190
			Au, Ag		Electrowinning from NH_3/NH_4^+ solution	191
			Cu, Au		Electrowinning from thiosulfate solution	192
			Cu		Electrowinning from HCl/Fe(III)-HCl/$(NH_2)_2CS$	166
			Au		$HCl/NaCl/H_2O_2$ slurry electrolysis	193
					Electrowinning in ethylene glycol	194
		Cell phones	Base metals		Electrowinning using HCl/Fe(II)	143
				Recovery process/system	**2nd-life application**	
	High added-value recycled products for a 2nd-life application	SIM/SMART cards	Au	DTO/I_2	Homogeneous catalysis	195
		Smartphone PCBs	Cu	$HNO_3/\gamma\text{-}Al_2O_3$ (NaOH)/Δ	Heterogeneous catalysis	196
		PCBs	Cu/Sn	H_2SO_4, H_2O_2/electrodeposition	Cu-Sn alloy for thin-film anod material for Li-ion batteries	197
		CPU pins	Au	HCl, H_2O_2/Na_3Citrate, ascorbic acid, polyvinylpyrrolidone	Plasmonic responsive Au NPs	198
		PCBs	Cu	Aqua regia leach/solvothermal process	Cu-ferrite nanocomposite photocatalysts	199
	Attention to wastewater, solid residues limitation and EoL fate	PCBs	—	Glass fiber residues	Organic pollutant sorbents	200
				Non metallic fraction	Reutilization as filler in polymer composites	201
		ITO		ITO-leaching wastewater	Reclamation by metal extraction and valorization	202

[a] Acronyms in the table: PVP = photovoltaic panel; NMs = noble metals; NPs = nanoparticles; ILs = ionic liquids; DESs = deep eutectic solvents; REEs = rare earth elements; VOCs = volatile organic compounds; PCBs = printed circuit boards; CPU = central unit processor; LCD = liquid crystal display; CRT = cathode ray tube; PGMs = platinum group metals; ITO = indium tin oxide.

violaceum, *Pseudomonas aeruginosa* and *Bacillus megterium*)[161,211,212] play a unique role in metal recovery from e-waste through a process called cyanide leaching. These bacteria have the ability to produce and utilize cyanide (CN^-) as a lixiviant. The biogenic cyanide binds strongly to many transitional metals (such as Au and Ag) to form metal–cyanide complexes that are soluble in water.

Several reviews have documented the use of microbially-assisted reactions to extract base metals such as Cu, Ni, Zn, Cr, precious metals such as Au, Ag, and critical metals such as REEs from e-waste.[213–217] To improve the performance of bioleaching, researchers have reported that a two-step metal extraction involving a growing stage before exposing the microbial culture to the e-waste;[210,218–220] a sequential process using an acidophilic ferrous iron-oxidising bacteria consortium followed by extremophilic microalgae;[221] and a combination of hydrometallurgy and microbial-mediated process[222–226] can enhance the recovery of the metals from e-waste.

Biosorption process is a physico-chemical and metabolism-independent process resulting in the removal of substances from solution by biological materials.[227] The properties of certain types of inactive or dead microbial biomass materials also allow them to bind and concentrate metal ions from industrial effluents and aqueous solutions through adsorption, ion exchange, complexation, chelation, reduction and precipitation. Biosorbents are prepared from different microorganisms including bacteria, fungi, algae, and some biowaste materials for metal biosorption.[204] For example, the combination of ammonium thiosulfate and *Lactobacillus acidophilus* has demonstrated selective biosorption of Au from printed circuit boards.[184] The fungus *Aspergillus tubingensis* was found to bioaccumulate and bioconcentrate Y and Cu from e-waste powder with a bioconcentration factor (BCF) >12.[228] A microalga *Chlorella vulgaris* has been used to recover Nd from aqueous solution derived from hard drive disk magnets, its uptake was highest (157.40 mg g^{-1}) at 35 °C.[229] Agricultural residues have also been utilized as biosorbents. These materials possess abundant cellulose, hemicellulose, and lignin components that provide binding sites for metal ions, they have shown success in recovering Cd, Pb and Ni from waste printed circuit board [230] and Cr from floppy disk leachate.[231]

It is important to note that bioleaching and biosorption require the involvement of active biomass during the process, directly or indirectly mediate the process itself. In that sense, the use of bio-derived leaching agents and sorbents operating after biomass separation cannot be considered bio-leaching and bio-sorption processes. However, the action of microorganisms on organic residues can be exploited to drive chemical transformations in low value organic residues (*e.g.* produced as waste by agro-industrial activities) to produce high value chemicals for metal recovery. In that sense, the possibility to apply the bio-refinery concept[232] to e-waste valorization have been recently published[153,154] and patented.[152] The goal is to promote integrated systems that, through a well-defined sequence of processes, mitigate the negative effects of poor waste management while recovering resources in line with sustainability and circular economy principles. Such an example, unlocking the potential of dairy waste through biotechnology offers an exciting pathway to produce organic acid mixtures, which can effectively dissolve and recover critical raw materials (CRMs) from discarded printed circuit boards (PCBs).[152,154] This innovative approach highlights a remarkable synergy between two significant industrial value chains: the dairy production sector and the IT industry. By collaborating, these industries can optimize resource utilization while minimizing waste and wastewater, creating a sustainable, circular economy that benefits both fields in a single, efficient process.

5.4. Recycling of e-waste plastics

Prior to recycling, appropriate sorting of WEEE plastics is important for the efficient process, especially for the materials containing BFRs such as cathode ray tubes and flat screen plastics.[233]

A number of developments have been made to advance the sorting technologies. For example, optical sensors can separate plastics based on their color using Near Infrared radiation or X-ray fluorescence detectors. PRISM technology[234] can sort plastics based on intelligent labels and invisible markers.

The most effective approach for a large-scale recycling of WEEE plastics is currently based on mechanical recycling where the plastic e-waste upon sorting is mechanically processed using techniques such as extrusion or injection moulding that leads to fresh plastics. A variety of recycling companies around the world operating recycling of WEEE plastics use this approach, among them Enva (UK), MGG Recycling (Austria), and Genesis Electronics Recycling (USA). Besides the simplicity and cost-effectiveness which make these processes the ones of choice for most industrial plastics recycling plants, the quality of plastics produced through mechanical recycling is usually lower cycle-by-cycle. As a result, plastic can be mechanically recycled only 2–5 times and eventually ends up in the landfill.

As mentioned above, the recycling of WEEE plastics containing BFRs is challenging due to the potential release of toxic chemicals during recycling. To avoid such situations, the Fraunhofer IVV Institute has developed a technology called the CreaSolv® Process where the BFRs are extracted from WEEE plastics using a special solvent system prior to mechanical processing.[235] The technology has also been implemented by Unilever[236] for the recycling of sachet waste and is considered to be the most promising for the recycling of WEEE plastic.

Distinct from mechanical recycling discussed above, chemical recycling processes depolymerise plastics to useful chemical feedstock or monomers that can be used for the production of virgin plastics.[130] Such processes use harsh reaction conditions or/and solvents. For example, pyrolysis and gasification can use temperatures up to 400–800 °C. The presence of BFRs presents the risk of degradation of BFRs to hazardous chemicals during the thermal degradation of plastics. However, some emerging technologies such as KDV technology can perform the depolymerisation at a relatively lower temperature (<250 °C).[237]

The use of supercritical fluids (SCFs) such as supercritical water (SCW), and supercritical CO_2 ($scCO_2$) has also received significant attention for the chemical recycling of e-waste plastics.[238] SCFs have useful properties such as high density (similar to liquids), low viscosity and high diffusivity that allow them to dissolve inert materials efficiently and enhance reactivity. For example, $scCO_2$ has been used for the dechlorination and debromination of electronic display housing plastic.[239] Although a number of research articles on the use of SCFs for recycling have been reported,[238] this approach has not been applied in industry for e-waste plastics due to the high cost associated with using the SCF technology although there are some emerging innovations in processes such as Circuplast that has been recently licensed to the Stopford.[240]

It is important to make sure that the plastics obtained from recycling e-waste plastics are free from contaminants as BFRs and POPs could remain persistent in the recycling if proper measures are not taken. This has been recently expressed as a matter of concern in a study commissioned by the Office for Product Safety and Standards (UK Government). According to the study, this is problematic especially if the e-waste plastic is exported to the countries where substantial informal recycling exists (*e.g.* plastic is recycled just by blending with virgin plastics) and the recycled plastic is then imported back to the UK or other countries.[241]

Finally, as mentioned in the previous section, reprocessing and use of plastic components for specific applications as well as fillers for polymer composite preparation[201] may represent an appealing strategy for a chemical transformation and recycling.

6. Life cycle and sustainability assessments

In a previous section, the focus was amongst others on the approaches underlying the concept of ecodesign and the principles of Green Chemistry. In a broader sense, the challenge is to combine these novel approaches and principles with the broadly accepted approach of LCA and incorporate them in the emerging concept of Safe-and-Sustainable-by-Design (SSbD) of products and materials, and to do so by comparing conventional *versus* innovative materials recovery methods from e-waste. In this section, a general description of the SSbD concept is given, followed by the key issues to be considered in LCAs in which novel and existing technologies for e-waste processing are compared. Finally, some examples of the main outcomes of (quantitative) LCA studies are highlighted. It is to be noted that a detailed analysis of individual LCAs is beyond the scope of this contribution, if only because of the specific issues that need to be considered in individual LCAs.

The SSbD concept merges Life Cycle Thinking (LCT) principles as founded on long-year experiences with LCA, with Social Life Cycle Assessment (S-LCA), Life Cycle Costing (LCC), carbon footprinting, and water footprinting.[242] SSbD is a broad approach that ensures that chemicals/advanced materials/products/services are produced and used in a way to avoid harm to humans and the environment whilst balancing possible harms with the triple bottom line and the ultimate goal of sustainability: protection of People, Planet and Profit (PPP). Even though PPP is considered mostly relevant to investors and decision making, the PPP bottom line also applies to the specific case of the management of WEEE. Sustainable processing of WEEE is possible only when safety assessment for man and the environment is integrated with (S-)LCA, LCC and environmental footprinting. Applying the SSbD concept to e-waste processing allows us to compare the overall sustainability of various processes and methods that might be brought forward, instead of the rather classical habit of focusing on hazards or economics only. The SSbD concept is specifically aligned for this integration and the concept is therefore especially in Europe embraced as a central element in the European Commission Chemical Strategy for Sustainability[243] which is part of the European Green Deal.[244] The Chemical Strategy for Sustainability is well-aligned with the European WEEE-directive and *vice versa* as it allows for sustainability assessment of WEEE along the whole life cycle from mining of raw materials *via* the production and use phase until the EoL.

Within the context of SSbD assessment of WEEE, classical LCA provides tools for comparing and quantifying impacts that are of a fully different nature, and which range from human health related impacts to endpoints dealing with climate change, most notably: Greenhouse Gas Emissions. Examples of the most important endpoints to consider in LCAs in which novel and existing electronic waste processing technologies are compared, and some of the relevant issues that will strongly impact the outcome of the LCA, are reported and described in Fig. 9.

These qualitative outcomes illustrate the diverse range of environmental, economic, and social factors that can be assessed through a comparative LCA of novel and existing electronic waste processing technologies. It is essential to consider these outcomes comprehensively to make informed decisions regarding the adoption and implementation of sustainable recycling practices. Quite a few scientific literature reporting life cycle assessment of electronic waste management with significant outcomes have up till now been published. A recent review of the trends, characteristics, research gaps, and challenges has fairly recently been published by Xue and Xu.[245] The research gaps and challenges identified by Xue and Xu include: (1) uneven distribution of life cycle assessment studies with studies commonly focusing on limited types of electronic waste, including mostly monitors, waste PCBs, mobile phones, computers, printers, batteries, toys, dishwashers, and LEDs; (2) the selection of the most suited combination of life cycle impact assessment methods, as 40% of the reviewed studies combined LCA with other environmental assessment tools including LCC, MFA, MCDA, energy analysis, and hazard assessment in order to generate more comprehensive conclusions about the various aspects related to impact assessment of electronic waste; (3) uniform guidance for proper comparison and interpretation of the results of LCAs; (4) harmonization of the assessment of the uncertainties of LCA studies. The authors concluded that generally speaking, the results of LCA studies on electronic of conventional and novel e-waste processing technologies cannot be properly compared, since the different methods used commonly have a different background with their featured parameters. However, for the same impact category the results from different methods can be used to analyze how the model and parameter selection affect the outcomes. Furthermore, different methods can be used in one study to investigate the sensitivity of LCA of electronic waste management.

Prospective LCA is the key method for guiding the sustainability assessment of emerging technologies for WEEE processing, as it allows the identification of environmental

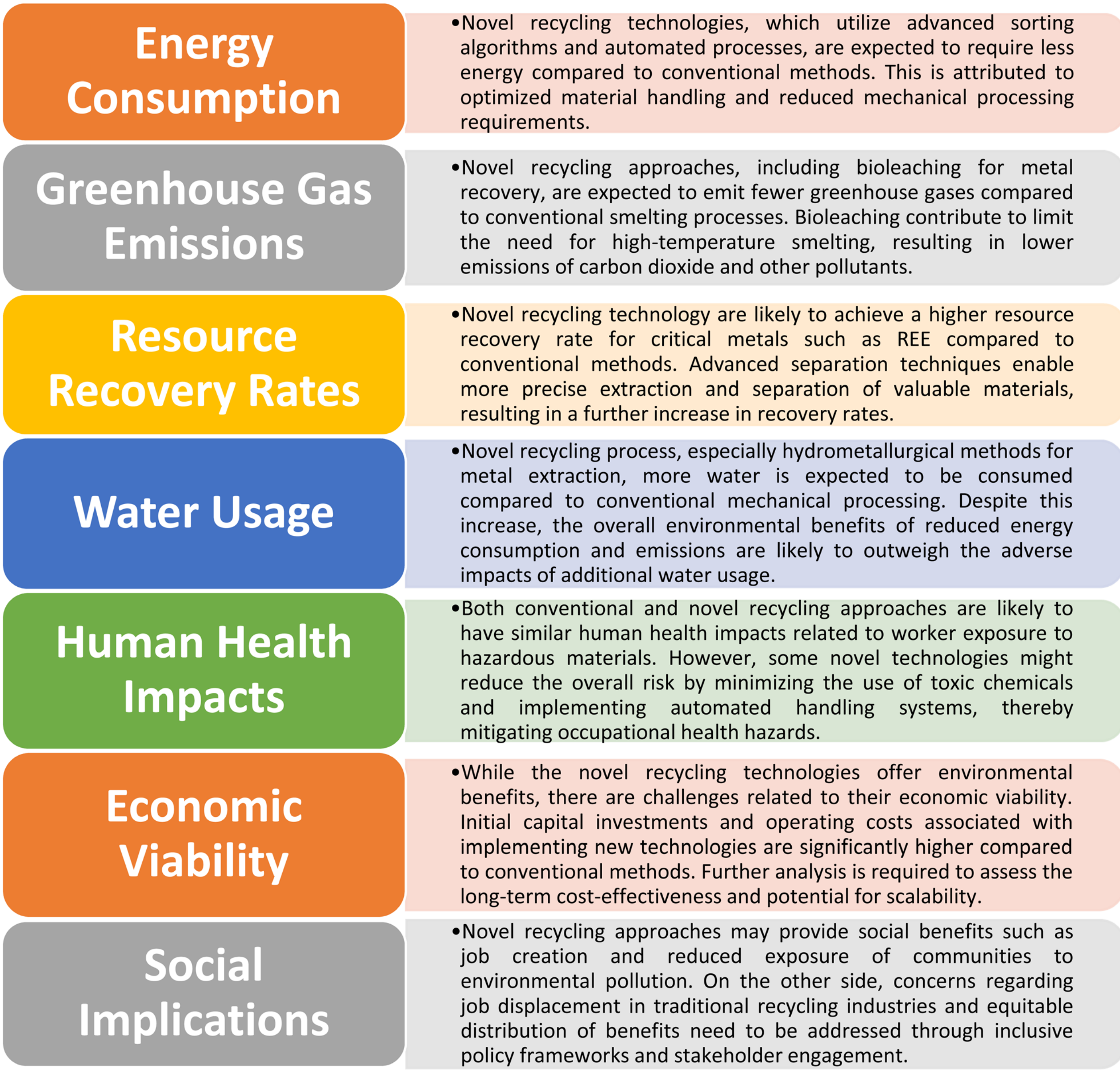

Fig. 9 Examples of key endpoints and relevant issues in LCAs for comparing WEEE processing.

hotspots in the early stages of technology development.[246] Prospective LCA, which is sometimes referred to as anticipatory or ex-ante LCA, is described as a specific mode in LCA that estimates future environmental impacts using scenario modelling.[247] Arvidsson *et al.* state that "an LCA is prospective when the (emerging) technology studied is in an early phase of development (*e.g.*, small-scale production), but the technology is modeled at a future, more-developed phase (*e.g.*, large-scale production)".[246] Predictive scenarios and/or scenarios ranges are used for prospective inventory modelling of foreground and background systems, and this is a key aspect for prospective LCA of newly developed technologies including e-waste processing. When applying prospective LCA in the early stages of process development, more opportunities are created to reduce the subsequent environmental impacts of the process, which can be utilized to influence process development towards the success of the e-waste processing technology. By identifying environmental hotspots as early as possible, burdens and costs can be reduced, investments and product substitutions can be avoided, and even changes in regulations can be anticipated. However, prospective LCA does not aim to predict the future as the focus is on exploring and evaluating a range of scenarios that explore the potential environmental scope of a technology and steer the technology towards a preferred future state that allows comparison with existing technologies.

The implementation of prospective LCA faces several challenges, such as data limitations, scale-up issues, uncertainty and comparability.[248,249] A framework for the implementation of prospective LCA of chemical recycling technologies was recently developed by Schulte *et al.*[250] The framework is intended to answer the specific question: How can prospective LCA of the chemical recycling of WEEE provide environmental decision support? The focus of the framework is on the plastics from WEEE at EoL as it has been suggested that the amount of plastic can reach up to 30% of WEEE. WEEE is in itself characterized by (potentially) hazardous as well valuable chemical elements and constituents of general societal concern like plastics. Most recycling technologies focus on preserving the metals whilst the recycling of plastics is still subordinated to the recovery of the precious metals. A specific topic of concern is the fact that flame retardants containing halogenated components are commonly added in EEE applications to reduce their flammability, whilst these toxic and persistent chemicals can cause difficulties in the EoL treatment.

Regarding the case study of Schulte *et al.*, the authors concluded that further validation of life cycle inventories and scenarios is advisable as soon as data is available.[250] This would increase the reliability with respect to the limitations of prospective LCA regarding comparability, data availability, and interpretation issues. Moreover, interpretation of all impact categories calculated is still needed to be able to make a holistic statement of all environmental impacts of a novel e-waste processing technology. Nonetheless, Schulte *et al.* demonstrated that the treatment of plastics with the novel technology identified in their study has a lower impact on climate change compared to existing treatment by means of shredding, mechanical separation, and incineration of plastic residues. The best identified scenario for obtaining valuable resources showed a savings potential of 74% compared to a current reference system. Schulte *et al.* furthermore showed that key results regarding the impact of EoL options can be obtained and compared by using the developed prospective LCA framework, whilst recognizing that most recycling technologies are still at low technology readiness level (TRL) and their environmental impacts are often unknown.

The latest trends in LCA of e-waste recycling have been recently reviewed by He *et al.*,[251] whereas the same authors previously published a study which focused on the identification of the critical related to comparative LCA applied to evaluate the environmental impacts of various technologies for gold recycling from e-waste.[252] The latter study highlighted the substantial reductions of environmental and human health impacts of various gold recycling technologies, but unfortunately, no consideration was given to most of the key endpoints mentioned in Fig. 9. Combining the outline provided above on the application of various forms of LCA for e-waste processing within sustainability assessment with the up-to-date review on LCA for e-waste recycling of He *et al.* (2024)[251] learns most of all that despite technological advancements in recycling e-waste, the existing processes and techniques still face various social, economic, and environmental challenges. While comparative LCA studies have been instrumental in evaluating traditional methods *versus* formal e-waste recycling, there remains a lack of consensus on the optimal assessment method and its constituents. This discrepancy can be attributed to variations in assumptions, system boundaries, and, crucially, the data utilized. To enhance the consistency of results and enable more accurate policy and decision-making, developing precise standards for LCA studies in e-waste recycling is imperative. Additionally, more attention is needed for the implementation of Contributable LCA (CLCA) as this allows for analysis of various future scenarios for e-waste processing. In addition to focus on the key economic and social endpoints within a sustainability assessment of e-waste processing, geographical and situational factors as well as policy and regulatory interactions become of increased importance. The positive outlook of the LCA approach towards e-waste recycling is anticipated to have a significant impact on the future of this sector, the more as using LCA will be imperative in advancing sustainability and mitigating the ecological ramifications of e-waste recycling as the industry undergoes continuous development and expansion.

7. Current trends and future perspectives in e-waste management

The last 20 years have been characterized by an increasing global effort to implement CE models in EEE production field. Collection and valorization (through reuse, recycling, and energy production) rates of e-waste are growing driven by the benefits related to the economical enhancement of the materials as well as the regulation requirements to achieve the fixed targets. Limited data availability and waste streams that follow illegal or “informal” paths, make challenging a correct estimation of the quantities of e-waste produced annually. Informal streams can be found operating within the regulated countries when the official supply chain is bypassed, or encountered concerning exports from developed to underdeveloped/developing nations, especially those without reference legislation.[14,16] Another relevant amount of e-waste difficult to catch is constituted of domestic electronic devices that, for various reasons, are not regularly conferred to the bodies in charge. An estimate of the amount of WEEE produced globally is shown in Fig. 10.[14,253]

As reported, in 2022 about 62 million tons (Mt) of WEEE, equivalent to an average of 7.8 kg per capita per year, were generated globally, of which only 22.3% were managed correctly.[254] A further trend constantly growing is expected for the next decade. The total consumption of EEE, in fact, increases annually by 2.3–2.5 Mt, given that it is expected to reach 82 Mt by 2030 (9 kg per inhabitant).

Several economic analyses have highlighted the significance of e-waste as an urban mine for CRMs. On one hand, the demand for technological production drives the criticality of materials, leading to shifts in CRM selection over the years.[21] On the other hand Hi-Tech goods serve as the best primary alternative source for these materials compared to primary minerals. As anticipated, raw materials, primarily metals, that can be recovered from the global e-waste generated in 2022 are estimated to be USD 92 billion, being the highest potential value related to copper (USD 19 billion), gold (USD 15 billion) and iron (USD 16 billion).[13] Despite their increasing economic value and criticality, REE are still recovered at a very low extent (on

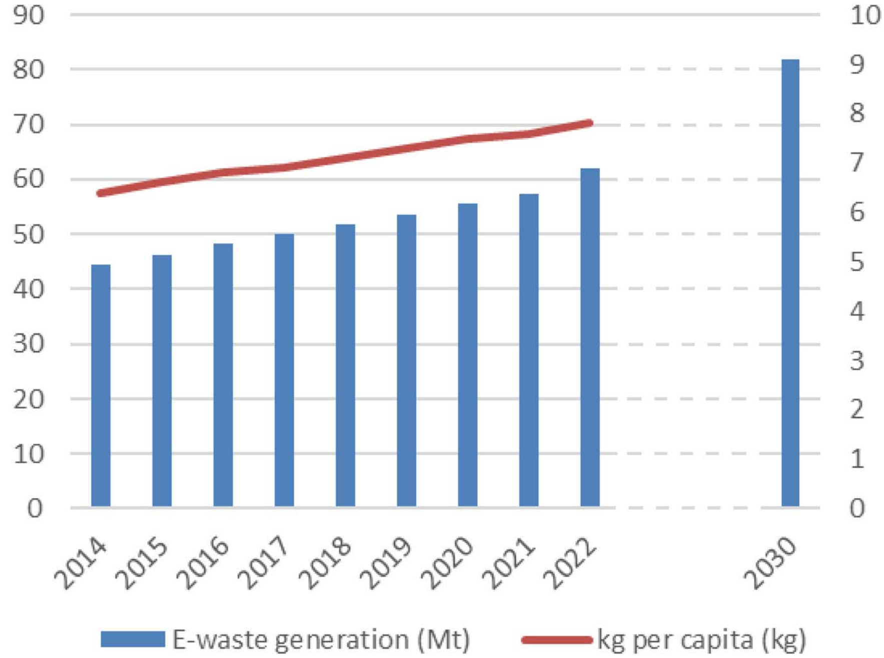

Fig. 10 Trends of global WEEE production, total and per capita, with estimates up to 2030 (data source: GEM2020 (ref. 14) and GEM2024 (ref. 13)).

average 1%) as they are challenging to recycle economically and low market prices hinder large-scale recycling efforts. Within the estimated potential, just around USD 28 billion worth of metals (around 30% of the potential) were turned into secondary raw materials globally by current e-waste management practices, regardless of documented formal (USD 9 billion), informal (USD 12 billion), and outside compliant (USD 7 billion) management routes. Further investigations focus on specific market segments. For example, the economic potential of 14 types of e-waste and 8 types of EoL vehicles in Hong Kong was evaluated to be USD 2 billion annually, mainly as a result of precious and rare metals recovery.[255] Similarly, e-waste generation in Indonesia as well as its potential recoverable metals' value from 1996 to 2040 has undergone a multivariate Input–Output Analysis (IOA), finding e-waste generation is projected to increase from approximately 2.0 (in 2021) to 3.2 Mt (in 2040), which corresponds to 7.3 (in 2021) to 10 kg per capita (in 2040) with corresponding economic values from USD 2.2 billion to USD 14 billion of copper, gold, silver, platinum and palladium in the e-waste.[256] Benefits in material recovery also involve the reduction of greenhouse gas emission whose monetized value for 2022 was USD 23 billion. Despite these very appealing and promising estimations, the current annual economic monetary impact of the global e-waste management is still shifted towards a negative balance, estimated of USD 37 billion in 2022 comparing the benefits (USD 51 billion) with the costs (88 billion) of e-waste treatments and the externalized costs to human health and the environment. Specific niches of application may represent interesting and particularly appealing case study. As an example, Talens Peiró *et al.* examined the feasibility of the urban mining of hard disk drives and concluded it is economically profitable to harvest the printed circuit board (PCB) and permanent magnets as the cost (€0.05–0.39) are well below the estimated economic value of the precious and critical metals present in the PCB (€0.85).[257] An interesting projection of possible e-waste management strategies made by UNITAR and ITU shows a variety of scenarios that can suggest governments implement wise strategies for reaching the desired goal of economic and environmental gain in the cost-benefit balance. Indeed, it has been estimated that by maintaining waste management activity as in 2022, an overall economic (benefit − costs) deficit of −40 billion USD is expected by 2030. More positive results are instead expected considering progressively improved scenarios. For example, a slight negative deficit (USD 4 billion) is expected in the case (i) voluntary collection schemes are implemented in regions without existing legislation; (ii) formal collection rates rise to 85% in areas covered by legislation and used to good e-waste management; (iii) waste PCBs are dismantled and treated more efficiently to maximize value extraction. Even better, a positive balance (USD +10 billion) can be reached if global collection schemes are efficiently improved and integrated by efforts to formalize the informal sector.

Continents contribute differently to global e-waste production and the corresponding collection and treatments. As shown in Fig. 11, in 2022, Asian countries produce nearly half of the world's e-waste (30 Mt) but have made limited progress in e-waste management, with few enacting legislation or setting clear collection targets. On the other hand, Europe generated the most in kg per capita (17.6 kg per capita) but was also the continent with the highest documented formal e-waste collection and recycling rate (7.53 kg per capita, and so 42.8%). Also, the rate of recycling of the different e-waste categories, documented as formally collected and recycled, variate significantly: small equipment (12%), large equipment excluding photovoltaic panels (34%), temperature exchange equipment (27%), screens and monitors (25%), small IT and telecommunication equipment (22%), lamps (5%), photovoltaic panels (17%). In all other continents, the e-waste documented as formally collected and recycled is substantially lower than the estimated e-waste generated. Current statistics show that in 2022 Oceania ranked second at 41.4%, the Americas and Asia stood at 30% and 11.8%, respectively, while Africa ranked last at 0.7%. However, statistics can vary substantially across different regions as the consumption and disposal behavior depends on a number of factors (*e.g.*, income level, policy in place, the structure of the waste management system, *etc.*) as detailed in the following sections.

To fulfil the requirements of wide spreading regulations a substantial improvement of decision-making processes for the effective management of e-waste is necessary and, even, unavoidable. Several studies have been carried out to provide relationship enabling e-waste generation prediction and good management practices suggestions. Among them a research of Kumar *et al.*[260] has examined the relationship between e-waste generation, gross domestic product (GDP), and population of a country, revealing that the GDP of a country is directly linked to the quantity of e-waste it produces. Against this, the population of the country does not appear to have a significant influence on e-waste generation. Besides, a strong linear correlation between global e-waste generation and GDP was pointed out by Awasthi *et al.*[261] In this framework, quantitative indicators have been defined by several authors. For example, Zuo *et al.* developed a model incorporating three indices (resource, technology and environment) to assess the criticality and potential of e-waste as an urban mine and recommend those clusters with high scores in all three areas to be prioritised for collection and material recovery in China.[262] 12 indicators in environmental, economic and social dimensions were also applied by Xavier *et al.* to the American bloc, comparing flows between different countries belonging to the developed NAFTA (comprising Canada, Mexico and United States) and the developing MERCOSUR (comprising Argentina, Brazil, Paraguay, Uruguay), in order to provide a better choice for e-waste reverse logistics routes.[263,264] These indicators, obtained by combining the cited correlation of GDP[260] and e-waste generation in different countries with a Material Flow Analysis (MFA),[261] are based on the distance between hotspots and recycling facilities, proximity between hotspots, the type of e-waste accepted by recycling companies and local contexts such as local management plans and educational campaigns. The same authors proposed classifying secondary raw materials from e-waste urban mining into strategic minerals, precious metals, base metals and toxic metals in a CE model to meet international demand and satisfy regulatory requirements. For optimal recovery of resources from small-sized EoL e-waste, Tesfaye *et al.* identified the volume of e-waste as a limiting factor and emphasised the need to establish effective e-waste collection mechanisms, appropriate government policies, public awareness campaigns and collection facilities installation at public places.[265] Multi-criteria decision methods have, hence, been adopted by most of the studies.[253] As an example Sharma *et al.* applied a multi-criteria approach, involving a stepwise weight assessment ratio analysis and, alternatively, the DEMATEL method, to examine e-waste management in India. They concluded that the 'Environmental Management System' (EMS) holds the utmost significance and acts as a key driving force in influencing all other existing enablers and that socio-economic

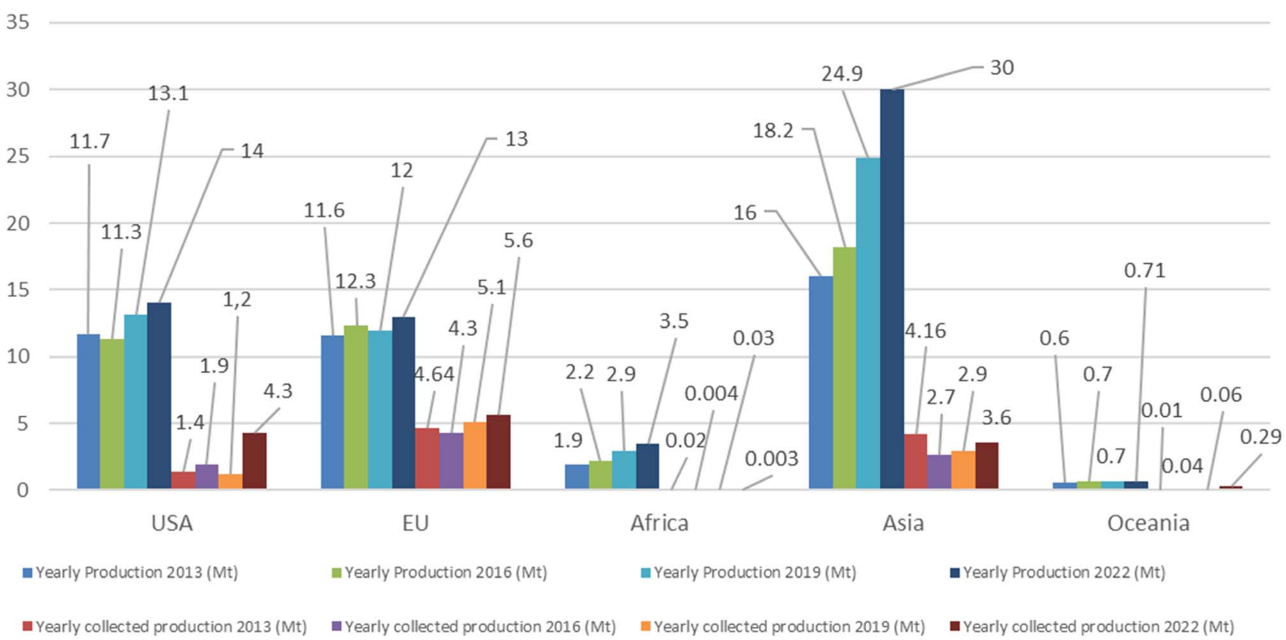

Fig. 11 WEEE flows and production of the different continents in different years (data sourced by GEM 2014, 2017, 2020, 2024).[14,258,259]

issues (such as e-waste awareness and tax incentives) are factors to enhance the urban mining of e-waste.[266,267] In that sense, specific attention was also devoted by Constantinescu *et al.* to the relationship between e-waste recycling and eco-investment and its evolution in European countries, in order to provide a widely applicable econometric model.[268] Specifically 10 indicators sourced by the Eurostat database, based on the quantity of WEEE collected in tons per year and also in kg per inhabitant per year in the different European countries, were analyzed in the period 2008–2018. The variable of interest in this analysis was the amount of e-waste recycled per inhabitant, while the independent variable was the eco-investment per inhabitant. The econometric analysis revealed that all EU member states experienced positive effects from eco-investment with better results in certain countries where a high level of e-waste recycling capacity has been reached. Furthermore, it pointed out the good impact of CE indicators and the importance of promoting the reduce-reuse-recycle paradigm.

In the following section, two case studies, one from emerging economies and one from emerged economies, will be discussed in more details as representative cases.

7.1. Emerging economies: a case study of selected middle eastern countries and Israel

7.1.1. Trends. E-waste management in emerging economies, including several middle eastern countries presents a complex landscape. The Arab states region, with varying economic and social indicators, witnessed a 30% increase in EEE placed on the market from 3.2 megatons (Mt), or 8.8 kilograms per inhabitant (kg per inh), in 2010 to 4.1 Mt (or 9.5 kg per inh) in 2019. In the same period, e-waste generation surged by 61%, indicating a substantial rise in discarded electronic products. However, e-waste collection and management in the Arab States remain alarmingly low, with only an estimated 0.1% being effectively managed in 2019, compared to the global average of 17%.[14] Lack of organized data is a significant challenge, but notable efforts were made by states like Jordan, the United Arab Emirates, Qatar, and Palestine, collected 1.3 kt (2.6%; 0.1 kg per inh); 0.7 kt; 0.2 kt (0.5%; 0.07 kg per inh) and 0.08 kt, respectively. However, a vast majority of e-waste is still either unmanaged or mismanaged, often ending up in landfills or being incinerated.[14] This improper disposal poses significant risks to both the environment and human health due to hazardous substances present in e-waste. Despite the challenges, there is an opportunity for a CE approach. In 2019, the e-waste in the Arab states contained valuable materials estimated at USD 3 billion. Transitioning to a CE could lead to the recycling of materials like gold, rare earth metals, iron, and steel, contributing to job creation and reduced greenhouse gas emissions. However, achieving this shift requires a comprehensive approach to policy development and enforcement.

E-waste management in the Arab States faces various challenges rooted in the absence of specific policies and legislation. Implementing the "polluter pays" principle and enforcing advanced recycling or disposal fees are crucial steps. This includes combating illegal e-waste import/export, preventing improper management practices, and establishing basic collection and treatment infrastructure. Public awareness campaigns, efficient monitoring, and reinforcement of existing e-waste management systems are vital elements of a holistic strategy.

7.1.2. Case-study: e-waste management in Israel. In Israel, the predominant consumption patterns of electronic appliances, coupled with a shorter product lifespan, contribute to a consistent increase in e-waste production. With an estimated annual volume of 156 000 tons, constituting 3% of all municipal-commercial waste, Israel faces challenges related to the heterogeneity and toxicity of e-waste.

Israel enacted the Electrical and Electronic Equipment and Batteries Law in 2012. The law is based on the European WEEE directive and aligns with the Extended Producer Responsibility principle, where producers and importers of electronic devices must treat EoL products to meet the recycling target. The law emphasizes recycling and reuse, defining authorized waste collection channels and recycling standards. It also facilitates the collection of e-waste through formal channels, enabling consumers to dispose of old products, when purchasing new ones, by suppliers. However, full implementation faces obstacles, including limited involvement of local authorities and unfair competition conditions in the recycling market.

Accredited Compliance Bodies (ACBs) like Ecommunity and M.A.I.-Electronics Recycling Corp. play a crucial role in collecting and recycling e-waste. Ecommunity is a social enterprise which strives to employ people with disabilities, reportedly collected 120 000 large electronic products (washing machines, dishwashers, ovens, dryers) in 2019, and about half a million small electronic devices. While M.A.I.-Electronics Recycling Corp. serves about 3 million residents in a variety of municipalities all over the country. M.A.I serves ∼90% of the B2B e-waste collection, as well as importers and manufacturers in a volume exceeding 60 000 tons per year and is currently the largest implementation body in Israel. However, a significant portion of e-waste is still collected by informal markets, leading to environmental and health hazards. Authorities in Israel employ strategies such as increased enforcement, pragmatic regulation of the informal market, and formal recognition to mitigate the impact of the informal sector. Efforts are made to transform the informal market into a legal industry, promoting standardization and investment in quality treatment facilities.

7.2. Developed countries: a case study of the European Union

7.2.1. Trends. E-waste management trends in developed countries have been characterized by increasing awareness, regulatory frameworks, and sustainable practices. Developed countries often adopt Extended Producer Responsibility (EPR) programs, where manufacturers and importers are held responsible for the entire life cycle of their electronic products. This encourages producers to design products with easier recycling in mind and take responsibility for the proper disposal of EoL electronics. Developed countries have established comprehensive regulatory frameworks for e-waste management. These regulations set collection and recycling targets, promote responsible disposal practices, and may include penalties for non-compliance. The European Union's WEEE directive is a notable example. Examples of EPR and related legislation in developed countries are presented in Table 9.

Developed countries invest in efficient collection infrastructure, including designated collection points, take-back programs, and convenient drop-off locations. These initiatives make it easier for consumers to properly dispose of their e-waste. There is a growing emphasis on raising public awareness about the environmental and health hazards associated with improper e-waste disposal. Education campaigns inform the public about the importance of recycling electronic devices and the availability of proper disposal methods. The concept of a CE, where products are designed for longevity, repairability, and recyclability, is gaining traction in developed countries. This involves promoting the repair and refurbishment of electronic devices, extending their lifespan, and reducing the overall e-waste generated. It also involves the development of advanced e-waste recycling technologies to recover valuable materials from electronic devices more efficiently that can be reused as source materials.

7.2.2. **Case-study: e-waste management in the European Union.** E-waste management in developed regions, particularly focusing on the European Union, showcases a comprehensive picture based on statistical data provided by EUROSTAT.[269,270] The data spans from 2012 to 2021, involving 27 EU countries. Examples from EU countries are presented in Table 9. Over the entire period (2012–2021), EEE market growth in the EU surged by 77.1%. The total collected Waste Electrical and Electronic Equipment (WEEE) increased from 3.0 to 4.0 million tonnes (+65.1%). Simultaneously, the treated WEEE escalated from 3.1 to 4.8 million tonnes (+54.2%). Recovered WEEE and items prepared for reuse saw a remarkable growth from 2.6 to 4.3 million tonnes (+65.1%) and 2.6 to 4.4 million tonnes (+69.8%), respectively, indicating a positive trajectory in sustainable e-waste management.[269]

The recast of the WEEE directive[28] introduced incremental collection targets, effective from 2016 and 2019 onwards. Collection targets rose from 45% in 2016 to 65% in 2019. Fig. 12 illustrates the collection of WEEE as a share of EEE put on the market, showcasing EU Member States' performance towards these targets.[269]

In 2021, 16 EU Member states surpassed the 45% collection target, with one more reporting a rate close to this target at 42.7%. Moreover, two EU Member States achieved the more ambitious 65% collection rate in 2021, while two others came close with rates at 60.2% and 63.8% respectively.[269] In the EU, the per capita WEEE collected in 2021 was estimated at 11.0

Table 9 Examples of extended producer responsibility programmes in developed countries

Country	Programme	Comments
European Union	Through the WEEE directive	Producers are obligated to finance and organise the collection, treatment and recycling of electronic waste. The direction also sets specific collection targets and encourages eco-design practice
Germany	Closed substance cycle waste management act	Manufacturers and distributors are responsible for taking back and recycling their products at the end of their life. It also sets specific targets for recycling rates
Sweden	The Swedish environmental code (Miljöbalken)	Overseas by the Swedish Environment Protection Agency. Producers must report annually on their collection and recycling efforts
Norway	Waste regulations	Producers are responsible for financing and organising the collection and recycling of their products. It encourages producers to design products with easier recycling in mind
Japan	Home appliance recycling law Small e-waste recycling act	Producers are responsible for recycling specified appliances, and they must establish collection and recycling systems. The law also encourages the development of eco-friendly products
South Korea	The act on resource circulation of electrical and electronic equipment and vehicles. eco-assurance system	Manufacturers are responsible for recycling and sets collection targets. Producers must register with the government and comply with recycling regulations
Canada (British Colombia)	Part of the environmental management act	Producers are responsible for funding and managing recycling programmes, ensuring that electronic products are properly collected and processed at the end of their life
Australia	National television and computer recycling schemes	Manufacturers and importers have the responsibility to fund and manage the recycling of televisions and computers

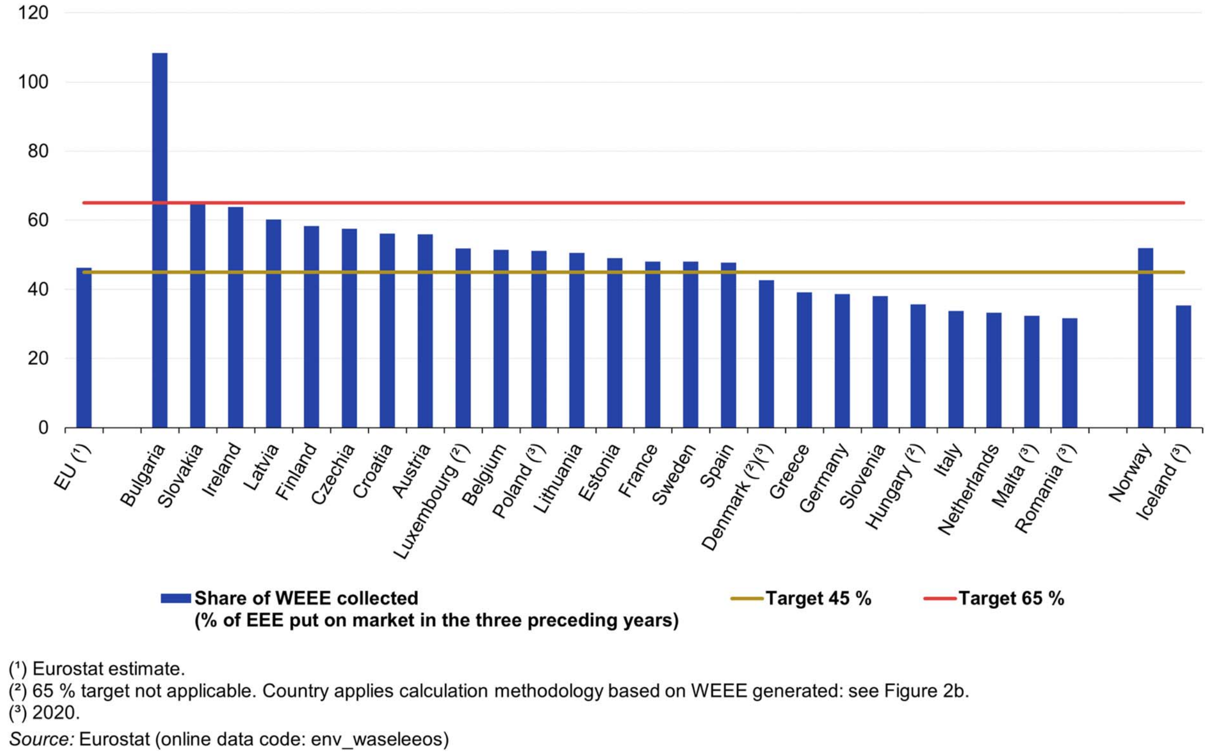

Fig. 12 Total collection rate for electric and electronic equipment (EEE), 2021 (% of weight of EEE put on the market in the three preceding years). Source: Eurostat (online data code: env_waseleeos).[269]

kilograms, compared to an average EEE put on the market of 23.7 kilograms per inhabitant over the period 2018–2020. These variations highlight disparities in EEE consumption levels and the performance of national waste collection schemes across EU countries.

8. Recommendations

To address the pressing challenges in e-waste management and promote a sustainable circular economy, a multifaceted approach is required, encompassing strengthened regulations, technological advancements, integration of informal sectors, enhanced resource recovery techniques, implementation of CE models, comprehensive LCAs, and increased public awareness.

Comprehensive policies and regulations are essential to enforce responsible e-waste disposal practices and incentivize recycling efforts. The direction taken in recent years is certainly encouraging, but it is further necessary to strengthen the network of agreements and collaborations among countries to significantly impact at a global level. Furthermore, easy and reliable access to robust data and information related to waste stream fluxes inside and outside countries, as well as on technical practices and industrial processes for e-waste management and valorization, is still a challenge. It represents a key and crucial point for assessing trends and setting policies and strategies for reaching the goal of a really sustainable implementation of CE models turning effectively waste into valued resources.

The development of more efficient and eco-friendly recycling techniques is imperative to maximize material recovery while minimizing energy consumption and emissions. Emphasizing the adoption of CE principles, including eco-design, reuse, and recycling, can create a more sustainable value chain. Policies and incentives that support CE practices should be prioritized to promote sustainable production and consumption patterns. The great efforts made in the last years by the scientific community towards more sustainable and appealing recovery methods, also driven by synergistic green chemistry and engineering principles, are today close to finding the right level of maturity to aspire to successful technology transfer. For this reason, efforts must persist in overcoming existing challenges and fostering a global transition towards a more sustainable and equitable future. In that way, despite the number being too low, the time seems ripe for companies to invest in innovative processes with a lower environmental impact and higher impacts with regard to socio-economic equality and human welfare. Furthermore, the Fourth Industrial Revolution offers significant opportunities for enhancing e-waste management through advanced technologies like AI, IoT, and robotics, which can optimize recycling processes, improve resource recovery, and enable better tracking of electronic waste. However, it also presents challenges, such as the need for sustainable design practices, potential increases in electronic consumption, and ensuring equitable access to these technologies across different regions, which are crucial for achieving circular economy and sustainability targets on a global scale.[271]

Conducting regular LCAs of e-waste management processes is essential for providing valuable insights into their environmental impacts and identifying areas for improvement. Incorporating these assessments into policy and practice can enhance sustainability outcomes by ensuring that new technologies and processes are evaluated for their environmental footprint.

Increasing public awareness about the importance of proper e-waste disposal and recycling is vital for the success of e-waste management programs. Educational campaigns and programs aimed at raising awareness and encouraging responsible disposal practices can significantly improve consumer participation rates. Engaging communities through various media and outreach initiatives is crucial to foster a culture of sustainability and responsible consumption.

9. Conclusions

The management of WEEE is a critical global challenge exacerbated by the increasing demand for technology and its rapid obsolescence. Thanks to the great effort of international organizations in collecting data and exploiting scientific journals and patent databases, this paper has reviewed the evolving landscape of international legislation, emerging technologies, and best practices designed to address this issue, emphasizing the need for a sustainable circular economy. Unfortunately, the lack of reliable information concerning waste stream fluxes around the world, as well as industrial practices for e-waste management and valorization represents the main limitation to this work and also to the most diffused monitoring and reporting available.

Anyway, the global regulatory frameworks, particularly those in the European Union, have made significant strides in curbing the environmental impact of e-waste by promoting recycling, reuse, and eco-design. Despite these advancements, the generation of e-waste continues to outpace formal recycling efforts, indicating a pressing need for more effective and widespread implementation of these practices.

In this review, we focused on significant aspects of the evolution of awareness and the management of WEEE driven by governmental regulations over the past two decades. The data on social, industrial, and political awareness show a growing global consensus on viewing end-of-life (EoL) electronic devices not as waste for disposal, but as valuable resources of secondary raw materials. This shift addresses material scarcity, prevents environmental damage, and reduces the waste of precious resources.

The development of regulations and policies in different countries, stating responsibilities and raising requests for innovation in product design (eco-design for effective end-of-life, EoL, management) and sustainability in treatments (green processes), drove the huge progress made in materials recycling from e-waste in the last 20 years, representing a significant stride towards sustainable resource management and environmental conservation. This advancement mitigates the adverse impacts of e-waste on ecosystems and human health and alleviates the strain on finite natural resources.

However, there is still considerable room for improvements to make industrial recycling technologies both reliable and sustainable. Patents and innovations focused on sustainable recycling are still in their infancy, with conventional, often eco-unfriendly recycling processes dominating the field. Recent studies highlighted how urban mining is becoming more cost-effective than traditional primary mining. Yet, despite social, political, and economic driving forces, much work remains to be done to optimize more eco-friendly e-waste recycling processes, demonstrate their technical-economical-environmental sustainability, and expand their accessibility worldwide.

As we enter the era of the fourth industrial revolution, the international community must harness the vast technological opportunities to create sustainable models that meet the sustainability needs of future generations. This calls for a collective effort to integrate innovations such as Artificial Intelligence and the Internet of Things into strategies for responsible resource management and environmental impact reduction while ensuring equitable and inclusive access to materials and technologies.

Abbreviations

ABS	Acrylonitrile–butadiene–styrene
ACBs	Accredited compliance bodies
a-Si	Amorphous silicon
BAN	Basel action network
BB209	Decabromobiphenyl; systematic name: 1,2,3,4,5-pentabromo-(6-(2,3,4,5,6-pentabromophenyl) benzene)
BCF	Bio-concentration factor
BFRs	Brominated flame retardants
BTBPE	1,2-Bis(2,4,6-tribromophenoxy)ethane; systematic name: 1,3,5-tribromo-2-[2-(2,4,6-tribromophenoxy)ethoxy]benzene
CdTe	Cadmium telluride
CE	Circular economy
CFL	Compact fluorescent lamps
CIGS	Copper indium gallium selenide
CPV	Concentrated photovoltaic
CRMs	Critical raw materials
CRT	Cathode ray tubes
c-Si	Crystalline silicon
D4S	Design for sustainability
DBDPE	1,2-Bis(perbromophenyl)ethane; systematic name: 1,2,3,4,5-pentabromo-6-[2-(2,3,4,5,6-pentabromophenyl)ethyl]benzene
DEMATEL	Decision making trial and evaluation laboratory
DP	Dechlorane plus®; systematic name: 1,2,3,4,7,8,9,10,13,13,14,14-dodecachloro-1,4,4*a*,5,6,6*a*,7,10,10*a*,11,12,12*a*-dodecahydro-1,4,7,10-dimethanodibenzo[*a*,*e*]cyclooctene
EC	European commission
EEE	Electrical and electronic equipment
EF	Enrichment factor
EMS	Environmental management system
EoL	End-of-life
EPEAT	Electronic product environmental assessment tool

EPR	Extended producer responsibility
EU	European Union
E-waste	Electrical and electronic waste
FR	Flame retardant
GC	Green chemistry
GDP	Gross domestic product
GE	Green engineering
GEM	Global e-waste monitor
GESP	Global e-waste statistics partnership
HBB	Hexabromobenzene; systematic name: 1,2,3,4,5,6-hexabromobenzene
HBCDD	Hexabromocyclododecanes
HFR	Halogeneted flame retardants
HIPS	High-impact polystyrene
HIT	Heterojunction with intrinsic thin layer technology
IERC	International electronic recycling conference
IGI	Igeo geoaccumulation index
IOA	Input–output analysis
IOs	Intergovernmental organizations
IRENA	International renewable energy agency
ITU	International telecommunication union
LCA	Life cycle assessment
LCC	Life cycle costing
LCD	Liquid crystal displays
LCT	Life cycle thinking
LED	Light emitting diode
LPCL	Low POP content limit
MCDA	Multiple-criteria decision analysis
MCI	Material circulal indicator
MERCOSUR	Mercado Comun del Sur
MFA	Material flow analysis
Mono-Si	Mono-crystalline silicon
MS	Member states
NAFTA	North America free trade agreement
NBFR	Novel brominated flame retardants
NIR	Near infra-red
NOP	No-plastic
OECD	Organization for economic cooperation and development
OPV	Organic photovoltaics
PA	Polyamide
PAHs	Polycyclic aromatic hydrocarbons
PBB	Polybrominated biphenyls
PBDEs	Polibrominated diphenyl ethers
PBT	Polybutylene terephtalate
PC	Polycarbonate
PCB	Printed circuit board
PCDD/Fs	Polychlorinated dibenzo[1,4]dioxyns and dibenzofurans
PERC	Passivated emitter rear cells
PFR	Organophosphate flame retardant
PIN	Newerow's pollution index
Poly-Si	Poly – crystaline silicon
POPs	Persistent organic pollutants
PP	Polyprolylene
PPO	Poly(*p*-phenylene oxide); systematic name: poly(oxy-2,6-dimethyl-1,4-phenylene)
PPP	People, planet and profit
PPP	Polluter pays principle
PROs	Producer responsibility organizations
PS	Polystyrene
PU	Polyurethane; systematic name: 1-ehylurea
PVC	Polyvinyl chloride; systematic name: chloroethane
PVP	Photovoltaic panels
RCRA	Resource conservation and recovery act
RE-CET	Redesigning electronics in a circular economy transition
REEs	Rare earth elements
RI	Potential ecological risk index
RoHS	Regulation on hazardous substances
RSR	Relative supply risk
SAN	Styrene-acrylonitrile
SCF	Supercritical fluids
SCL	Supercritical liquids
SCW	Supercritical water
S-LCA	Social life cycle assessment
SPCBs	Spent printed circuit boards
SSbD	Safe-and-sustainable-by-design
TBB	2-Ethylhexyl 2,3,4,5-tetrabromobenzoate
TBBP-A	Tetrabromobisphenol-A; systematic name: 2,6-dibromo-4-[2-(3,5-dibromo-4-hydroxyphenyl) propan-2-yl]phenol
TBP	2,4,6-Tribromophenol
TBPH	Bis(2-ethylhexyl) 3,4,5,6-tetrabromophthalate; systematic name: bis(2-ethylhexyl) 3,4,5,6-tetrabromobenzene-1,2-dicarboxylate
TCEP	Tris(2-chloroethyl) phosphate
TCP	Tris-*p*-cresyl phosphate; systematic name: tris(2-methylphenyl) phosphate
TCPP	Tris(1-chloropropan-2-yl) phosphate
TEQ	Toxic equivalent
TRL	Technology readiness level
UEEE	Used electric and electronic equipment
UN	United Nations
UNEP	United Nation Environmental Programme
UNITAR	United Nations Institute for Training and Research
USD	United States dollar
VCS	Vacuum chlorinated separation
VD	Vacuum distillation
VM	Vacuum metallurgy
VOCs	Volatile organic compound
VP	Vacuum pyrolysis
VR	Vacuum reduction
WEEE	Waste from electrical and electronic equipment
WPCB	Waste printed circuit board
XRF	X-ray fluorescence

Data availability

Data from Global E-Waste Monitor by the United Nations Institute for Training and Research (UNITAR) and International Telecommunication Union (ITU) under the Global E-waste Statistics Partnership (GESP); **https://globalewaste.org/** (accessed 2024-07-17). Data from the International Renewable

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Author contributions

L. B. and S. V. wrote the original draft and reviewed the section on legislation; A. S., D. P., D. C., G. D. G. wrote the metal recovery section; A. K. wrote and curated the plastics recycling section; V. M. I. P. and M. C. carried out statistic data curation for the manuscript; W. J. G. M. P. wrote the LCA section; H. G., Y. S. and D. P. wrote and curates the last section on trends and case studies. A. S and D. P. took care of the conceptualization, writing, review & editing as well as project administration.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors thank the International Union of Pure and Applied Chemistry, Funder ID: 10.13039/100006987, Grant Number: 2014-031-3-600, Project website: https://iupac.org/project/2014-031-3-600; and the Italian Ministry of the Ecological Transition, in the framework of the project "Sustainable MAterials Recycling Technology for Printed Circuits Boards-SMART PCBs"—CUP F57G20000050001, for the financial support of research and dissemination activity behind this manuscript. The authors acknowledge the contributions of M. S. Ermolin and P. Fedotov of the National University of Science and Technology "MISIS", Moscow, for the inspiration and initial development of the manuscript.

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