



# Electronic waste in emerging countries: current scenario of generation, policies, and recycling technologies regarding the coronavirus pandemic

A. B. Botelho Junior<sup>1</sup> · M. D. C. R. da Silva<sup>2</sup> · P. S. S. Camargo<sup>3</sup> · D. D. Munchen<sup>3</sup> · M. P. Cenci<sup>3</sup> · D. A. Bertuol<sup>2</sup> · H. M. Veit<sup>3</sup> · J. A. S. Tenório<sup>1</sup> · D. C. R. Espinosa<sup>1</sup>

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## Abstract

The coronavirus pandemic severely impacted on society, from medical to waste generation. In the case of electronic waste, it was no different. The behavior change increased the consumption of electronic equipment and will likely change the generation of electronic waste in the following years. Furthermore, the impacts were different in emerging and developed countries. Emerging countries must improve their electronics collection and recycling policies, and even among developed countries, there is much difference. This review article aimed to analyze the differences between developed and emerging countries and the impacts of the pandemic on the generation of electronic waste. An analysis of the public policies of these groups of countries and electronic waste management was carried out, as well as the current approaches of Brazil, India, China, and South Africa for treating their waste. Developed countries' policies and legislation have shown that electronic waste governance is better addressed comprehensively than in emerging economies. The increased consumption of electronic equipment will result in a rise in electronic waste generation in the coming years. Future perspectives show that emerging countries should concentrate efforts on their waste management policies to achieve recycling targets with a focus on circular economy and sustainable development goals.

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✉ A. B. Botelho Junior  
amilton.junior@usp.br

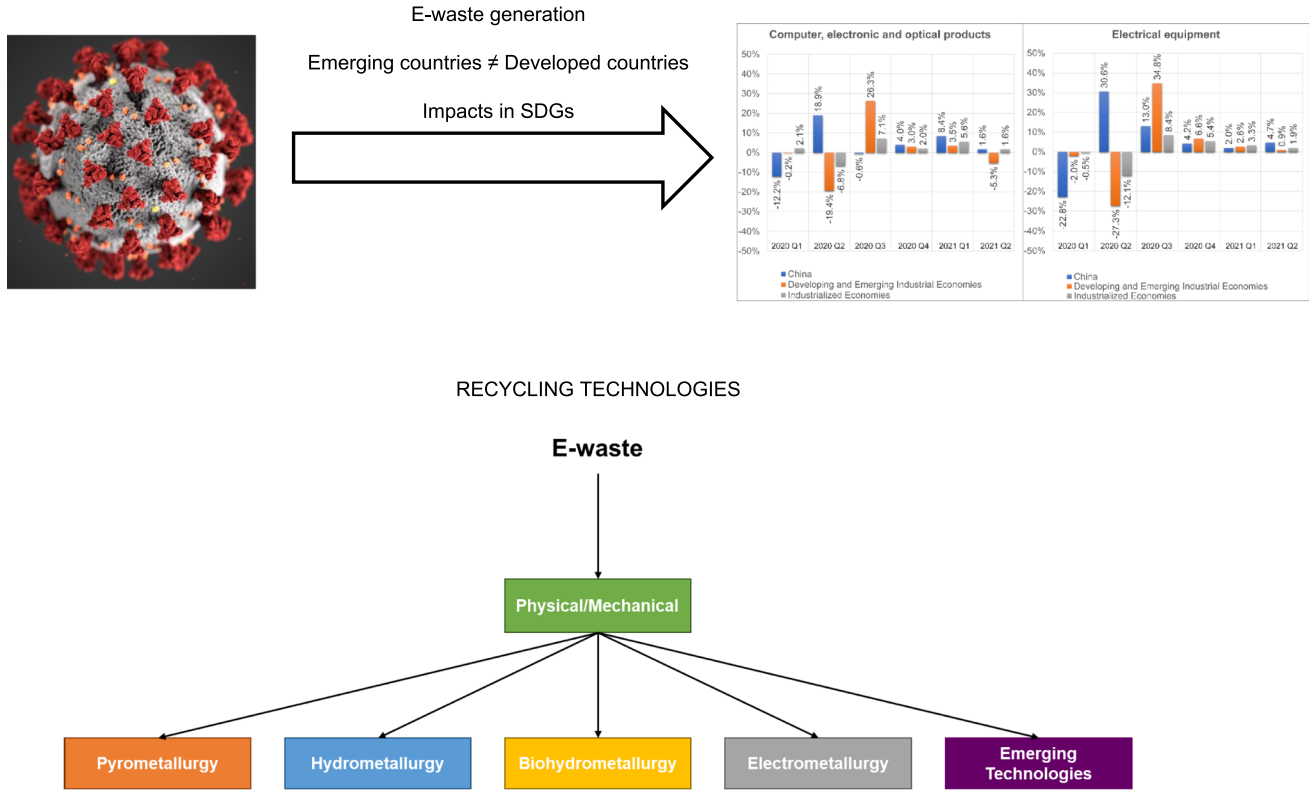
<sup>1</sup> Department of Chemical Engineering, Polytechnic School, University of Sao Paulo, São Paulo, Brazil

<sup>2</sup> Department of Chemical Engineering, Federal University of Santa Maria—UFSM, Santa Maria, Brazil

<sup>3</sup> Department of Materials Engineering, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil



## Graphical abstract



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## Introduction

The global pandemic of the new coronavirus infectious disease (COVID-19) at the beginning of 2020 changed the scenario all over the world, making humanity face several different situations, such as lockdowns and work and study at a distance (online) (Sachs et al. 2020). Furthermore, besides the huge number of people contaminated and deaths, which put massive pressure on medical systems worldwide, the change of demeanor raised the consumption rate and consequently the waste generation (Zhang et al. 2022).

For instance, the amount of plastic medical instruments consumption increased due to the production of personal protection equipment, face masks, and shields due to the pandemic. In addition, plastic waste generation increased caused of the consumption of packaged food (single-use packages) in *the home office*, also due to the concern of contaminations (Al-Salem et al. 2022; Lima et al. 2022). The generation of medical waste, for example, increased by about 425% in some parts of the world due to the use of personal protective equipment (Liang et al. 2021).

The “consumer's acquisition attitude” has changed, focusing on online and digital platforms (Larios-Gómez et al. 2021). Several people started to work or study at home, boosting demand for consumer electronics usage (such as notebooks, tablets, batteries, and smartphones) (Ikiz et al. 2021). This type of waste is a known issue due to social and economic problems.

Electrical and electronic equipment (EEE) consumption worldwide achieved 2.5 million tons per year (Forti et al. 2020), and the material footprint rose from 73.2 in 2010 to 85.9 billion tons (2017). The consumption of metal ores for the EEE market increased by 27% globally. These products, called electronic waste (e-waste) or WEEE (waste electrical and electronic equipment), are poorly collected/recycled at the end of life. Their generation growth rate is threefold higher than any other waste (3–5% per year) (Kumar et al. 2017a). Up to 83% of e-waste is not documented, whereas 43.7 M has an unknown destiny. The amount of e-waste will reach 75 Mt in 2030 due to the higher consumption rates, short lifespan, fast technological change, and low repair rate (Forti et al. 2020). Such e-wastes are also found in medical equipment, and their



consumption increased due to the 2019 pandemic (Xin et al. 2023).

As already reported, the increasing demand to supply online activities rose the commerce of notebooks, tablets, cellphones, and other EEEs for work and studies. At the same time, transportation and management declined due to the lockdowns (Zhang et al. 2022). Despite the observations and preliminary results, the literature could be better about the amount of growth in EEEs consumption and e-waste generation caused by the pandemic. Quantitative data on the subject need to be included.

In addition to the severe health and economic impacts, the pandemic had several environmental consequences. Emerging countries commonly landfill e-waste despite recycling, resulting in losses of valuable materials. Such an increase in consumption puts pressure on extractive processes from primary sources and waste generation (Borthakur 2020).

The impacts of the pandemic are different in developed and emerging countries, which may not be directly linked to wealth. Several other points must be raised to assess the impacts of the pandemic on e-waste generation. Despite the literature regarding the e-waste generation due to the pandemic (Rene et al. 2021), the most updated data comparing the last years, legislation, and policies for e-waste management focused on emerging countries need to be better reported. Furthermore, the importance of recycling processes in light of sustainable development must be discussed regarding the advance in the quantity and different types of electronic waste. Public policies and recycling technologies are available and are an important edge to e-waste management. Innovations are necessary to improve the recycling rate and to meet the new e-waste generation under new technologies.

This work critically analyzes the pandemic's impacts on e-waste generation in emerging countries. For this, Brazil was selected as the representative of Latin America, South Africa from the African continent, India represented Asia, and China as the most powerful economy in the world as part of the BRICS group. Nevertheless, there needs to be literature regarding the impact of the pandemic on e-waste generation in emerging economies and future environmental and social issues.

Public policies of e-waste were compared between developed and emerging countries, as depicted in “[Global e-waste policies](#)” section. The USA and Australia, respectively, representative of North America and Oceania, and Italy and the UK representing Europe, were chosen to compare the e-waste policies with emerging economies (“[Emerging countries](#)” section) as examples from developed economies (“[Developed countries](#)” section). EEE and e-waste generation statistics were discussed in light of the most recent data and previsions (“[Consumption/production of EEEs and e-waste generation—focus on the COVID-19 pandemic](#)”

section). Current recycling technologies in emerging countries are discussed in “[Emerging countries](#)” section, as well as the most innovations for future applications. Finally, future perspectives are presented in “[Discussion and future perspectives](#)” section, considering the impact of the pandemic on e-waste generation in the coming years. This research was carried out by Brazilian researchers located in Brazil (Sao Paulo and Rio Grande do Sul states) and Germany (Aachen) between December 2021 and June 2022.

## Global e-waste policies

This chapter will discuss the current policies and legislation for e-waste in emerging and developed countries. Asia is responsible for 46% of global e-waste generation, followed by America (24.4%), Europe (22.4%), Africa (5.4%), and Oceania (1.3%), while Europe has the highest generation per capita (30.2%) (Forti et al. 2020).

Despite the highest e-waste generation, the amount per capita in China is like the global average due to social inequality (Zeng et al. 2020). Countries with low GDPs, like South Africa, have the lowest e-waste generation per capita. The richest, as Italy and the UK, have the highest amount. Brazil has the highest GDP in Latin America, with the largest e-waste generation and the second generation per capita (Borthakur 2020).

Solely 17.4% of e-waste generated globally was reported to be collected and correctly recycled. Comparing the data, European countries have the highest e-waste formally collected, which is not only related to the economy. The USA and China collect 15% and 16% of their e-waste. On the other hand, Australia and Brazil have similar GDPs and have completely different collection rates (11% and 0%, respectively) (Baldé et al. 2021a, b, c, d, e, f, g).

The difference relates to implementing national policies focused on e-waste, which is the case in high-income countries. European policies have an outstanding influence on the policies of emerging economies. On the other hand, these countries still need to work hard on creating and implementing public policies (Borthakur 2020; Castro et al. 2023).

Further chapters will discuss the history and current national policies of emerging (“[Global e-waste policies](#)” section) and developed (“[Developed countries](#)” section) countries for e-waste. Examples of different continents/regions were used—Latin and North America, Africa, Asia, and Oceania. Each country's ongoing generation and collection are presented and correlated with laws and legislations.

## Emerging countries

Among the countries in Latin America, only 38% have legislation, policies, or regulations strictly linked to e-waste.



Brazil is the largest country and the leading economy in Latin America. It is responsible for 40% of e-waste generated, producing twice as much as Mexico (1220 kt) with a 50% higher GDP (Forti et al. 2020).

Brazilian waste management is defined by the National Solid Waste Policy, which includes e-waste (LEI No 12.305, DE 2 DE AGOSTO DE 2010, 2010). According to this policy, all stakeholders of EEE (traders, importers, distributors, and manufacturers) must implement a reverse logistic system for e-waste, where the operation is defined by the sectoral agreement (MMA et al. 2019), recently replicated in the Decree N° 10,240 (DECRETO No 10.240, DE 12 DE FEVEREIRO DE 2020, 2020a).

Decree N° 10,240 considers 215 EEE for a reverse logistic plan divided into two phases. First, it was determined that the Performance Monitoring Group, manufacturers, importers, retailers, and distributors or to individually operate and manage the reverse logistic, as well as establish a financial mechanism for implementing and operationalizing; and the creation of a mechanism for control and monitoring. The second phase consists of the elaboration of communication plans to disclose the reverse logistic and the installation of drop-off or consolidation points involving 400 municipalities until 2025 (> 80 thousand inhabitants) with one collection point for every 25 thousand inhabitants (DECRETO No 10.240, DE 12 DE FEVEREIRO DE 2020, 2020b).

The current scenario of e-waste formally collected in Brazil represents the worst-case scenario in Latin America. Only 0.14kt of e-waste is formally collected. It occurs because this type of waste mixes with municipal solid waste and is further landfilled, making it impossible collection and recycle (Forti et al. 2020; The World Bank 2020a). For this reason, it is important to have specific reverse logistics and legislation for e-waste (Otoni et al. 2020). Decree N° 10,240 represents a significant advance in e-waste management. The aim is to achieve a 17% in collection rate by 2025, which is very ambitious considering the current rate.

South Africa, as well as Brazil, faces several issues with e-waste generation. First, the country needs legislation focused on e-waste, but increasing generation puts pressure on creating policies for the following years (Borthakur 2020). In 1991, Africa adopted the Bamako Convention, complementing the Basel Convention's focus on the continent. It restricts the importation and movement of hazardous waste into and within Africa. In addition, the Bamako Convention aims to protect the population and environment against indiscriminate waste dumping and uncontrolled incineration (Shittu et al. 2021).

The South African National Environment Management Act 107 of 1998 recommended the reuse and refurbishing of EEE. In recent years, on the other hand, the adoption of extended producer responsibility (EPR) has begun in South Africa, requiring the reverse logistics of e-waste to

producers and its treatment (Industrial Waste Management Plan) (Forti et al. 2018).

As occurs in Brazil, the National Waste Management Strategy in South Africa includes e-waste in the list of hazardous waste. The legislation is very restrictive, limiting the number of companies operating formally. Conflicts would result in informal recyclers. Frameworks focused only on environmental protection limit the handling of recycling companies, where e-waste would be used as raw material (Hankoon et al. 2018).

No national platform and obligations are imposed on recyclers for data about e-waste generation, receiving, and recycling, even though the country is considered the main pollutant in Africa. Despite their economic importance and rise in EEE consumption, there needs to be data about e-waste generation and policies in Africa (Borthakur 2020).

India is part of the BRICS group and has similarities among the countries, with 3.2 million tons of e-waste generated (2019) and a 1% of collection rate. However, unlike in Brazil and South Africa, electronic equipment put on the market is more than twice the e-waste currently generated (Baldé et al. 2019); it demonstrates that the amount of waste will increase more than twice shortly.

The e-waste policies in India started in 2008 with the guideline for management titled “Guidelines for Environmentally Sound Management of E-Waste.” Several stakeholders from the government and industries did it. The first legislation came in 2011—“E-waste (Management and Handling Rules),” complemented further in 2016 by the “E-waste (Management) Rules,” which implemented an EPR approach. In 2018, the targets of collection rates were revised and increased, despite the continuing dominance of the informal sector (Borthakur and Govind 2017; Borthakur 2020; Sengupta et al. 2022).

China, another country in the BRICS group, is the biggest e-waste producer in Asia and the world. The generation rate increases by 20% per year (Cao et al. 2018), and it is expected to achieve 28.4 million tons of e-waste in 2030 (Borthakur 2020). In addition to internal generation, China received waste from abroad—up to 350 million tons of e-waste within 40 years (Wong 2018). As a result, the government implemented the “Ban on WEEE for managing waste import” in 2000 (Patil and Ramakrishna 2020), making China the first Asia country to focus on a circular economy through public policy (Borthakur 2020).

- After that, several other important regulations emerged (Song et al. 2019):
- “Administrative measures on the prevention and control of environmental pollution by WEEE” (2008): obligated all recyclers and treatment plants to report an environmental impact assessment. Open-air incineration, dis-



solution in crude acid baths, and direct landfilling were prohibited;

- “Administration regulation for the collection and treatment of waste electronic and electrical equipment” (2011);
- “Administrative measures on the qualification of WEEE treatment” (2011): stated multiple channels for e-waste collection, obligated the labeling for reconditioned and remanufactured products, and subsidies for e-waste recycling and treatment companies. Producers and importers have to pay a fee for each EEE put on the market;
- “Administrative measures on the distribution of used electrical and electronic products” (2013): put efforts into the collection and sale of used EEE;
- “The restriction of hazardous substances in electrical and electronic equipment” (2016): aimed at reducing hazardous substances in EEEs.

However, as occurs in most countries in Asia, the collection of e-waste is dominated by informal workers, and the regulations aimed to strengthen formal collection. Nowadays, e-waste is considered a commodity, and users are well paid in the informal market for their waste to be refurbished and resold—e-waste collection is higher than the formal (30–90% and 7.8–24%, respectively) (Borthakur and Govind 2017).

From 2013 to 2017, the standard recycling rate increased from 38.6 to 62.2% due to legislations aforementioned (Song et al. 2019). Chinese policies are related to environmental and economic issues—e-waste is considered a secondary source (Borthakur 2020).

## Developed countries

In the USA, e-waste is considered non-hazardous, and its management is the responsibility of states and municipalities since there is no unified national legislation for it. In 2003, for instance, California adopted a management system where customers paid for e-waste treatment. In 2004, Maine implemented a law based on EPR, where responsibilities are shared with all stakeholders on e-waste management—the first state to adopt a household e-waste law (Shittu et al. 2021). The State of Columbia and 25 other states promulgated laws for e-waste management (Ilankoon et al. 2018).

There are two main federal initiatives in the USA: the US-EPA Sustainable Materials Management (SMM) (a partnership between EPA and manufacturing for collecting and “green” product certification) and the National Strategy for Electronics Stewardship (NSES) (environmentally safe e-waste management, to reduce its exportation to abroad, and new products concept) (Ilankoon et al. 2018).

Allied to state and federal policies, there are two certification programs for e-waste recycling plants throughout

550 industries across the USA: The Responsible Recycling Standard for Electronic Recyclers (R2) Sustainable Electronics Recycling International—SERI) and the E-Stewards certification program (Basel Action Network—BAN) (Shittu et al. 2021).

In Oceania, Australia is the leading country and one of the richest in the southern hemisphere, with a low population among the largest countries in the world. Comparing the amount of e-waste generated between the leading economies in the southern hemisphere, Australia generated 554 kt of e-waste (11% of collection rate). In contrast, Brazil, China, and India generated 2143 kt (0%), 10,129 kt (16%), and 3230 kt (1%), respectively.

In contrast to countries of the southern hemisphere, Australian policies about e-waste started in the 1990s with the National Waste Minimisation and Recycling Strategy. The goals, however, were not achieved ultimately (Pickin et al. 2018a). The National Waste Policy released in 2009 presented directions and strategies to improve waste management and supported policies and decision-makers with waste and resource recovery data reports.

In 2018, a new National Waste Policy focused on reducing, improving, and reusing waste toward a circular economy considering economic, social, and environmental aspects. As a result, the forecast is an 80% increase in the recycling rate in forthcoming years (Borthakur and Govind 2017).

The National Waste Policy regulates the disposal of e-waste for all stakeholders responsible for collection and recycling. In 2019, the government stated targets and actions (the National Waste Policy Action Plan) to implement the policy. Only South Australia and Victoria states banned waste to landfill, including e-waste. However, recycling rates rise with the support of education, infrastructure investment, and targets (Pickin et al. 2018b). As a result, up to 93% of the e-waste collected is recycled in Australia (Borthakur and Govind 2017).

Countries as part of the European Union follow the same directives. The first European directive about e-waste was released in 2003 (Directive 2002/96/EC), implementing the reverse logistics to improve the recycling and reuse rate (European Parliament 2003). In 2012, the directive was replaced by Directive 2012/19/EU to meet the EPR principle (European Parliament 2012a). The directive focused on reducing e-waste generation and improving the rates of reuse, recycling, and recovery, reducing landfill, and improving resource efficiency (European Parliament 2012b).

After regulations, the amount of e-waste collected in Europe rose. The Directive 2012/19/EU demanded a collection rate to increase from 4 kg per capita per year to 45% of the average weight of EEE placed on the market in the last 3 years (2016–2018). From 2019 onwards, the collection rate, according to the directive, must achieve 85%, representing 65% of the EEE placed on the market. As observed in



Table 1, the rate of e-waste formally collected in Italy and the UK is 34% and 57%, respectively.

The countries in Europe with the highest e-waste collection rate are the UK (871kt), Germany (772kt), France (750kt), and Italy (369kt). Considering the amount per capita collected, Liechtenstein, Austria, and Sweden are on top with 15 kg, 13 kg, and 12 kg, respectively.

In Italy, the e-waste guidelines for management are provided by the Legislative Decree n. 49 (2014), in compliance with the European Directive 2012/19/EU (European Parliament 2012b). The e-waste is collected by distributors and then sent to centers or treatment industries. Municipalities are responsible for the collection framework. In 2019, there were 5,196 collection points in Italy, where the municipality provided 84%, and citizens could deliver e-waste without fees (CdC RAEE 2019a).

The EEE producers are responsible from collection centers to the treatment industries, individually or by a consortium (Coordination Center). About 13 collective systems were operating in Italy in 2019 (CdC RAEE 2019b), where all stakeholders can participate.

The e-waste collection target is defined by the Italian Legislative Decree n. 49, the same described in the European e-waste Directive (2014). Despite that, collection rates in Italy must be improved over the years. In 2017, the target (45%) was not achieved—39% of EEE placed on the market was collected, representing 4.89 kg per capita of e-waste collected (CdC RAEE 2017).

Efforts resulted in the collection rate increasing. In 2018, the collection rate per capita achieved 5.12 kg; in 2019 increased by 10.45% (5.68 kg) (CdC RAEE 2019b). Nevertheless, improvements are required to achieve the 65% of collection rate, representing 16% of e-waste collected per capita (Croci and Colelli 2017).

Conversely, the UK has one of the largest e-waste collections—57% (Table 1). The reverse logistic system was elaborated after the first e-waste Directive (2002/96/EC) (Ongondo and Williams 2012). In 2013, it was released the

agreement with Directive 2012/19/EU, where e-wastes are collected in EEE retail shops.

The 2015 target of 4 kg per capita was achieved—10 kg of e-waste per capita. Between 2016 and 2018, the target of 45% defined by Directive 2012/19/EU was also achieved (Harper 2020; Langley 2020; Grant 2020). The e-waste regulations are enforced by the EA in England; the Natural Resources Body for Wales; the SEPA; and the Department of the Environment in Northern Ireland. Despite similar cases and the same legislation between European countries, several differences are observed in the UK and Italy, for instance. The COVID-19 pandemic and Brexit may raise the difference between them. The next chapter presents a discussion of EEEs production and generation of e-waste in light of the COVID-19 pandemic aiming attention at emerging countries.

### Consumption/production of EEEs and e-waste generation—focus on the COVID-19 pandemic

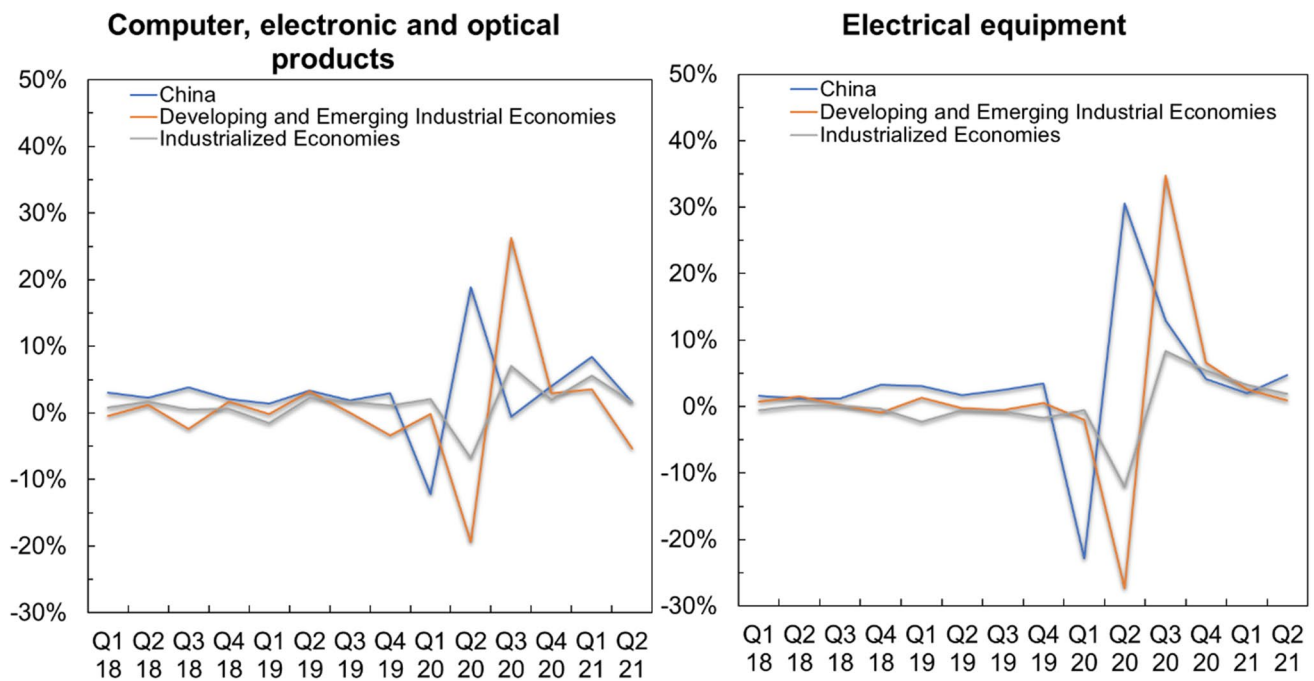
The pandemic changed life drastically on the planet, forcing humans to distance themselves to prevent the spread of the SARS-CoV-2 virus worldwide. This change led companies, universities, and schools to adopt home office methodologies and, consequently, the use of electronic devices to bridge this gap. In this sense, the amount of e-waste is expected to be impacted by this sudden change in life.

Figure 1 shows the estimated growth rates of computer, electronic, optical products, and electrical equipment manufacturing from the first quarter of 2020 until the second quarter of 2021. The forecast for 2020 and 2021 was the generation of 55.5Mt and 57.4Mt of e-waste, respectively (Forti et al. 2020). However, these projections did not consider the economic outcomes caused by the pandemic.

It impacts e-waste where shrinkage of 4.9 Mt in EEEs acquired during the first three quarters of 2020 and,

**Table 1** GDP (in US\$) in different countries and their e-waste generation (2019) (The World Bank 2020b)

Country	GDP (in a million US\$) (2019)	Generation (kt)	Generation (kg per capita)	Formally collected (kt)	E-waste formally collected (%)	National legislation/policy or regulation
Australia	1,392,680.59	554	21.7	58	11	Yes
Brazil	1,839,758.04	2143	10.2	0.14	0	No
China	14,342,902.84	10,129	7.2	1546	16	Yes
India	2,660,245.25	3230	2.4	30	1	Yes
Italy	2,001,244.39	1063	17.5	369	34	Yes
South Africa	351,431.65	416	7.1	18	5	No
UK	2,827,113.18	1598	23.9	871	57	Yes
USA	21,374,418.88	6918	21	1020	15	Yes



**Fig. 1** Estimated manufacturing growth rates of computer, electronic and optical products, and electrical equipment (% compared to the previous quarter) (UNIDO Statistics 2020a, b, c, d, 2021a, b)

consequently, a likely reduction in e-waste generation in the future due to the health crisis (Baldé and Kuehr 2021).

The pandemic highlighted the disparity in consumption in EEE and available data: low- and middle-income countries presented the most significant reductions in consumption compared to other countries (Baldé and Kuehr 2021). Furthermore, the number of countries with datasets for analysis per region varied, which could be related to e-waste policy differences among nations and difficulties in collecting data during this period. Additionally, facing COVID-19, different countries have adopted different prevention and control policies, which would increase the demand for EEE in some countries.

The lockdowns during the first phases of the outbreak also impacted the supply chains of key materials for EEE production. In addition, the pandemic revealed the increasing vulnerability of supply chains that provide crucial raw materials for manufacturing electronics due to social, geopolitical, and technical disruptions. The results obtained by the authors suggested that rare earth elements and some technology-critical metals (such as Co, Ga, and In) had high risks for supply chain vulnerabilities (Althaf and Babbitt 2021).

Regarding these metals, China is the top producer of Ga, In, and Nd (rare earth elements), and the second producer of Co, being the Democratic Republic of the Congo as the top producer (Royal Society of Chemistry, 2021). The early lockdown of China and the pandemic's social impact corroborates the supply chains' vulnerability (Althaf and Babbitt 2021). For

example, in November 2021, the prices of Co, Ga, In, and Nd increased 91.2%, 27.9%, 37.0%, and 67.9%, respectively, compared to the beginning of 2021 (Trading Economics 2021).

The manufacturing production output during 2020–2021 also suffered the impact of the global health crisis. China, which accounted for 28.7% of the global manufacturing output in 2019 (Statista 2021), was the first country to establish lockdowns as a control measure to prevent the dissemination of the SARS-CoV-2 virus worldwide. Regarding the manufacturing of computers, electronic and optical products, and electrical equipment, production was greatly impacted at the beginning of the pandemic (Fig. 1). However, improving control policies for disseminating the virus led to the reopening factories and other facilities. As a result, the economies started to show signs of recovery. However, new variants could bring more uncertainties to supply chains and marketing.

Further, “**Importance of recycling**” section states the importance of e-waste recycling, considering the circular economy and challenges for sustainable development to turn waste into wealth.

## Importance of recycling

Global waste generation is estimated to double by 2050 and triple by 2100 compared to 2016 data (Ferdous et al. 2021). Thus, it is necessary to study alternatives for recycling and

reuse, increasing the cycle of materials used and reducing the extraction speed of natural resources to meet industrial demand (Beccarello and Di Foggia 2018).

Currently, one of the greatest generators of solid waste is post-consumer EEEs (Shittu et al. 2021). Many e-waste and batteries are disposed of with domestic or industrial waste, resulting in material losses (Pekarkova et al. 2021). This scenario varies according to the country; however, an efficient management system still needs to be updated in some regions.

The e-waste generally has a short useful life, as new models with new technologies emerge daily (Işıldar et al. 2018). Production and consumption have grown a lot in recent decades, transforming the electronics industry into one of the most important industrial sectors (Pollard et al. 2021). It tends to generate many obsolete materials that are interesting from an economic point of view and worrying from an environmental perspective (Shittu et al. 2021).

Among the main materials contained in electronics, it can be mentioned base metals (such as Cu, Fe, Al, Zn, and Ni), precious metals (such as Au, Ag, Pd, and Pt), and critical metals (such as rare earth elements, Li, Co, and In) (Dias et al. 2016a; München and Veit 2017; Marra et al. 2018; Cenci et al. 2021a; Andrade et al. 2022a). The simple presence of these metals in residues already demonstrates the importance of correct disposal to allow their reuse. Allied with this, many of these metals have higher content in e-waste than their primary sources (Andrade et al. 2022a, b; Botelho Junior et al. 2019a, 2021b; Botelho Junior et al. 2021d; Cenci et al. 2021a; Dias et al. 2016a; Martins et al. 2021; Perea et al. 2021).

The supply of these metals to produce EEEs also corroborates the strategic recycling issue. For example, Zhang et al. (2017) demonstrated that 14% of Pd, 9.7% of Au, 42% of Ag, 30% of rare earth elements, 37% of Co, and 31% of Li extracted globally from mining in 2014 were used in the manufacture of EEEs (Zhang et al. 2017).

Brazil recently listed the metals considered critical and strategic for the country, where the vast majority can be found in e-waste as a secondary source (2021). Similarly, the European Union has also listed the critical raw materials, and several metals found in electronic waste are included in this list (European Commission 2020). The USA and China also have a list of critical/strategic metals (Botelho Junior et al. 2021d; Martins et al. 2021).

In addition to the intrinsic value of the metals in all electronics, an environmental/social issue must also be evaluated to measure the importance of recycling. This is because electronics not only have metals of economic interest but also contain toxic metals, such as Pb, Cd, Hg, Cr, and flame retardants (Cardamone et al. 2021).

Thus, their correct disposal, preferably with a recycling step, would prevent these hazardous components from being

exposed to the environment. The vast majority of the base, precious, and critical metals leave significant impacts in their primary extraction (Méndez et al. 2021). Decreased primary extraction rates with increased recycling rates could reduce the environmental impacts.

The social issue is also closely linked to the development of recycling processes. Therefore, it could bring the same benefits as any other type of industry—job creation, taxes, development of supply chains, and new technologies (ILO 2019; Panchal et al. 2021).

This is even more relevant for emerging countries that lack formal jobs, the development of technology-based industries, and income generation for society. In such countries, these residues are commonly landfilled, burned, or even deposited directly on the environment without any control, causing soil, water, and air pollution and diseases in the population close to these places (Stubbings et al. 2019). Moreover, the materials are no longer recyclable or reusable.

Meanwhile, new sources of raw materials are increasingly scarce and difficult to find, as well as places that can be used to dispose of waste at a low cost. As a result, the importance of recycling grows in proportion to all these problems mentioned by the mismanagement of e-waste.

“Collection and recycling technologies” section depicts the current scenario for recycling technologies applied to e-waste, considering the consolidated and emerging technologies (“Consolidated and emerging technologies for e-waste recycling” section) and processes in emerging countries (5.2). In this case, the examples used were countries from different continents/regions—Brazil was the example from Latin America (5.2.1), South Africa from Africa (5.2.3), and China and India from Asia (5.2.3 and 5.2.4, respectively). Further, the industrial processes for e-waste recycling are depicted in 5.2.5.

## Collection and recycling technologies

### Consolidated and emerging technologies for e-waste recycling

EEEs can have several components: printed circuit boards (PCBs), printed wiring boards (PWB), semiconductors, magnets, lithium-ion batteries (LIBs), housing, casing, cables, wires, and screens as liquid crystal display (LCD). Electronics have in their composition all classes of materials—metals, ceramics, and organic materials like polymers. Figure 2 shows a general flowchart of materials, components, and processes that starts from e-waste generation through disassembly, component segregation, and recycling into raw materials. For instance, e-wastes such as components of computers, mobile phones (or cellphones), tablets, and TV are the first disassemblies to release the components,



which may carry out manual, semiautomatic, or automatic. Further, recycling processes are performed to separate and recover the primary materials—metals, ceramics, and polymers. Finally, all of them will be treated to obtain new products.

The metallic fraction comprises base, precious, hazardous, and rare earth elements. The ceramic fraction can contain silica, alumina, alkaline earth oxides, mica, and barium titanate. Organic materials or nonmetallic fractions can have polymers with flame retardants, epoxy resin, and fiberglass (Cenci et al. 2021b).

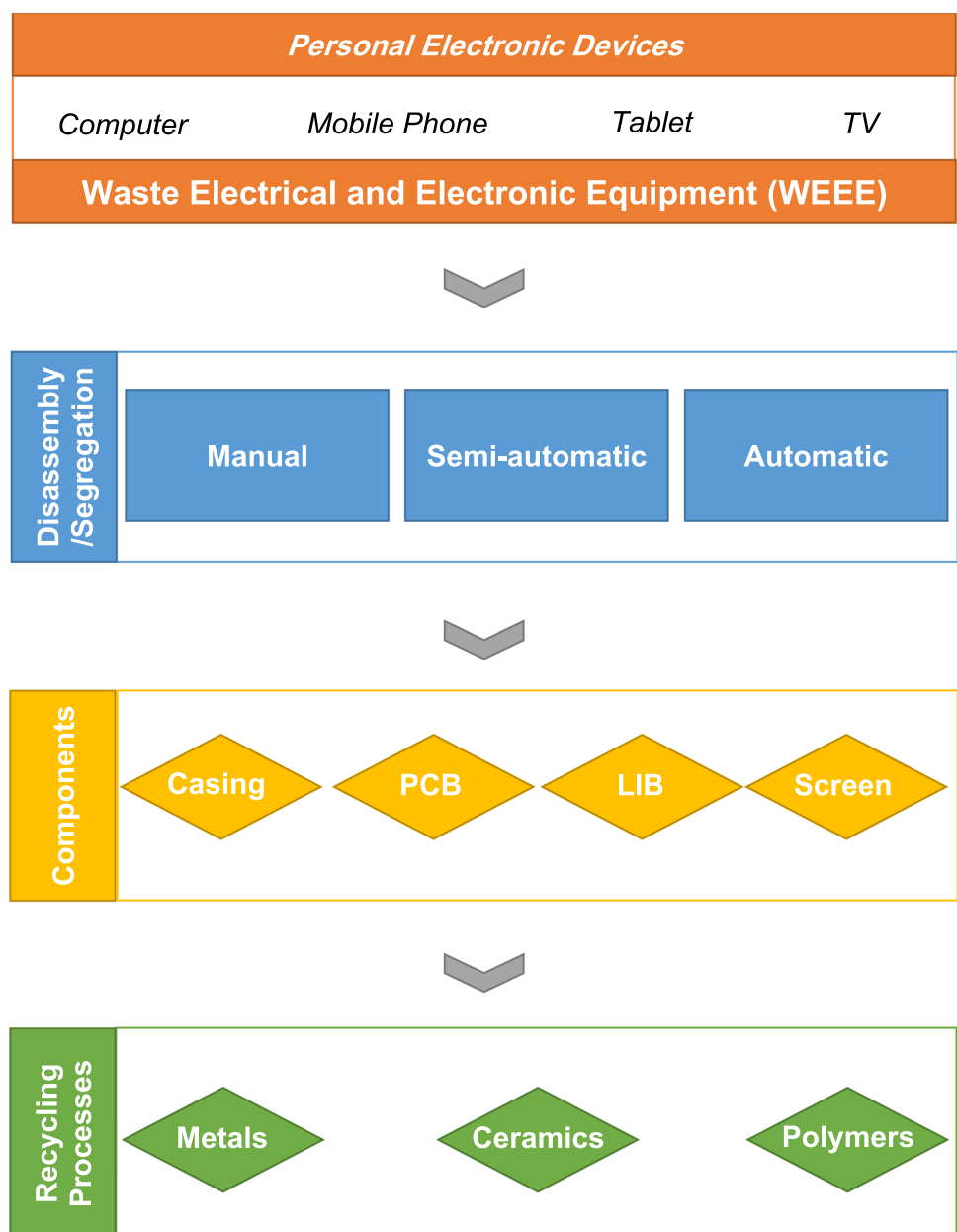
Since there are various materials, e-waste recycling requires integrating different methods. Figure 3 presents an overview of the different recycling processes for e-waste.

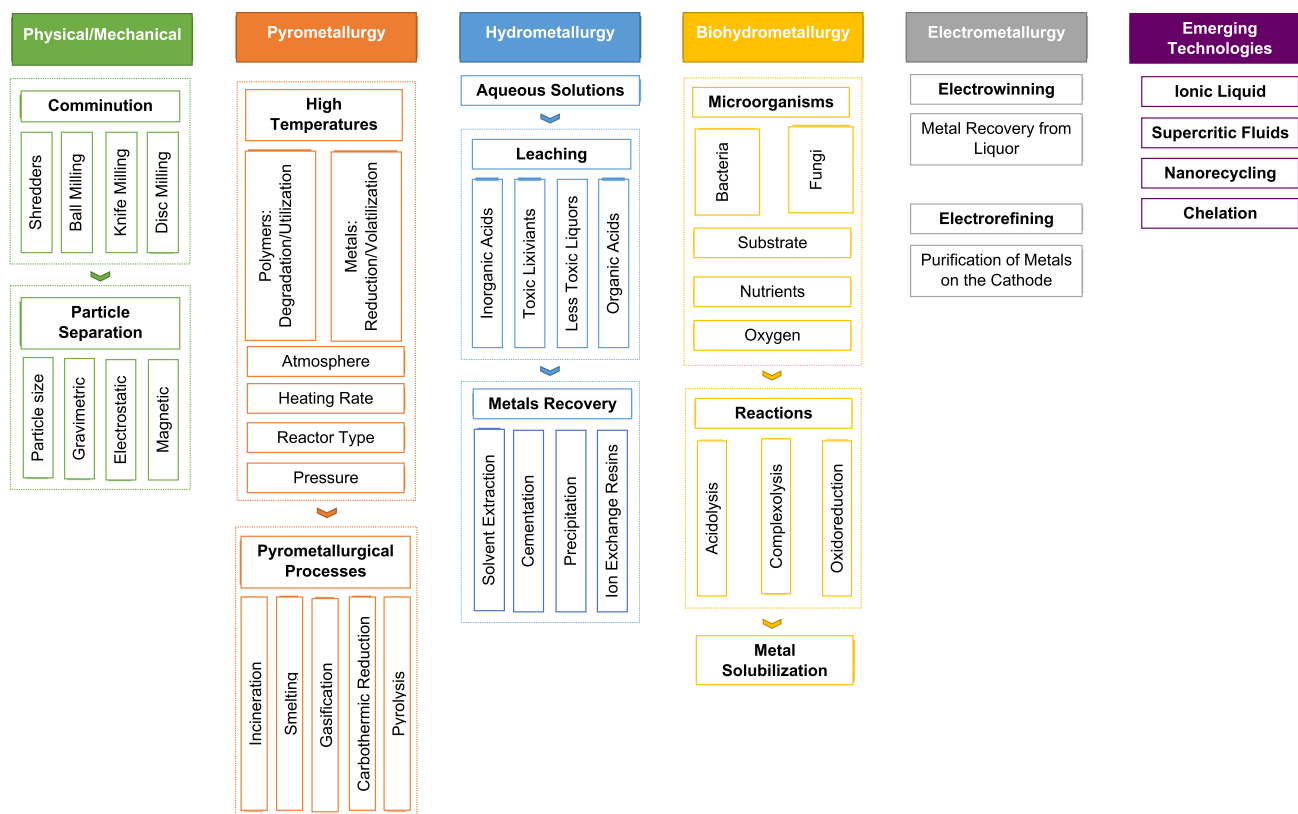
Most are based on physical/mechanical, pyrometallurgical, hydrometallurgical, biohydrometallurgical, and electrometallurgical processes (Ayode Otitoju et al. 2020; Baldé et al. 2020; Islam et al. 2021a; dos Santos et al. 2022; Andrade et al. 2022b). Details of each process are further presented.

**Physical processing**

Physical/mechanical methods are called "first-stage recycling," which directly influences achieving a high-quality final recovery product. They have been applied as pretreatment of e-waste to release, concentrate, and different materials with higher value. Polymers and ceramics are separated from the metallic fractions, and specific metals are

**Fig. 2** Flow of materials, components, and processes after disposal of e-waste for recycling





**Fig. 3** Recycling processes applied to e-waste and their main techniques/technologies

concentrated in different fractions (Hubau et al. 2019; Martins et al. 2020b; Pinheiro et al. 2021; Premathilake et al. 2023; Vasconcelos et al. 2023). The method is important to prepare the material for further chemical/thermal treatment.

The disassembly of e-waste can be useful for selecting more valued components and removing hazardous ones from the process (Kaya 2016; Thakur and Kumar 2020). However, manual dismantling requires a significant workforce. It is a challenge to economic viability in both developed and emerging countries because of the valorization of labor (Ilankoon et al. 2018; Islam et al. 2021b).

There are also semiautomatic and automatic disassembly units, but the equipment and sensors have a high economic cost (Işıldar et al. 2018). Usually, comminution equipment such as shredders, balls, knives, and disk milling is used to decrease the particle size (Ghosh et al. 2015).

After the comminution, particle fractions can be separated by sieving, gravity-based system (density-based fluid bed separation), magnetic and electrostatic separation. Physical/mechanical separation processes have lower capital costs, are easier to operate, and do not require chemical reagents and high temperatures. However, they lose material and generate dust and noise pollution. These methods can also reduce the recovery of metals in lower concentrations, such as precious and critical elements (Işıldar et al. 2018;

Marra et al. 2018; Martins et al. 2020a; Andò 2020; Cenci et al. 2021a, b). For instance, in recycling LIBs, the valuable components from the cathode material present in the e-waste are concentrated before the recycling process by milling and separation by particle size. In addition, plastics and metallic aluminum from the case (external structure) were separated before acid leaching (Guimarães et al. 2022).

Then, the material might be treated as "downstream recycling," such as pyrometallurgy, hydrometallurgy, biohydrometallurgy, and electrometallurgy. Pyrometallurgical processes accept different types of waste with minimal initial treatment. It includes a variety of techniques: incineration, smelting, gasification, carbothermic reduction, and pyrolysis. The most common objectives are the degradation and utilization of the polymeric fraction as a carbon source and the reduction or volatilization of the metallic elements for subsequent recovery (Zhang and Xu 2016).

### Pyrometallurgy

As reported by Faraji et al. (2022), the pyrometallurgical process has the potential to be both a rapid and large-scale recycling route. The flowchart process, after pretreatment, may be smelting (emission of  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{Zn}$ ,  $\text{Sn}$ , and  $\text{Hg}$  and production of slag composed of  $\text{CaO}$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and

FeO<sub>x</sub>), electrorefining (to produce Cu), and anode refining (for production precious metals as Au, Pt, and Ag). The separation of plastics and ceramics from metals is fast, requiring high energy consumption and gas release (Faraji et al. 2022).

Carbothermic reduction is employed for polymers degradation, reduce the metals as metallic, use of base metal as a collector of minority metals, and recovery of other elements in the slag and refining products (Ilankoon et al. 2018; Avamaa et al. 2018; Kaya 2019).

Pyrolysis is another pyrometallurgical technique in decomposing organic matter at high temperatures in an inert atmosphere. The main process variables are temperature, heating rate, residence time, reactor type, pressure, and catalysis. The pyrolysis treatment produces a liquid and gaseous fraction with high energy value and/or rich in valuable chemicals and a solid fraction with a concentration of metals of interest with a minimized carbon fraction. In the solid fraction, metals and ceramics remain mostly unchanged and concentrated (Al-Salem et al. 2017; Diaz et al. 2018; Du et al. 2018, 2019; Flerus et al. 2019; Jadhao et al. 2020; Abdou et al. 2021).

Chu et al. (2022) used calcination as a pretreatment before recovering metals from PCBs through bioleaching. According to the authors, it was used as an alternative route to provide a process with less energy consumption, less hazardous, flexible operation, and more cost-effective than pyrometallurgy. So, the thermal route has used a pretreatment with comminution (Chu et al. 2022).

These processes have some limitations: high cost, large solid waste generation, emission of toxic gases, need for large scale, and low selectivity for recovering precious and critical metals. Furthermore, it is required hydrometallurgical and electrometallurgical steps (Cenci et al. 2021b).

## Hydrometallurgy

Metals from e-waste can be solubilized by hydrometallurgical treatments (Fig. 3) using aqueous solutions, such as leaching with inorganic acids. Nitric, sulfuric, and hydrochloric acids are traditional leaching agents which can be used combined with hydrogen peroxide. Organic acids have also been explored (Botelho Junior et al. 2021a; Garcia et al. 2021; Hammadi et al. 2017; Jadhav and Hocheng 2015; Martins et al. 2021; Takahashi et al. 2020).

Several studies for the recovery of precious metals, such as Au and Ag, have been focused on cyanide replacement due to the environmental risks for less toxic lixivants, such as thiourea, ferrous sulfate, halide, and iodide (Zhang et al. 2012; Chauhan et al. 2018; Wang et al. 2020).

Following leaching, the solution is treated for separation and purification, and the metals can be recovered by solvent extraction, cementation, selective precipitation, and ion

exchange (Botelho Junior et al. 2019a, b, c, d; Botelho Junior et al. 2019b, 2021c; Dias et al. 2016b; Kaya 2019).

The advantages of hydrometallurgical methods are high selectivity to extract metals; high recovery rates of precious, critical, and base metals; and low dependence on the scale of operation. On the other hand, hydrometallurgical techniques generate large amounts of toxic effluents and sludge (Botelho Junior et al. 2019c; Botelho Junior et al. 2018; Ilankoon et al. 2018; Işıldar et al. 2018; Islam et al. 2020; Kaya 2016; Perez et al. 2020). Moreover, as plastics and ceramics are important materials in e-wastes, these materials may be recovered after leaching. The leaching of PCBs removes the metals from the solid material, and the leaching residue is composed of ceramic (mainly glass) and polymers, which may be separated by physical separation (density separation) (Andrade et al. 2022b). In the case of Li-ion batteries, the leach residue is composed of graphite and plastics, and physical separation may recover the plastic fraction (Guimarães et al. 2022). For this reason, such a route may improve the materials' circularity.

## Biohydrometallurgy

In the biohydrometallurgical process (Fig. 3), microorganisms solubilize metals from e-waste by acidolysis, complexolysis, and oxidoreduction reaction (Utamura et al. 2017). However, adapting microorganisms to the process to achieve high efficiency is a challenge, such as suitable substrate, nutrients, and oxygen (Veit and Bernardes 2014). For instance, Cu, Ni, and Al have been extracted by chemolithoautotrophic bacteria, such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* (Hong and Valix 2014).

To solubilize precious metals, *Chromobacterium violaceum* and *Pseudomonas aeruginosa* have also been used (Ilyas et al. 2013). Co and Li have been solubilized from spent LIBs by mixed acidophilic bacteria (Xin et al. 2009). There is fungal bioleaching, in which acids are organically excreted, occurring acidolysis, complexolysis, and redoxolysis. Fungal bioleaching has been explored as *Aspergillus niger*, *Aspergillus ficuum*, *Aspergillus terreus*, *Penicillium simplicissimum*, and *Penicillium tricolor* (Desouky et al. 2016).

Electrometallurgical methods have often been used at the end of the process. For example, electrowinning has been applied to recover metals from the leach solution. Dissolved metal is recovered by applying an electric potential to induce electrochemical reactions. Another electrometallurgical technique is electrorefining, which is used to purify metals to achieve desired high purity levels. The metallic anode of intermediate purity (95–99.5%) is electrolytically dissolved in the cell, which is then electrodeposited onto the cathode with higher purity (99.9%). Electrorefining is

like electrowinning, but consumes a fraction of the energy required since the cell voltage is lower (Segura-Bailón and Lapidus 2021).

Although conventional e-waste recycling techniques are feasible and result in higher metal recovery efficiencies, these methods still need to be more eco-friendly. As a result, effluents and toxic gases are generated, causing corrosion and excessive energy consumption. Hence, new greener techniques are being developed (Fig. 3), which promote safer, more efficient, and closer to global harmless processes. The most cited research within these greener techniques is named ionic liquids (ILs), supercritical fluids (SF), nanotechnology, and chelation (Fig. 3).

Chelation comprises the metal-ion stable complexes formation soluble in water. A few organic molecules, such as EDTA (ethylenediaminetetraacetic acid), were already employed to recover metals from PCBs (Jadhao et al. 2016) and batteries (Sharma et al. 2017). The advantages are low temperature, non-corrosive, biodegradability properties, and reuse of chelating agent after metal extraction; however, the heterogeneous chemical reactions are pH-dependent (Sharma et al. 2017; Jadhao et al. 2020).

ILs are organic liquids that only contain ions at high temperatures ( $> 100\text{ }^{\circ}\text{C}$ ) which can comprise direct leaching, separation, cementation, and electrowinning. Advantages such as nonflammability, chemical stability, and low volatility are highlighted. Attempts to recover Cu from PCBs (Chen et al. 2015) with nearly 100% efficiency were reported.

SF is also in development for e-waste recycling. These substances remain in a single phase above the critical temperature ( $T_c$ ) and pressure ( $P_c$ ), having a gas-like diffusion rate and viscosity. It was reported that  $> 88\%$  of Cu extraction from PCBs with supercritical  $\text{CO}_2$  combined with  $\text{H}_2\text{SO}_4$  and  $\text{H}_2\text{O}_2$  as co-solvents (Calgaro et al. 2015). Also, Ag and Pt were recovered from PCBs with high efficiencies in only 10 min (Liu et al. 2016). Its development in e-waste recycling has achieved important results. However, this technology demands elevated costs and difficulty in scaling up.

Carbon nanostructured materials have been studied due to the high oxidation surface with a more hydrophilic surface. These compounds promote sorption through electrostatic force. Different allotropic forms of carbon can be used, such as graphene oxide and carbon nanofibers or dots. La and Dy from aqueous solution were adsorbed in multiwalled carbon nanotubes and subsequently desorbed at low pH showing promising results (Koochaki-Mohammadpour et al. 2014).

## Recycling in emerging countries

This section briefly describes the current scenario of the recycling routes present in emerging countries considering the countries' regulations and how they could be improved.

For this, recycling methods are divided into first-stage methods and downstream methods.

As mentioned in “Emerging countries” section, developed and emerging countries generally must face a huge informal sector relying on hazardous and polluting techniques such as outdoor burning and artisanal acidic leaching. The magnitude of the informal sector is difficult to measure, but it is consolidated and comprises most of the e-waste collected (Ghosh et al. 2016). Therefore, the most urgent initiative is to bring these actors into formality to promote social and health security and eco-friendliness.

### Brazil

In Brazil, the main model for formal recyclers to gather e-waste is through a partnership with other companies. This may assure a permanent and known raw material supply in suitable conditions. Other models, such as direct handover and private collectors, also play an important role. Formal recyclers rely on something other than hand pickers as significant material providers, indicating that the informal sector can operate in the entire cycle. There needs to be a stronger connection between the two sectors. Regarding the tools and processes that recyclers apply to the recycling treatment, Brazilian companies only operate at the first stages (Dias et al. 2018).

Pieces of materials easily to separate (mainly copper wires, aluminum and steel parts, and a range of polymers) are removed and sold domestically. However, complex parts such as PCBs and computer memories mainly flow to foreign companies to recycle by downstream processes. About 89% of the Brazilian recycling companies only undertake manual dismantling steps without any process of enrichment. The destination of these complex and valuable parts is mainly the USA and Europe (Xavier et al. 2021).

### South Africa

South Africa needs a stronger formal sector operating in e-waste recycling. The main challenge the recyclers faces is the availability of raw materials, forcing recyclers to rely on partnerships with governments to collect e-waste. (Approximately 80% of the formally collected is from government initiatives.) According to the authors, the activity of the recyclers is limited to dismantling and shredding, separating some valuable parts, and landfilling others (Ghosh et al. 2016).

In 2017, a report detailed the landscape of e-waste recycling routes in a country like Brazil. It identified 27 companies directly working on e-waste recycling; only two undertake downstream recycling activities. Technological and skill issues are not the main limiting factors to the development of a downstream industry but the access to adequate

volumes, economic incentives, and the organization of a productive chain (Lydall et al. 2017).

Companies mainly undertake dismantling processes, separating some simple components for the internal market and selling the complex ones to Asia and Europe. As a result, about 90% of the PCBs are exported. Additionally, e-waste recycling is not profitable for small companies, is not a self-sufficient sector, and has low employment rates (Ichikowitz and Hattingh 2020).

## China

Unlike other emerging countries, China has issued many policies and incentives to better channel e-waste into the formal routes (formal and informal sectors are comparable in importance, and compared with the theoretical generation, the standard recycling rate is approximately 60%) (Ghosh et al. 2016).

It has implanted a collection model based on the EPR approach, which made a vibrant recycling industry flourish, from small enterprises to the largest capacity and most updated downstream industries among all emerging countries (Awasthi and Li 2017).

Usually, household e-waste is primarily collected by the informal sector, while businesses and public bodies are sent to formal routes. By the end of 2014, China has already constructed 49 urban mining centers, which yield valuable materials (such as Cu and Au) below world market prices (ILO 2019), bringing informal actors to formality, bridging a connection between recycling companies and other industries (Ignatuschtschenko 2017).

Complex components are processed within the country, not being exported. Indeed, the recycling capacity of China could exceed the e-waste generated in the country, despite the increment of illegal transboundary shipment of e-waste that feed both the formal and informal sectors (Ghosh et al. 2016).

## India

The informal sector dominates the Indian scenario of e-waste recycling. Studies report a fraction of 95% of e-waste entering the informal system and being manipulated improperly (Ghosh et al. 2016; Awasthi and Li 2017), including, in some cases, child labor, widespread respiratory ailments, and severe environmental contaminations (Pathak et al. 2017). The informal sector is active in all the stages of the recycling chain, from collection to the recovery and selling of valuable material. Over 2000 informal recycling sites are reported (Borthakur 2020; Jeyaraj 2021).

Collectors and small dealers carry out primary segregation and sell the profitable parts to big traders, who decide the fate of the materials. Finally, recyclable materials are

recovered by crude methods and sold to industries (Ghosh et al. 2016; Awasthi and Li 2017). It is also important to mention that there is a huge market of reused and refurbished electronic devices in place in India, which buy EoL devices from consumers and collectors and re-sell them (Priya Jeyaraj 2021).

The Indian government released, in 2016, regulations to implement an EPR approach in the management of e-waste, with collection targets for the formal system (Pathak et al. 2017; Borthakur 2020). The expectation is to achieve an increase in the flow of e-waste into the formal chains (Panchal et al. 2021). Indeed, the Indian scenario presents the opportunity to integrate the formal and informal systems (Sengupta et al. 2022), especially providing existing formal recyclers with proper and sufficient materials. The country has 468 active formal recycling industries (Sengupta et al. 2022), some performing modern downstream processes (Shirodkar and Terkar 2017). However, Shirodkar and Terkar (2017) and Jeyaraj (2021) reported that these facilities commonly face a shortage of raw material due to insufficient proper collection and require authorization for importing e-waste from other countries (Shirodkar and Terkar 2017; Jeyaraj 2021).

Generally, most formal recyclers rely only on first-stage activities for developing economies since downstream enterprises are technologically complex and need large scales. The financial viability of the formal system is still a challenge, being less profitable than the informal one due to technological, social, and environmental obligations. Another concern is that the downstream industries of the formal sector cannot compete with the higher profitable informal collection system, resulting in insufficient e-waste to achieve adequate efficiencies. (They frequently operate below the maximum capacity.) As observed, China is constructing a robust e-waste recycling system, but still has a long way to achieve high efficiencies in recovering valuable and strategic materials. The downstream industries of the formal sector need better cooperation and incentives from the public and private stakeholders. The possible solution passes by integrating the informal collection system into the formal recycling scheme (Ignatuschtschenko 2017).

## Benchmark recycling routes

As aforementioned, each emerging country has its own challenges, and all of them must allocate many efforts to achieve the desired efficiency in recycling e-waste. At this point, it is important to highlight the benchmark downstream companies worldwide as good examples of what can be done in emerging countries.

Economic and strategic factors play an important role in determining recycling routes, as these are the key factors that maintain and grow the activities (Iankoon et al. 2018; Cenci



et al. 2021b). Metals are valuable raw materials for high-tech industries, minimizing the dependence on primary minerals and the global market. An adequate recycling route must be aligned with sustainable development goals. In this sense, efficiency in materials recovery and reduced energy use and waste generation are essential parameters. Some large-scale examples of consolidated e-waste recycling industries which combine relevant economic and environmental aspects and are considered the most advanced (Botelho Junior et al. 2021a, b, c, d; Cenci et al. 2021b; Işıldar et al. 2018; Takahashi et al. 2020).

Umicore, located in Belgium, processes approximately 25,000 tons of e-waste per annum (10% of the total input) (Ilankoon et al. 2018). The company has many sub-routes (for batteries, catalysts, jewelry, and others) applying diverse approaches and can recover 20 different metals (Veit and Bernardes 2014). The company receives devices without batteries for electronics and valorizes mainly Cu, Ag, Au, and Pd. About 95% of efficiency is achieved for precious metals. The process is based on two integrated parts: a lead blast furnace and a copper IsaSmelt furnace (Ilankoon et al. 2018).

After the pyrometallurgical steps, a complex hydrometallurgical refining route follows (Veit and Bernardes 2014). The plant contains a complex off-gas treatment, which includes a sulfuric acid regeneration from the emitted SO<sub>2</sub> and can sell the blast furnace residue as a substitute for sand in concrete (Cenci et al. 2021b). The company has been considered unique in its approach to efficiency and sustainability and adopts goals such as improving energy efficiency and becoming carbon neutral (Kaya 2019).

Other companies have similar approaches to recycling. For example, in Quebec, Canada, Xstrata (known as Noranda smelter) can process 840,000 tons of materials per annum (15% being e-waste). Boliden, in Sweden, and Aurubis, in Germany, are other examples. However, these companies focus on the significant materials (mainly Cu and Pb), being Umicore the most flexible plant to valorize e-waste to recover minor elements (Kaya 2019).

Some parts of the materials need to be recovered along the process for all these downstream industries. For example, polymers are used as fuel and reducing agents, and aluminum is lost in the smelter slag. Indeed, Umicore advises its suppliers to preferably separate aluminum (Veit and Bernardes 2014) and iron parts before sending the material to the company as much as possible. This exemplifies the importance of first-stage methods in promoting efficient recycling routes. In this sense, Kaya (2019) described the recycling route employed by MGG in Austria. The group runs a polymer factory (PP, HIPS, ABS, and PC/ABS), in which the main raw materials are end-of-life plastics from e-waste. The group handles first-stage and downstream methods (generating enriched fractions of different

materials), such as collection, depollution, shredding, magnetic, density, optical, and electrostatic separation. It sends concentrates to smelters to recover Cu and precious metals. The overall recovery rate is approximately 85%.

All evaluated emerging countries need help dealing with the informal collection system, and there need to be more raw materials to foment formal recycling industries. Thus, the main challenge is constructing a robust collection system that adequately feeds formal first-stage recyclers and, posteriorly, developing a downstream industry to valorize materials within the countries' borders.

All benchmark companies operate in a global market of suppliers and stakeholders (they receive and sell materials to the entire globe), demonstrating that there is demand and opportunities for developing such an industry. E-waste must be faced with valuable resources as it can be a source of strategic and precious materials. Especially for emerging countries, recycling industries can be essential in promoting other industries, such as electronics and automotive.

The COVID-19 pandemic has shown the importance of the materials provided through safe and stable market routes. For example, during the pandemic, the automotive and electronic industries were severely impacted by the lack of semiconductors, as China prioritized its internal market. Indeed, the market of many strategic materials is dominated by a few countries, resulting in high supply risks.

## Discussion and future perspectives

The problem of waste generation challenges the global population to achieve a more sustainable and circular economy. The increasing consumption rate of electronics has pressured the extraction of primary sources. In addition, the consumption of EEEs was impacted by the pandemic. Consequently, future e-waste generation will bring several environmental and social implications. Indeed, the behavior changed due to the COVID-19 pandemic for remote work, and studies caused an increase in waste generation. For instance, organic waste generation increased by 13.3% in comparison to 2019, allied to the fact that many recycling industries had to close or reduce their industrial capacities for social distance (Naughton 2020). Another example is the growth of single-use plastic and personal protective equipment consumption (Lima et al. 2022).

The pandemic also affects EEEs consumption (to supply remote work and studies), which will raise the e-waste generation in the further years. Considering the lifespan of a computer of 5 years (Kumar et al. 2017) and the generation is threefold higher than any other waste, the amount of global e-waste will achieve 74.4 Mt before 2030, as previously expected (United Nations 2021). Thus, urban mining comes to provide a suitable destination for e-waste.

However, challenges for collection and recycling still need to be completed, especially in emerging countries.

Developed countries have the world's most extensive e-waste collection and recycling rates. As aforementioned, it occurs not only due to economic power. Social inequality in emerging countries may be one of the causes as well. For example, the GDPs of Brazil and Australia are similar in the generation of e-waste per capita twice (10.2 kg and 21.7 kg, respectively) and more than 400-fold the difference in collected waste (0.14 kt and 58 kt, respectively). Nevertheless, the collection model of the formal recyclers, based on partnerships with other companies, can ensure a permanent supply of raw material, making Brazil an opportune market in Latin America that can be further explored by downstream industry.

Developed countries, such as Australia, the USA, China, and the European Union countries, have extensive and strong policies for e-waste involving all stakeholders. Emerging countries should join efforts to create and put into practice national policies and regulations focused on e-waste toward a circular economy. China is successfully bringing informal actors into formality and closing the materials cycle within its borders through recycling. An efficient collection system and construction of a downstream industry are essential steps that can be studied and adapted for other emerging countries. As observed, solid national policies focused on e-waste are the key to achieving high collection and recycling rates. Due to the impact of health emergency caused by the ongoing pandemic (COVID-19), the need for more attention to the e-waste policies in medical equipment—management and recycling—was observed.

The pandemic affected the production of EEEs worldwide, highlighting the fragility of supply chains for key materials for producing this equipment. Additionally, uncertainties about the future of manufacturing due to the new mutations of the SARS-CoV-2 virus have been followed because it could jeopardize the delicate progress achieved. The forecast for the e-waste generation in the 2020–2021 period will likely suffer changes since different countries have adopted different prevention and control policies, which would lead to an increase in the demand for EEE in some countries. However, the higher consumption/production of EEEs does not mean a higher production of e-waste in a year. Furthermore, longer researches on this topic are crucial to developing strategies for e-waste management in the following years.

Regarding the recycling chains, emerging countries suffer from an uncontrollable informal sector (actuating in the first stages of the recycling chain) which is generally more profitable than the formal one. In general terms, it shows that the activity of these recyclers can be run by itself, and the focus for the emerging countries could be on creating channels to

bring these informal actors into formality through enforcing regulations and economic incentives.

Indeed, this is the most urgent initiative in promoting social and health security and eco-friendliness. However, developing downstream industries in these countries is also a big challenge. Some limitations are imposed by the necessity of a stable collection system and enough materials (due to the scale needed) to run them.

Thus, there is a need for a robust collection system that adequately feeds formal recyclers to posteriorly develop a downstream industry to valorize materials within the countries' borders. As an emerging country, China is succeeding in these tasks, which can be studied and adapted for other emerging countries. Effective regulations (based on the EPR approach) and incentives for the formal system are good marks of the Chinese system, but there is still a long way to go to improve it.

Regarding recycling, the COVID-19 pandemic has shown the importance of materials provided through safe and stable market routes. For instance, the automotive and electronic industries were severely impacted by the lack of semiconductors in the market, as China prioritized its internal market (Wu et al. 2021). The effects were observed in 2022.

The market of many strategic materials is dominated by a few countries, resulting in high supply risks (Blengini et al. 2020). Within a country's borders, recycling strategic and valuable materials may attenuate these breakdowns in material provision when adverse external events occur. In this sense, developing a recycling industry in emerging countries is of major importance to ensure the activity of essential production chains and sustainable economic prosperity. Indeed, recycling and diversification of supply chains are the keys to reducing long-term risks (Althaf and Babbitt 2021).

As stated, it is clear that the consequence of the pandemic affects e-waste generation. Therefore, future studies and reports should focus on accounting for the volume of e-waste generated during the pandemic. The current data demonstrated the rise in waste generation worldwide with the same recycling rate (or none caused by stoppages for social distances). For this reason, the amount will be completed differently from any projections—it was expected to achieve 60Mt of e-waste in 2023 (Forti et al. 2020), which certainly will occur before. Further, recycling developments to meet sustainability must be improved and adapted to treat different e-wastes.

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## References

- Abdou TR, Botelho Junior AB, Espinosa DCR, Tenório JAS (2021) Recycling of polymeric composites from industrial waste by pyrolysis: deep evaluation for carbon fibers reuse. *Waste Manag* 120:1–9. <https://doi.org/10.1016/j.wasman.2020.11.010>
- Al-Salem SM, Antelava A, Constantinou A et al (2017) A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *J Environ Manag* 197:177–198. <https://doi.org/10.1016/j.jenvman.2017.03.084>
- Al-Salem SM, Alosairi Y, Constantinou A (2022) Effect of COVID-19 lockdown measures on the plastic waste generation trends and distribution of microplastics in the Northwestern Arabian/Persian Gulf. *Ocean Coast Manag* 216:105979. <https://doi.org/10.1016/j.ocecoaman.2021.105979>
- Althaf S, Babbitt CW (2021) Disruption risks to material supply chains in the electronics sector. *Resour Conserv Recycl*. <https://doi.org/10.1016/j.resconrec.2020.105248>
- Andò S (2020) Gravimetric separation of heavy minerals in sediments and rocks. *Minerals* 10:273. <https://doi.org/10.3390/min10030273>
- Andrade DF, Castro JP, Garcia JA et al (2022a) Analytical and reclamation technologies for identification and recycling of precious materials from waste computer and mobile phones. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2021.131739>
- Andrade LM, Botelho Junior AB, Rosario CGA et al (2022b) Copper recovery through biohydrometallurgy route: chemical and physical characterization of magnetic (m), non-magnetic (nm) and mix samples from obsolete smartphones. *Bioprocess Biosyst Eng*. <https://doi.org/10.1007/s00449-022-02775-z>
- Avarmaa K, Yliaho S, Taskinen P (2018) Recoveries of rare elements Ga, Ge, In and Sn from waste electric and electronic equipment through secondary copper smelting. *Waste Manag* 71:400–410. <https://doi.org/10.1016/j.wasman.2017.09.037>
- Awasthi AK, Li J (2017) Management of electrical and electronic waste: a comparative evaluation of China and India. *Renew Sustain Energy Rev* 76:434–447. <https://doi.org/10.1016/j.rser.2017.02.067>
- Ayode Otitoju T, Ugochukwu Okoye P, Chen G et al (2020) Advanced ceramic components: materials, fabrication, and applications. *J Ind Eng Chem* 85:34–65. <https://doi.org/10.1016/j.jiec.2020.02.002>
- Baldé CP, Forti V, Gray V et al (2021a) Australia. In: The global e-waste. Accessed 7 Feb 2021
- Baldé CP, Forti V, Gray V et al (2021b) Brazil. In: The global e-waste. Accessed 7 Feb 2021
- Baldé CP, Forti V, Gray V et al (2021c) China. In: The global e-waste. <https://globalewaste.org/statistics/country/china/2019/>. Accessed 8 Feb 2021
- Baldé CP, Forti V, Gray V et al (2021d) United States of America. In: The global e-waste. <https://globalewaste.org/statistics/country/united-states-of-america/2019/>. Accessed 10 Nov 2021
- Baldé CP, Forti V, Gray V et al (2021e) South Africa. In: The global e-waste. <https://globalewaste.org/statistics/country/south-africa/2019/>. Accessed 10 Nov 2021
- Baldé CP, Forti V, Gray V et al (2021f) Italy. In: The global e-waste. <https://globalewaste.org/statistics/country/italy/2019/>. Accessed 10 Nov 2021
- Baldé CP, Forti V, Gray V et al (2021g) United Kingdom of Great Britain and Northern Ireland. In: The global e-waste. <https://globalewaste.org/statistics/country/south-africa/2019/>. Accessed 10 Nov 2021
- Baldé CP, Kuehr R (2021) Covid19 pandemic on e-waste: the first three quarters of 2020. Bonn, Germany
- Baldé CP, Forti V, Gray V et al (2019) India. <https://globalewaste.org/statistics/country/india/2019/>. Accessed 13 Jun 2022
- Baldé CP, Forti V, Gray V et al (2020) Nigeria. In: The global e-waste. <https://globalewaste.org/statistics/country/nigeria/2019/>. Accessed 10 Feb 2021
- Beccarello M, Di Foggia G (2018) Moving towards a circular economy: economic impacts of higher material recycling targets. *Mater Today Proc* 5:531–543. <https://doi.org/10.1016/j.matpr.2017.11.115>
- Behnamfard A, Salarirad MM, Veglio F (2013) Process development for recovery of copper and precious metals from waste printed circuit boards with emphasize on palladium and gold leaching and precipitation. *Waste Manag* 33:2354–2363. <https://doi.org/10.1016/j.wasman.2013.07.017>
- Blengini GA, Latunussa CEL, Eynard U et al (2020) European Commission, study on the EU's list of critical raw materials—final report (2020)
- Borthakur A (2020) Policy approaches on e-waste in the emerging economies: a review of the existing governance with special reference to India and South Africa. *J Clean Prod* 252:119885. <https://doi.org/10.1016/j.jclepro.2019.119885>
- Borthakur A, Govind M (2017) Emerging trends in consumers' e-waste disposal behaviour and awareness: a worldwide overview with special focus on India. *Resour Conserv Recycl* 117:102–113. <https://doi.org/10.1016/j.resconrec.2016.11.011>
- Botelho Junior AB, Dreisinger DB, Espinosa DCR, Tenório JAS (2018) Pre-reducing process kinetics to recover metals from nickel leach waste using chelating resins. *Int J Chem Eng* 2018:1–7. <https://doi.org/10.1155/2018/9161323>
- Botelho Junior AB, Dreisinger DB, Espinosa DCR (2019a) A review of nickel, copper, and cobalt recovery by chelating ion exchange resins from mining processes and mining tailings. *Min Metall Explor* 36:199–213. <https://doi.org/10.1007/s42461-018-0016-8>
- Botelho Junior AB, Espinosa DCR, Dreisinger D, Tenório JAS (2019b) Recovery of nickel and cobalt from nickel laterite leach solution using chelating resins and pre-reducing process. *Can J Chem Eng* 97:1181–1190. <https://doi.org/10.1002/cjce.23359>
- Botelho Junior AB, Jiménez Correa MM, Espinosa DCR et al (2019c) Recovery of Cu(II) from nickel laterite leach using prereduction and chelating resin extraction: Batch and continuous experiments. *Can J Chem Eng* 97:924–929. <https://doi.org/10.1002/cjce.23306>
- Botelho Junior AB, Vicente AA, Espinosa DCR, Tenório JAS (2019d) Recovery of metals by ion exchange process using chelating resin and sodium dithionite. *J Mater Res Technol* 8:4464–4469. <https://doi.org/10.1016/j.jmrt.2019.07.059>
- Botelho Junior AB, Vicente ADA, Espinosa DCR, Tenório JAS (2020) Effect of iron oxidation state for copper recovery from nickel laterite leach solution using chelating resin. *Sep Sci Technol* 55:788–798. <https://doi.org/10.1080/01496395.2019.1574828>





- Botelho Junior AB, Espinosa DCR, Tenório JAS (2021a) The use of computational thermodynamic for yttrium recovery from rare earth elements-bearing residue. *J Rare Earths* 39:201–207. <https://doi.org/10.1016/j.jre.2020.02.019>
- Botelho Junior AB, Espinosa DCR, Tenório JAS (2021b) Selective separation of Sc(III) and Zr(IV) from the leaching of bauxite residue using trialkylphosphine acids, tertiary amine, tri-butyl phosphate and their mixtures. *Sep Purif Technol* 279:119798. <https://doi.org/10.1016/j.seppur.2021.119798>
- Botelho Junior AB, Espinosa DCR, Vaughan J, Tenório JAS (2021c) Recovery of scandium from various sources: a critical review of the state of the art and future prospects. *Miner Eng* 172:107148. <https://doi.org/10.1016/j.mineng.2021.107148>
- Botelho Junior AB, Stopic S, Friedrich B et al (2021d) Cobalt recovery from Li-ion battery recycling: a critical review. *Metals (basel)* 11:1999. <https://doi.org/10.3390/met11121999>
- Botelho Junior AB, Pinheiro ÉF, Espinosa DCR et al (2022) Adsorption of lanthanum and cerium on chelating ion exchange resins: kinetic and thermodynamic studies. *Sep Sci Technol* 57:60–69. <https://doi.org/10.1080/01496395.2021.1884720>
- Calgaro CO, Schlemmer DF, Da Silva MDCR et al (2015) Fast copper extraction from printed circuit boards using supercritical carbon dioxide. *Waste Manag* 45:289–297. <https://doi.org/10.1016/j.wasman.2015.05.017>
- Cao J, Xu J, Wang H et al (2018) Innovating collection modes for waste electrical and electronic equipment in China. *Sustainability (switzerland)* 10:1446. <https://doi.org/10.3390/su10051446>
- Cardamone GF, Ardolino F, Arena U (2021) About the environmental sustainability of the European management of WEEE plastics. *Waste Manag* 126:119–132. <https://doi.org/10.1016/j.wasman.2021.02.040>
- Castro FD, Botelho Júnior AB, Bassin JP et al (2023) E-waste policies and implementation: a global perspective. In: Singh P, Verma P, Singh R et al (eds) *Waste management and resource recycling in the developing world*. Elsevier, First, pp 271–307
- CdC RAEE (2017) Rapporto annuale ritiro e trattamento dei rifiuti da apparecchiature elettriche ed elettroniche in italia 2017
- Croci E, Colelli F (2017) Sfide E prospettive Del Gestione Dei Raee
- CdC RAEE (2019a) Rapporto Annuale Ritiro e Trattamento dei Rifiuti da Apparecchiature Elettriche ed Elettroniche in Italia
- CdC RAEE (2019b) Rapporto Annuale Ritiro e Trattamento dei Rifiuti da Apparecchiature Elettriche ed elettroniche in Italia
- Cenci MP, Dal Berto FC, Camargo PSS, Veit HM (2021a) Separation and concentration of valuable and critical materials from wasted LEDs by physical processes. *Waste Manag* 120:136–145. <https://doi.org/10.1016/j.wasman.2020.11.023>
- Cenci MP, Scarazzato T, Munchen DD et al (2021b) Eco-friendly electronics—a comprehensive review. *Adv Mater Technol* 2001263:2001263. <https://doi.org/10.1002/admt.202001263>
- Chauhan G, Jadhao PR, Pant KK, Nigam KDP (2018) Novel technologies and conventional processes for recovery of metals from waste electrical and electronic equipment: challenges and opportunities—a review. *J Environ Chem Eng* 6:1288–1304. <https://doi.org/10.1016/j.jece.2018.01.032>
- Chen M, Huang J, Ogunseitan OA et al (2015) Comparative study on copper leaching from waste printed circuit boards by typical ionic liquid acids. *Waste Manag* 41:142–147. <https://doi.org/10.1016/j.wasman.2015.03.037>
- Chu H, Qian C, Tian B et al (2022) Pyrometallurgy coupling bioleaching for recycling of waste printed circuit boards. *Resour Conserv Recycl* 178:106018. <https://doi.org/10.1016/j.resconrec.2021.106018>
- Desouky OA, El-Moughith AA, Hassanien WA et al (2016) Extraction of some strategic elements from thorium–uranium concentrate using bioproducts of *Aspergillus ficuum* and *Pseudomonas aeruginosa*. *Arab J Chem* 9:S795–S805. <https://doi.org/10.1016/j.arabjch.2011.08.010>
- Dias P, Javimczik S, Benevit M et al (2016) Recycling WEEE: extraction and concentration of silver from waste crystalline silicon photovoltaic modules. *Waste Manag* 57:220–225. <https://doi.org/10.1016/j.wasman.2016.03.016>
- Dias P, Machado A, Huda N, Bernardes AM (2018) Waste electric and electronic equipment (WEEE) management: a study on the Brazilian recycling routes. *J Clean Prod* 174:7–16. <https://doi.org/10.1016/j.jclepro.2017.10.219>
- Diaz F, Flerus B, Nagraj S et al (2018) Comparative analysis about degradation mechanisms of Printed Circuit Boards (PCBs) in slow and fast pyrolysis: the influence of heating speed. *J Sustain Metall* 4:205–221. <https://doi.org/10.1007/s40831-018-0163-7>
- dos Santos DM, Buzzi DC, Botelho Junior AB, Espinosa DCR (2022) Recycling of printed circuit boards: ultrasound-assisted comminution and leaching for metals recovery. *J Mater Cycles Waste Manag* 24:1991–2001. <https://doi.org/10.1007/s10163-022-01453-2>
- Du N, Ma H, Lin X et al (2018) Experimental investigation on the heat transfer characteristics in process of printed circuit boards pyrolysis under nitrogen flow. *Sci Total Environ* 636:1032–1039. <https://doi.org/10.1016/j.scitotenv.2018.04.365>
- Du N, Ma H, Zhang H et al (2019) Simulation study on the heat transfer characteristics of a single printed circuit board particle in the pyrolysis process. *Fuel Process Technol* 192:45–56. <https://doi.org/10.1016/j.fuproc.2019.04.016>
- DECRETO LEGISLATIVO 14 marzo 2014, n. 49 (2014) Consiglio dei ministri
- DECRETO N° 10.240, DE 12 DE FEVEREIRO DE 2020 (2020a) Presidência da Republica, Secretaria-Geral, Subchefia para Assuntos Jurídicos, Brasília
- DECRETO N° 10.240, DE 12 DE FEVEREIRO DE 2020 (2020b) Presidência da Republica, Secretaria-Geral, Subchefia para Assuntos Jurídicos, Brasília
- European Parliament (2003) DIRECTIVE 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). *Off J Eur Union L* 37:24–38
- European Parliament (2012a) DIRECTIVE 2012a/19/EU of the European Parliament and of the Council of 4 July 2012a on waste electrical and electronic equipment (WEEE) (recast) (Text with EEA relevance), pp 38–71
- European Parliament (2012b) DIRECTIVE 2012b/19/EU of the European Parliament and of the Council of 4 July 2012b on waste electrical and electronic equipment (WEEE) (recast) (Text with EEA relevance), pp 38–71
- European Commission (2020) Critical raw materials resilience: charting a path towards greater security and sustainability. <https://ec.europa.eu/docsroom/documents/42849>. Accessed 6 Oct 2020
- Faraji F, Golmohammadzadeh R, Pickles CA (2022) Potential and current practices of recycling waste printed circuit boards: a review of the recent progress in pyrometallurgy. *J Environ Manag* 316:115242. <https://doi.org/10.1016/j.jenvman.2022.115242>
- Ferdous W, Manalo A, Siddique R et al (2021) Recycling of landfill wastes (tyres, plastics and glass) in construction—a review on global waste generation, performance, application and future opportunities. *Resour Conserv Recycl*. <https://doi.org/10.1016/j.resconrec.2021.105745>
- Flerus B, Billmann L, Bokelmann K et al (2019) Recovery of gallium from smartphones—part I: thermal and mechanical pretreatment. In: *Proceedings of the 10th European metallurgical conference, EMC 2019, vol 3*, pp 959–972
- Forti V, Barde CP, Kuehr R (2018) E-waste statistics: guidelines on classification reporting and indicators. Bonn



- Forti V, Baldé CP, Kuehr R, Bel G (2020) The global e-waste monitor 2020. In: The global e-waste. <https://www.itu.int/myitu/-/media/Publications/2020-Publications/Global-E-waste-Monitor-2020.pdf>. Accessed 21 Nov 2021
- García JA, da Silva JRA, Pereira-Filho ER (2021) LIBS as an alternative method to control an industrial hydrometallurgical process for the recovery of Cu in waste from electro-electronic equipment (WEEE). *Microchem J*. <https://doi.org/10.1016/j.microc.2021.106007>
- Ghosh B, Ghosh MK, Parhi P et al (2015) Waste Printed Circuit Boards recycling: an extensive assessment of current status. *J Clean Prod* 94:5–19. <https://doi.org/10.1016/j.jclepro.2015.02.024>
- Ghosh SK, Debnath B, Baidya R et al (2016) Waste electrical and electronic equipment management and Basel Convention compliance in Brazil, Russia, India, China and South Africa (BRICS) nations. *Waste Manag Res J Sustain Circ Econ* 34:693–707. <https://doi.org/10.1177/0734242X16652956>
- Grant W (2020) DEFRA confirm household WEEE collection targets for 2020
- Guimarães LF, Botelho Junior AB, Espinosa DCR (2022) Sulfuric acid leaching of metals from waste Li-ion batteries without using reducing agent. *Miner Eng* 183:107597. <https://doi.org/10.1016/j.mineng.2022.107597>
- Hammadi MQ, Yassen RS, Abid KN (2017) Recovery of platinum and palladium from scrap automotive catalytic converters. *Al-Khwarizmi Eng J* 13:131–141. <https://doi.org/10.22153/kej.2017.04.002>
- Harper M (2020) DEFRA release the proposed 2020 household WEEE collections targets
- Hong Y, Valix M (2014) Bioleaching of electronic waste using acidophilic sulfur oxidising bacteria. *J Clean Prod* 65:465–472. <https://doi.org/10.1016/j.jclepro.2013.08.043>
- Hubau A, Chagnes A, Minier M et al (2019) Recycling-oriented methodology to sample and characterize the metal composition of waste Printed Circuit Boards. *Waste Manag* 91:62–71. <https://doi.org/10.1016/j.wasman.2019.04.041>
- Ichikowitz R, Hattingh TS (2020) Consumer e-waste recycling in South Africa. *S Afr J Ind Eng* 31:44–57. <https://doi.org/10.7166/31-3-2416>
- Ignatuschtschenko E (2017) E-waste management in China: bridging the formal and informal sectors. *J Chin Govern* 2:385–410. <https://doi.org/10.1080/23812346.2017.1379629>
- Ikiz E, Maclaren VW, Alfred E, Sivanesan S (2021) Impact of COVID-19 on household waste flows, diversion and reuse: the case of multi-residential buildings in Toronto, Canada. *Resour Conserv Recycl* 164:105111. <https://doi.org/10.1016/j.resconrec.2020.105111>
- Ilanakoon IMSK, Ghorbani Y, Chong MN et al (2018) E-waste in the international context—a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. *Waste Manag* 82:258–275. <https://doi.org/10.1016/j.wasman.2018.10.018>
- ILO (2019) Decent work in the management of electrical and electronic waste (e-waste)
- Ilyas S, Lee JC, Chi RA (2013) Bioleaching of metals from electronic scrap and its potential for commercial exploitation. *Hydrometallurgy* 131–132:138–143. <https://doi.org/10.1016/j.hydromet.2012.11.010>
- Işıldar A, Rene ER, van Hullebusch ED, Lens PNL (2018) Electronic waste as a secondary source of critical metals: management and recovery technologies. *Resour Conserv Recycl* 135:296–312. <https://doi.org/10.1016/j.resconrec.2017.07.031>
- Islam A, Ahmed T, Awual MR et al (2020) Advances in sustainable approaches to recover metals from e-waste—a review. *J Clean Prod* 244:118815. <https://doi.org/10.1016/j.jclepro.2019.118815>
- Islam A, Swaraz AM, Teo SH et al (2021a) Advances in physiochemical and biotechnological approaches for sustainable metal recovery from e-waste: a critical review. *J Clean Prod* 323:129015. <https://doi.org/10.1016/j.jclepro.2021.129015>
- Islam A, Swaraz AM, Teo SH et al (2021b) Advances in physiochemical and biotechnological approaches for sustainable metal recovery from e-waste: a critical review. *J Clean Prod* 323:129015. <https://doi.org/10.1016/j.jclepro.2021.129015>
- Jadhao P, Chauhan G, Pant KK, Nigam KDP (2016) Greener approach for the extraction of copper metal from electronic waste. *Waste Manag* 57:102–112. <https://doi.org/10.1016/j.wasman.2015.11.023>
- Jadhao PR, Ahmad E, Pant KK, Nigam KDP (2020) Environmentally friendly approach for the recovery of metallic fraction from waste printed circuit boards using pyrolysis and ultrasonication. *Waste Manag* 118:150–160. <https://doi.org/10.1016/j.wasman.2020.08.028>
- Jadhav U, Hocheng H (2015) Hydrometallurgical recovery of metals from large printed circuit board pieces. *Sci Rep* 5:14574. <https://doi.org/10.1038/srep14574>
- Jeyaraj P (2021) Management of e-waste in India—challenges and recommendations. *World J Adv Res Rev* 11:193–218. <https://doi.org/10.30574/wjarr.2021.11.2.0329>
- Kaya M (2016) Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. *Waste Manag* 57:64–90. <https://doi.org/10.1016/j.wasman.2016.08.004>
- Kaya M (2019) Electronic waste and printed circuit board recycling technologies
- Koochaki-Mohammadpour SMA, Torab-Mostaedi M, Talebizadeh-Rafsanjani A, Naderi-Behdani F (2014) Adsorption isotherm, kinetic, thermodynamic, and desorption studies of lanthanum and dysprosium on oxidized multiwalled carbon nanotubes. *J Dispers Sci Technol* 35:244–254. <https://doi.org/10.1080/01932691.2013.785361>
- Kumar A, Holuszko M, Espinosa DCR (2017) E-waste: an overview on generation, collection, legislation and recycling practices. *Resour Conserv Recycl* 122:32–42. <https://doi.org/10.1016/j.resconrec.2017.01.018>
- Langley J (2020) WEEE targets missed for third consecutive year
- Larios-Gómez E, Fischer L, Peñalosa M, Ortega-Vivanco M (2021) Purchase behavior in COVID-19: a cross study in Mexico, Colombia, and Ecuador. *Heliyon*. <https://doi.org/10.1016/j.heliyon.2021.e06468>
- Lee CH, Tang LW, Popuri SR (2011) A study on the recycling of scrap integrated circuits by leaching. *Waste Manag Res* 29:677–685. <https://doi.org/10.1177/0734242X10380995>
- Liang Y, Song Q, Wu N et al (2021) Repercussions of COVID-19 pandemic on solid waste generation and management strategies. *Front Environ Sci Eng*. <https://doi.org/10.1007/s11783-021-1407-5>
- Lima LR, Gutierrez RF, Cruz SA (2022) A perspective of the COVID-19 pandemic in the plastic waste management and cooperatives of waste pickers in Brazil. *Circ Econ Sustain*. <https://doi.org/10.1007/s43615-021-00130-0>
- Liu K, Zhang Z, Zhang FS (2016) Direct extraction of palladium and silver from waste printed circuit boards powder by supercritical fluids oxidation-extraction process. *J Hazard Mater* 318:216–223. <https://doi.org/10.1016/j.jhazmat.2016.07.005>
- Lydall M, Nyanjowa W, James Y (2017) Mapping South Africa's waste electrical and electronic equipment (WEEE) dismantling, pre-processing and processing technology landscape—waste research development and innovation roadmap research report. [https://www.ewasa.org/wp-content/uploads/2018/04/weee\\_technology\\_landscape\\_assessment\\_report.pdf](https://www.ewasa.org/wp-content/uploads/2018/04/weee_technology_landscape_assessment_report.pdf). Accessed 21 Nov 2021
- LEI N° 12.305, DE 2 DE AGOSTO DE 2010 (2010) Presidência da República, Casa Civil, Subchefia para Assuntos Jurídicos

- Marques ACAC, De SU, De SU et al (2016) Hidden impacts of the Samarco mining waste dam collapse to Brazilian marine fauna—an example from the stauzoans (Cnidaria). *Biota Neotrop* 16:1–3. <https://doi.org/10.1590/1676-0611>
- Marra A, Cesaro A, Belgiorio V (2018) Separation efficiency of valuable and critical metals in WEEE mechanical treatments. *J Clean Prod* 186:490–498. <https://doi.org/10.1016/j.jclepro.2018.03.112>
- Martins TR, Mrozinski NS, Bertuol DA, Tanabe EH (2020a) Recovery of copper and aluminium from coaxial cable wastes using comparative mechanical processes analysis. *Environ Technol (united KINGDOM)*. <https://doi.org/10.1080/09593330.2020.1725141>
- Martins TR, Tanabe EH, Bertuol DA (2020b) Innovative method for the recycling of end-of-life LED bulbs by mechanical processing. *Resour Conserv Recycl* 161:104875. <https://doi.org/10.1016/j.resconrec.2020.104875>
- Martins LS, Guimarães LF, Botelho Junior AB et al (2021) Electric car battery: an overview on global demand, recycling and future approaches towards sustainability. *J Environ Manag* 295:113091. <https://doi.org/10.1016/j.jenvman.2021.113091>
- Méndez L, Forniés E, Garrain D et al (2021) Upgraded metallurgical grade silicon and polysilicon for solar electricity production: a comparative life cycle assessment. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2021.147969>
- MMA, ABINEE, ABRADISTI et al (2019) Acordo Setorial de Eletro-eletrônicos. In: SINIR
- München DD, Veit HM (2017) Neodymium as the main feature of permanent magnets from hard disk drives (HDDs). *Waste Manag* 61:372–376. <https://doi.org/10.1016/j.wasman.2017.01.032>
- Naughton CC (2020) Will the COVID-19 pandemic change waste generation and composition? The need for more real-time waste management data and systems thinking. *Resour Conserv Recycl* 162:105050. <https://doi.org/10.1016/j.resconrec.2020.105050>
- Neto IF, Sousa CA, Brito MSCA et al (2016) A simple and nearly-closed cycle process for recycling copper with high purity from end life printed circuit boards. *Sep Purif Technol* 164:19–27. <https://doi.org/10.1016/j.seppur.2016.03.007>
- Nogueira CA, Paiva AP, Oliveira PC et al (2014) Oxidative leaching process with cupric ion in hydrochloric acid media for recovery of Pd and Rh from spent catalytic converters. *J Hazard Mater* 278:82–90. <https://doi.org/10.1016/j.jhazmat.2014.05.099>
- Ongondo FO, Williams ID (2012) A critical review of the UK household WEEE collection network. *Proc Inst Civil Eng Waste Resour Manag* 165:13–23. <https://doi.org/10.1680/warm.2012.165.1.13>
- Otoni M, Dias P, Xavier LH (2020) A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil. *J Clean Prod* 261:120990. <https://doi.org/10.1016/j.jclepro.2020.120990>
- Panchal R, Singh A, Diwan H (2021) Economic potential of recycling e-waste in India and its impact on import of materials. *Resour Policy* 74:102264. <https://doi.org/10.1016/j.resourpol.2021.102264>
- Park YJ, Fray DJ (2009) Recovery of high purity precious metals from printed circuit boards. *J Hazard Mater* 164:1152–1158. <https://doi.org/10.1016/j.jhazmat.2008.09.043>
- Pathak P, Srivastava RR (2017) Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India. *Renew Sustain Energy Rev* 78:220–232. <https://doi.org/10.1016/j.rser.2017.04.062>
- Patil RA, Ramakrishna S (2020) A comprehensive analysis of e-waste legislation worldwide. *Environ Sci Pollut Res* 27:14412–14431. <https://doi.org/10.1007/s11356-020-07992-1>
- Pekarkova Z, Williams ID, Emery L, Bone R (2021) Economic and climate impacts from the incorrect disposal of WEEE. *Resour Conserv Recycl* 168:105470. <https://doi.org/10.1016/j.resconrec.2021.105470>
- Perea CG, Baena OJR, Ihle CF, Estay H (2021) Copper leaching from wastes electrical and electronic equipment (WEEE) using alkaline monosodium glutamate: thermodynamics and dissolution tests. *Clean Eng Technol* 5:100312. <https://doi.org/10.1016/j.clet.2021.100312>
- Perez ID, Botelho Junior AB, Aliprandini P, Espinosa DCR (2020) Copper recovery from nickel laterite with high-iron content: a continuous process from mining waste. *Can J Chem Eng* 98:957–968. <https://doi.org/10.1002/cjce.23667>
- Pickin J, Randell P, Trinh J et al (2018a) National waste report 2020. <https://www.environment.gov.au/system/files/resources/7381c1de-31d0-429b-912c-91a6dbc83af7/files/national-waste-report-2018a.pdf>
- Pickin J, Randell P, Trinh J et al (2018b) National waste report 2020. <https://www.environment.gov.au/system/files/resources/7381c1de-31d0-429b-912c-91a6dbc83af7/files/national-waste-report-2018b.pdf>
- Pinheiro RF, Michielin L, Martins TR et al (2021) Application of mechanical processing operations for the recycling of nickel metal hydride batteries. *J Mater Cycles Waste Manag* 23:2148–2161. <https://doi.org/10.1007/s10163-021-01280-x>
- Pollard J, Osmani M, Cole C et al (2021) A circular economy business model innovation process for the electrical and electronic equipment sector. *J Clean Prod* 305:127211. <https://doi.org/10.1016/j.jclepro.2021.127211>
- Premathilake DS, Botelho Junior AB, Tenório JAS et al (2023) Designing of a decentralized pretreatment line for EOL-LIBs based on recent literature of LIB recycling for black mass. *Metals (basel)* 13:374. <https://doi.org/10.3390/met13020374>
- RESOLUÇÃO Nº 2, DE 18 DE JUNHO DE 2021 (2021) In: Brasil. <https://www.in.gov.br/en/web/dou/-/resolucao-n-2-de-18-de-junho-de-2021-327352416>. Accessed 22 Nov 2021
- Rabatho JP, Tongamp W, Takasaki Y et al (2013) Recovery of Nd and Dy from rare earth magnetic waste sludge by hydrometallurgical process. *J Mater Cycles Waste Manag* 15:171–178. <https://doi.org/10.1007/s10163-012-0105-6>
- Rene ER, Sethurajan M, Kumar Ponnusamy V et al (2021) Electronic waste generation, recycling and resource recovery: technological perspectives and trends. *J Hazard Mater* 416:125664. <https://doi.org/10.1016/j.jhazmat.2021.125664>
- Sachs J, Schmidt-Traub G, Kroll C et al (2020) The sustainable development goals and COVID-19. *Sustainable development report 2020*
- Savvilotidou V, Hahladakis JN, Gidarakos E (2015) Leaching capacity of metals-metalloids and recovery of valuable materials from waste LCDs. *Waste Manag* 45:314–324. <https://doi.org/10.1016/j.wasman.2015.05.025>
- Segura-Bailón B, Lapidus GT (2021) Selective recovery of copper contained in waste PCBs from cellphones with impurity inhibition in the citrate-phosphate system. *Hydrometallurgy*. <https://doi.org/10.1016/j.hydromet.2021.105699>
- Sengupta D, Ilankoon IMSK, Dean Kang K, Nan Chong M (2022) Circular economy and household e-waste management in India: Integration of formal and informal sectors. *Miner Eng* 184:107661. <https://doi.org/10.1016/j.mineng.2022.107661>
- Sharma N, Chauhan G, Kumar A, Sharma SK (2017) Statistical optimization of heavy metal (Cu<sup>2+</sup> and Co<sup>2+</sup>) extraction from printed circuit boards and mobile batteries using chelation technology. *Ind Eng Chem Res* 56:6805–6819. <https://doi.org/10.1021/acs.iecr.7b01481>
- Shirodkar N, Terkar R (2017) Stepped recycling: the solution for e-waste management and sustainable manufacturing in India. *Mater Today Proc* 4:8911–8917. <https://doi.org/10.1016/j.matpr.2017.07.242>
- Shittu OS, Williams ID, Shaw PJ (2021) Global e-waste management: Can WEEE make a difference? A review of e-waste trends,



- legislation, contemporary issues and future challenges. *Waste Manag* 120:549–563. <https://doi.org/10.1016/j.wasman.2020.10.016>
- Silveira AVM, Fuchs MS, Pinheiro DK et al (2015) Recovery of indium from LCD screens of discarded cell phones. *Waste Manag* 45:334–342. <https://doi.org/10.1016/j.wasman.2015.04.007>
- Song X, Lu B, Wu W (2019) Environmental management of E-waste in China. In: *Electronic waste management and treatment technology*. Elsevier Inc., pp 285–310
- Statista (2021) Consumer electronics. <https://www.statista.com/outlook/dmo/ecommerce/electronics-media/consumer-electronics/worldwide>. Accessed 22 Nov 2021
- Stubbings WA, Nguyen LV, Romanak K et al (2019) Flame retardants and plasticizers in a Canadian waste electrical and electronic equipment (WEEE) dismantling facility. *Sci Total Environ* 675:594–603. <https://doi.org/10.1016/j.scitotenv.2019.04.265>
- Takahashi VCI, Botelho Junior AB, Espinosa DCR, Tenório JAS (2020) Enhancing cobalt recovery from Li-ion batteries using grinding treatment prior to the leaching and solvent extraction process. *J Environ Chem Eng* 8:103801. <https://doi.org/10.1016/j.jece.2020.103801>
- Thakur P, Kumar S (2020) Metallurgical processes unveil the unexplored “sleeping mines” e-waste: a review. *Environ Sci Pollut Res* 27:32359–32370. <https://doi.org/10.1007/s11356-020-09405-9>
- Trading Economics (2021) Commodities. <https://tradingeconomics.com/commodities>. Accessed 20 Nov 2021
- The World Bank (2020a) GDP. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD>. Accessed 31 Aug 2020
- The World Bank (2020b) GDP. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD>. Accessed 30 Aug 2020
- UNIDO Statistics (2020a) World manufacturing production statistics for quarter I, 2020
- UNIDO Statistics (2020b) World manufacturing production statistics for quarter III 2020
- UNIDO Statistics (2020c) World manufacturing production statistics for quarter II 2020
- UNIDO Statistics (2020d) World manufacturing production statistics for quarter I, 2020
- UNIDO Statistics (2021a) World manufacturing production statistics for quarter III 2021
- UNIDO Statistics (2021b) World manufacturing production statistics for quarter I 2021
- United Nations (2021) The sustainable development goals report 2021
- Utamura SK, Rosario CGA, Botelho AB et al (2017) Bioleaching process for metal recovery from waste materials. In: Zhang L, Drelich JW, Neelameggham NR et al (eds) *Energy technology 2017*. Springer, Cham, pp 283–290
- Vasconcelos DS, Tenório JAS, Botelho Junior AB, Espinosa DCR (2023) Circular recycling strategies for LFP batteries: a review focusing on hydrometallurgy sustainable processing. *Metals (basel)* 13:543. <https://doi.org/10.3390/met13030543>
- Veit HM, Bernardes AM (2014) *Electronic waste—recycling techniques*. Elsevier
- Wang J, Xie F, Wang W et al (2020) Eco-friendly leaching of gold from a carbonaceous gold concentrate in copper-citrate-thiosulfate solutions. *Hydrometallurgy* 191:105204. <https://doi.org/10.1016/j.hydromet.2019.105204>
- Wong NWM (2018) Electronic waste governance under “one country, two systems”: Hong kong and mainland china. *Int J Environ Res Public Health* 15:2347. <https://doi.org/10.3390/ijerph15112347>
- Wu D, Lee Y, Ngui Y (2021) Chip shortage set to worsen as covid rampages through Malaysia. In: Bloomberg. <https://www.bloomberg.com/news/articles/2021-08-23/chip-shortage-set-to-worsen-as-covid-rampages-through-malaysia>. Accessed 23 Nov 2021
- Xavier LH, Ottoni M, Lepawsky J (2021) Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks. *J Clean Prod* 297:126570. <https://doi.org/10.1016/j.jclepro.2021.126570>
- Xin B, Zhang D, Zhang X et al (2009) Bioleaching mechanism of Co and Li from spent lithium-ion battery by the mixed culture of acidophilic sulfur-oxidizing and iron-oxidizing bacteria. *Biore-sour Technol* 100:6163–6169. <https://doi.org/10.1016/j.biortech.2009.06.086>
- Xin L, Xi C, Sagir M, Wenbo Z (2023) How can infectious medical waste be forecasted and transported during the COVID-19 pandemic? A hybrid two-stage method. *Technol Forecast Soc Change* 187:122188. <https://doi.org/10.1016/j.techfore.2022.122188>
- Yoon HS, Kim CJ, Chung KW et al (2014) Leaching kinetics of neodymium in sulfuric acid from E-scrap of NdFeB permanent magnet. *Korean J Chem Eng* 31:706–711. <https://doi.org/10.1007/s11814-013-0259-5>
- Zeng X, Ali SH, Tian J, Li J (2020) Mapping anthropogenic mineral generation in China and its implications for a circular economy. *Nat Commun* 11:1–9. <https://doi.org/10.1038/s41467-020-15246-4>
- Zhang L, Xu Z (2016) A review of current progress of recycling technologies for metals from waste electrical and electronic equipment. *J Clean Prod* 127:19–36. <https://doi.org/10.1016/j.jclepro.2016.04.004>
- Zhang Y, Liu S, Xie H et al (2012) Current status on leaching precious metals from waste printed circuit boards. *Proc Environ Sci* 16:560–568. <https://doi.org/10.1016/j.proenv.2012.10.077>
- Zhang S, Ding Y, Liu B, Chang C (2017) Supply and demand of some critical metals and present status of their recycling in WEEE. *Waste Manag* 65:113–127. <https://doi.org/10.1016/j.wasman.2017.04.003>
- Zhang Z, Malik MZ, Khan A et al (2022) Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability. *Sci Total Environ* 807:150856. <https://doi.org/10.1016/j.scitotenv.2021.150856>

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