



# E-waste recycled materials as efficient catalysts for renewable energy technologies and better environmental sustainability

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## Abstract

Waste from electrical and electronic equipment exponentially increased due to the innovation and the ever-increasing demand for electronic products in our life. The quantities of electronic waste (e-waste) produced are expected to reach 44.4 million metric tons over the next five years. Consequently, the global market for electronics recycling is expected to reach \$65.8 billion by 2026. However, electronic waste management in developing countries is not appropriately handled, as only 17.4% has been collected and recycled. The inadequate electronic waste treatment causes significant environmental and health issues and a systematic depletion of natural resources in secondary material recycling and extracting valuable materials. Electronic waste contains numerous valuable materials that can be recovered and reused to create renewable energy technologies to overcome the shortage of raw materials and the adverse effects of using non-renewable energy resources. Several approaches were devoted to mitigate the impact of climate change. The cooperate social responsibilities supported integrating informal collection and recycling agencies into a well-structured management program. Moreover, the emission reductions resulting from recycling and proper management systems significantly impact climate change solutions. This emission reduction will create a channel in carbon market mechanisms by trading the CO<sub>2</sub> emission reductions. This review provides an up-to-date overview and discussion of the different categories of electronic waste, the recycling methods, and the use of high recycled value-added (HAV) materials from various e-waste components in green renewable energy technologies.

**Keywords** Sustainability · E-waste · Global market · Recycling · Metal recovery · Hydrometallurgy · Energy conversion · Green hydrogen · Energy storage · Supercapacitor

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## 1 Introduction

The electronics and telecommunications industry has witnessed significant technological and market developments over the past two decades (Khetriwal et al., 2009). Electronics are increasingly used in transportation, healthcare, telecommunications, and security (Nithya et al., 2021). However, these electronic systems become electronic waste (e-waste) when the owner unintentionally disposes them as waste with no intention of reuse. In this regard, e-waste is valuable for achieving a future circular economy and sustainability. Each product has its own material composition that requires recycling strategy. E-waste is an important industry growing at a rate of about 2 million tons (Mt) annually, potentially reaching 74.7 Mt in 2030 (Nithya et al., 2021). This growth is mainly due to economic and rapid technological advances that affect lifestyles and industry. As new devices with the latest features enter the market, consumers will dispose older devices, thus increasing waste rates (Kaliyavaradhan et al., 2022). In terms of quantity, e-waste is one of the fastest-growing global waste streams and significantly affects toxicity (Chung et al., 2011). This massive and increasing amount of electronic waste disposal will have a long-term impact on the planet due to landfill pollution and informal recycling protocols, such as manual sorting, disassembly, and open burning of waste without using safety precautions (Mohammadi et al., 2021). Various electrical and electronic devices (EEEs) contain various toxic substances and precious metals (Gurgul et al., 2018). The heavy metals and toxic substances in e-waste include lead, nickel, antimony, mercury, cobalt, thallium, cadmium, beryllium, polyvinyl chloride (PVC), brominated flame retardants, etc. The e-waste is considered a reservoir of precious and base metals such as silver, gold, copper, and palladium. It serves as a secondary resource for recovery at low operating costs (Kumar et al., 2017a). The valuable recycled metals from electronic waste constitute the essential backbone for a plethora of applications.

Energy is another important factor in our daily life, where fossil fuels are the main source of energy production. The US Energy Information Agency states that fossil fuels accounted for approximately 79% of the total US primary energy production in 2020 (US EPA, 2017). Maintaining today's fossil fuel consumption rate will deplete petroleum and natural gas resources in the coming 35–70 years (US EPA, 2017). Moreover, greenhouse gases (GHG) and toxic pollutant emissions account for more than 70% of carbon dioxide (CO<sub>2</sub>) emissions (IRENA, 2018). In 2015, the Paris agreement stated the long-term temperature goal of “*holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.*”

Consequently, by 2050, the contribution of renewable energy to the global primary supply needs to increase from 12 to 65% to meet the projected energy demand (Abbasi et al., 2020; Gao et al., 2017). The green climate fund, established in 2010, was devoted to helping developing countries to mitigate and comply with climate change and reduce greenhouse gas emissions. Developed countries pledged to allocate US \$ 100 billion each year from 2020 to 2025 to support the most exposed and small island developing states in adaptation and mitigation efforts (COP 26 2021). However, the transition to renewable energy in the world is practically limited. For this purpose, the recovered valuable metallic elements from e-waste recycling, such as copper, gold, silver, can be used as excellent catalytic materials in a variety of energy conversion and storage applications, such as oxygen evolution reaction (OER) (Jothi et al., 2018), hydrogen evolution reaction (HER) (Sengeni

et al. 2020), methanol oxidation reaction (MOR) (Li & Kanan, 2012), and carbon dioxide reduction reaction (CRR) (Hazra et al., 2019). Specifically, water-splitting (OER and HER) to generate green  $H_2$  from water is particularly interesting due to its  $120 \text{ MJ kg}^{-1}$  energy density and  $CO_2$ -free combustion (Karthik et al., 2022).

Corporate Social Responsibility (CSR) restricts firms from continuing the commitment to being socially responsible in contributing to communities and economic growth (Abbas et al., 2019). The environmental analysis emphasizes the efficient management of electronic waste initiated by firms to implement CSR in various schemes for collection and recycling systems. (Al Halbusi et al., 2022; Mubeen et al., 2022). The emergence of social media technology has provided a platform for business firms to interact and communicate with customers, suppliers, retailers, and other stakeholders. Social media marketing application typically facilitates information sharing, and individuals' content generation, where technological innovations have played an essential role in improving firm's performance (Yu et al., 2022). The efficient collection and recycling management systems will support by the creation of a channel in international carbon market mechanisms. The carbon market can help countries to achieve article 6 of Paris agreement and adopt more ambitious mitigation targets in the waste sector (Deng et al., 2022).

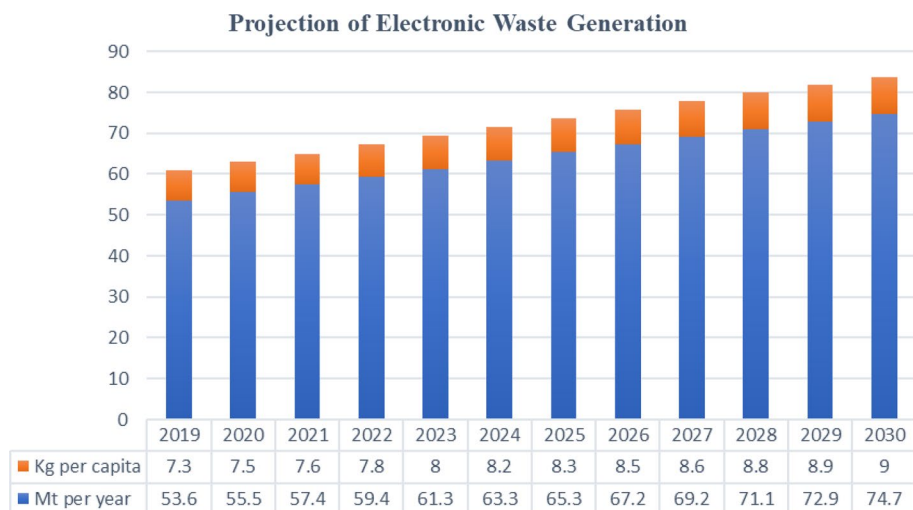
Hence, this review discusses the e-waste market value, e-waste generation, type, and composition. In addition, the available opportunities for e-waste recycling and the categories of recovered value-added materials for energy conversion and storage are highlighted and discussed.

## 2 Global e-waste management market

By 2026, the global electronics recycling market will cost \$65.8 billion, with a compound annual growth rate (CAGR) of 12.7%. Metals, one of the segments, are projected to increase at a CAGR of 13.3% and reach \$ 53.6 billion by 2026. The electronics recycling market grew to \$7.5 billion in 2021. In China, the market size is expected to hit \$15.3 billion by 2026, and the annual compound interest growth rate is expected to be 16.3%. Canada and Japan are expected to grow by 9% and 8.9%, respectively. While a CAGR of 12.5% is projected for Germany, other European markets are expected to reach \$6.1 billion. Europe is expected to have the largest market share in waste recycling. This is due to the rapid growth and adoption of waste recycling solutions, software, systems, and platforms in a variety of industries, such as security, automotive, marketing, healthcare, retail, information technology, and telecommunications. The USA, Canada, Japan, China, and Europe will promote a 12% CAGR in the global consumer electronics segment. These regional markets have estimated a total of \$14.5 billion in 2020 and will grow to \$35.4 billion by 2026. China is one of the fastest-growing countries in this regional market cluster. The Asia Pacific market will reach \$5.8 billion by 2026, while Latin America will grow at a 16.2% CAGR (Global Electronics Recycling Industry 2022).

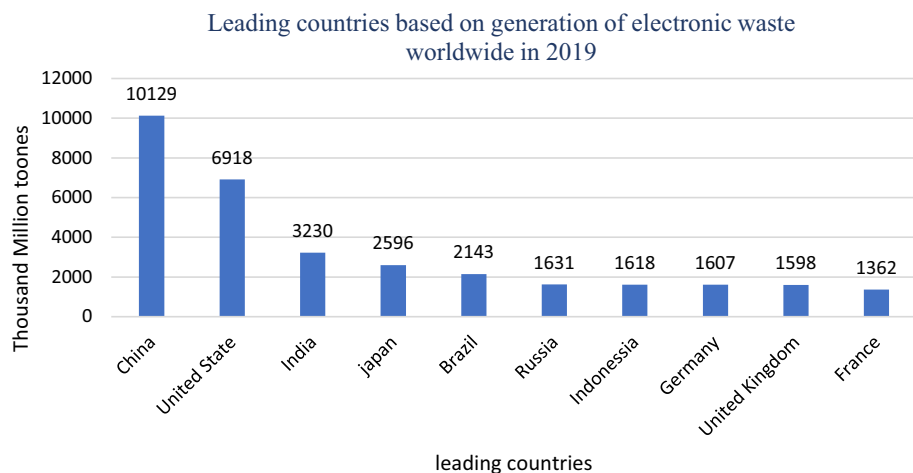
## 3 E-waste generation, type, and composition

Every year, about 40 million metric tons (Mt) of electronic waste are generated worldwide, accounting for 5% of total solid waste (Kumar et al., 2017a, 2017b). Fig. 1 shows the top countries based on the generation of e-waste around the world (Forti et al.,



**Fig. 1** Projection of e-waste generation (Forti et al., 2020)

2020). The European Union's telephones, televisions, and computers generate about 9 million tons of e-waste. The United Nations Environment Program (UNEP) reported that the electronic waste from mobile phones will increase 18-fold. In contrast, computer e-waste will increase about fivefold, and television e-waste will double in 2020. Fig. 2 shows the annual forecast of e-waste and the future forecast per capita (Forti et al., 2020). In 2019, about 53.6 million tons of electronic and electrical waste were generated worldwide. However, only 17.4% of this waste is adequately recycled (Forti et al., 2020).



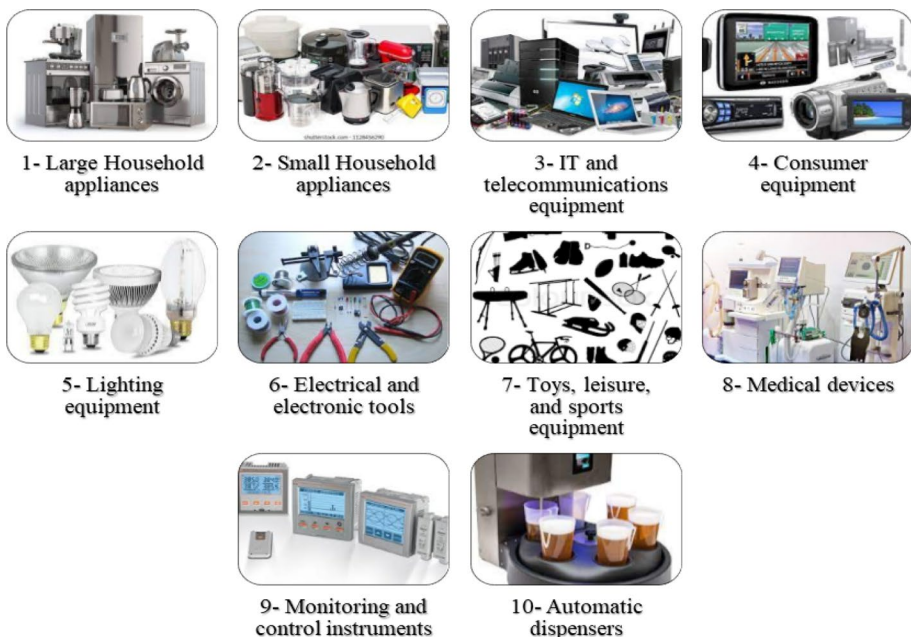
**Fig. 2** Leading countries in the generation of e-waste worldwide (Forti et al., 2020)

## a Different categories of electronic waste

E-waste includes all non-functional or obsolete electronic items. Based on the European Directives of WEEE 2012/19/EU and 2002/96/EC ((WEEE 2012), E-waste can be classified into ten categories, see Fig. 3. These categories include information technology and communications equipment, large and small home appliances, consumer equipment, non-industrial electrical and electronic appliances, lighting devices, toys, sports equipment, relaxation, non-infected medical devices, control and monitoring units, and automated devices dispensers ((WEEE 2012). About 10% are accessories, 14% are electronic equipment, 34% are communication equipment, and 42% are home appliances (Forti et al., 2020).

## b Electronic waste composition

The structural composition of e-waste is generally determined by the electronic device's manufacturer, its model and type, its date of manufacturing, and its age. IT and communication system chips contain more precious metals than home appliances (Chancerel et al., 2009). A mobile phone, for example, involves more than 40 elements, including precious metals such as gold (Au), silver (Ag), and palladium (Pd), and base metals such as tin (Sn) and copper (Cu) (Liu et al., 2009). Table 1 describes the metal composition of various electrical devices and components (Gautam et al., 2022). Due to the rapid development in electronic industries and high consumer demand, electrical and electronic equipment have a shorter lifetime in developed and developing countries markets, leading to tons of electronic waste. The waste printed circuit boards (PCBs) contain many valuable metals



**Fig. 3** WEEE categories according to the EU directive on WEEE

**Table 1** Metal content in a plethora of electronic equipment and components (Gautam et al., 2022) with permission from Elsevier

Elements (wt %)	PCB of mobile phones	Smart- phones	Desktop personal computer	Laptop	Printer	TV scrap	LCD panel	Internet Routers	DVD player	Portable audio	Hard disk drive	Random access memory (RAM)	Lithium- ion batter- ies
Cu	37.81	39.5	7	17.61	19.19	3.4	0.0175	21.6333	5	21	5.47	15	1.3
Al	0.61	1.78	–	1.9	7.06	1.2	0.19	5.4433	2	1	54.89	1.4	1
Ni	2.54	1.54	0.8	0.57	5.35	0.038	–	0.4637	0.05	0.03	1.75	4.2	5.5
Zn	1.82	0.67	2.2	0.45	0.73	0.3	0.00171	0.869	–	–	0.67	<0.01	–
Fe	4.85	0.87	21	3.74	3.56	–	0.133	5.05	62	23	22.48	7	2
Sn	2.55	3.22	1	–	2.03	–	0.00539	3.52	0.2	0.1	0.12	1.9	–
Pb	1.23	0.026	7	2.24	1.01	0.2	–	0.3413	0.3	0.14	–	0.8	–
As	–	0.0141	14	–	–	–	–	<0.007	–	–	–	–	–
Cd	–	<0.0002	0.01	–	–	–	–	0.0006	–	–	–	–	–
Cr	–	0.1219	–	0.1	–	–	–	0.0474	–	–	–	<0.01	–
Mn	–	–	–	–	–	–	–	–	–	–	–	0.06	5.8
Hg	–	0.0003	–	–	–	–	–	0.0004	–	–	–	–	–
Ti	–	0.1	–	–	0.04	–	–	0.1	–	–	–	–	–
Co	–	–	–	–	0.04	–	–	–	–	–	–	–	22.7
Li	–	–	–	–	–	–	–	–	–	–	–	–	3.7
In	–	–	–	–	–	–	0.0178	–	–	–	–	–	–
Au	0.09	0.1083	0.001	–	0.007	<0.001	–	0.0199	0.0015	0.0015	0.002	0.08	–
Ag	0.05	0.2773	0.02	–	0.01	0.002	–	0.1213	0.0115	0.0115	0.06	0.04	–
Pd	–	0.00554	–	–	–	–	–	0.00195	0.0004	0.0004	0.002	0.06	–
Pt	–	0.0008	–	–	–	–	–	<0.0005	–	–	–	–	–
Refer- ences	(Kasper et al., 2011)	(Holgers- son et al., 2018)	(Bhuie et al., 2004)	(İşildar et al., 2016)	(Yoo et al., 2009)	(Cui & Fors- berg, 2007)	(Lahti et al., 2020)	(Holgers- son et al., 2018)	(Christian Hagelüken, 2006)	(Christian Hagelüken, 2006)	(Nguyen et al., 2017)	(Lands- iedel et al., 2010)	(Atia et al., 2019)

like gold and copper and hazardous materials like lead. Therefore, recycling the metallic and non-metallic fractions from waste PCBs using environmentally friendly and suitable sustainable resource utilization techniques is in high demand. The rapid growth in technology creates significant challenges in developing e-waste management policies. The reuse market, the recycling industry, economic conditions, and waste segregation programs all have an impact on the management system of electronic waste (Gautam et al., 2022).

## 4 Electronic waste management system

Generally, a waste management system consists of three essential steps: collection, pre-treatment (dismantling, sorting, and size reduction), and recovery, as seen in Fig. 4 (Islam & Huda, 2018). Recycling e-waste can be informal or formal to extract valuable metals. Informal recycling refers to open burning to recover economically valuable metals, such as copper, aluminum, gold, lead, mercury, cadmium, palladium, and platinum. In addition, several chemicals, such as cyanide,  $\text{HNO}_3$ ,  $\text{HCl}$  and  $\text{H}_2\text{SO}_4$ , are highly toxic when used informally.

### 4.1 Proposed system to enhance the collection system worldwide

Improving e-waste management begins with establishing a proper collection system. Everyone can easily download mobile phone applications from the Google play store. Creating an application allows all stakeholders who benefit from it to collect more e-waste. Figure 5 depicts a description of a design application for e-waste collection. The application is classified into four categories based on the type of e-waste and the beneficiary customer. The first category includes smart electronics (laptops, cell phones, tablets, etc.) as well as places to sell old electronics. The second category is divided into two subcategories: large-size equipment and small-size equipment. The customer can submit a request on the application for large-size equipment, and the call center will respond for more information on how to receive the old equipment. The small-size equipment can easily be dropped off by the customer to the available locations. The third category is more specialized in collection agencies, private sectors, and governmental agencies. This category contains the locations and dates of auctions that assist recycling factories in collecting raw materials. The final category includes a list of electronic points for each device. This category consists of the points equivalent for each device to sell and the year in which the device was manufactured. The customer can only replace the device with points for locations agreed upon and found via the application. The points can be exchanged for money by adding them to the customer's card, used in any purchasing market.

### 4.2 Recycling processes of different types of e-waste

In Egypt, Twelve WEEE management firms have obtained environmental approval from the Egyptian Environmental Affairs Agency (EEAA) and an operational permit from Industrial Development Authority and are listed as a formal sector. Ten are based in the Cairo governorate, and two are located in the Alexandria governorate. Four WEEE management firms conduct in-depth dismantling, and two show complete recycling on the WEEE, in which mechanical and chemical processes are involved in the recycling process.



The in-depth dismantling WEEE management firms mainly collect, dismantle, and sort extracted fractions for resalable in the local market. In contrast, other bits are exported abroad to China, Korea, the USA, Belgium, and Italy. Specialized WEEE refining carries forward shredding, smelting and refining mechanical and chemical processes on exported WEEE fractions (United Nations Development Programme 2015).

Egypt's recycling and recovery are limited due to the lack of environmental policies integrated with specific laws governing the disposal and management of WEEE, the lack of precise databases and accurate mapping of the e-waste in Egypt, illegal incineration and dumping of hazardous e-waste with other non-hazardous/hazardous solid waste, releasing highly toxic emissions of furans, dioxins, and other gases that possess imminence risks on the environment and human health. Furthermore, the lack of technical expertise and equipment related to the recycling of e-waste (Abdelbasir et al., 2018). Currently, recycling is more expensive than exporting e-waste or metal concentrate due to the lack of local integrated treatment facilities and economic factors. Only 15–20% of Egypt's electronic waste is locally recycled, according to the United Nations Environment Program (UNEP). The rest will go directly into incinerators and landfills (United Nations Development Programme 2015). Improving the electronic waste management system in Egypt requires raising public awareness among the relevant stakeholders, establishing an e-waste database, formulating national strategies and legislation, and gaining technical expertise in various recycling. Furthermore, capacity building with the best environmental practices (BEP) and technology available (BAT) (Abdelbasir et al., 2018).

Recycling of e-waste involves three significant steps (Atia et al., 2019): (a) Dismantling: the main process in e-waste recycling that focuses on identifying valuable or hazardous components for special treatment, (b) Upgrading: using metallurgical/mechanical processing protocols to prepare the desirable materials for a refining process, and (c) Refining: in the final step, purifying/retreating the recovered materials using chemical/metallurgical

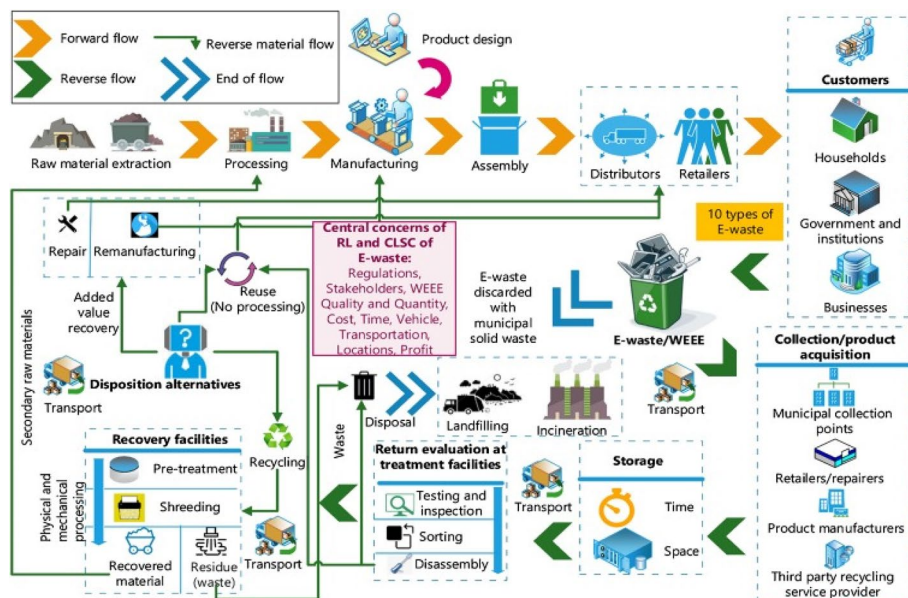
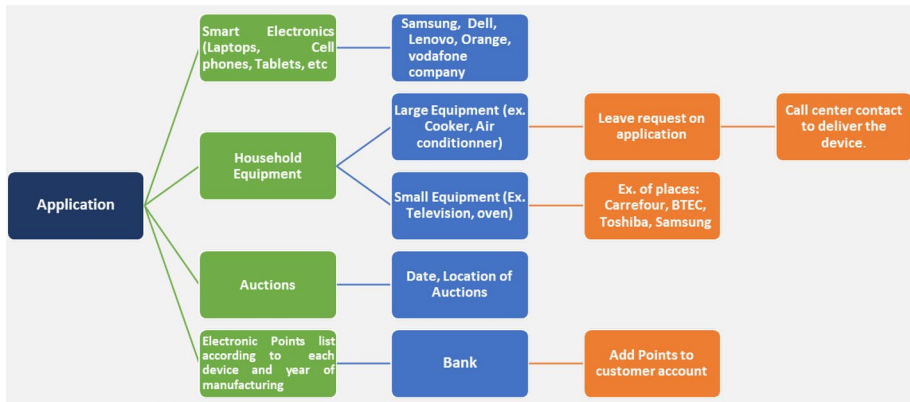


Fig. 4 Closed Loop supply chain of e-waste (Islam & Huda, 2018) with permission from Elsevier





**Fig. 5** Design application for the collection of e-waste

processing protocols to be functional for their original use. Disassembly and mechanical processes are primarily employed to pre-treat the e-waste to improve the content of the desirable materials. Several researchers have thoroughly reviewed and investigated the mechanical recycling of electronic waste (Cui & Forssberg, 2003; Matsukami et al., 2015). On the other hand, mechanical recycling is inefficient at recovering precious metals. Finally, pyrometallurgical and hydrometallurgical processes are used to dissolve or melt the recovered metals to remove any existing impurities. This step involves a number of chemical reactions (Cui & Forssberg, 2003). This review provides a comprehensive literature survey on the methods used to recycle lithium-ion batteries, precious metals from mobile phones, and copper recovery from computer-printed circuit boards to provide a detailed research status for future studies.

#### 4.2.1 Hydrometallurgical recycling of precious metals from mobile phones PCBs

The number of mobile phone subscriptions globally has exceeded the total population. In 2017, mobile phone subscriptions for the global population reached 1.04 per capita (Tan et al., 2018). Due to technological developments, social-psychological reasons, and upgrades, the lifespan of a mobile phone may be less than two years (Wilson et al., 2017). In 2017 alone, 800 million mobile phones were discarded in China (Guo & Yan, 2017). The massive consumption and rapid obsolescence of mobile phones pose serious challenges to the management of used mobile phones (WMP). WMPs are rich in resources, and their metal content is much higher than natural ores (Zeng et al., 2016). On average, each ton of WMP contained 0.15 kg of palladium, 0.347 kg of gold, 1 kg of antimony, 3.63 kg of silver, 6 kg of lead, 10 kg of tin, 15 kg of nickel, and 128 kg of copper (Valero Navazo et al., 2014). Recycling elements from electrical and electronic waste equipment is more cost-effective than mining (He et al., 2018).

High-quality precious metals, for example, silver and gold, are extracted via hydrometallurgical processing. The procedure is usually performed using different reagents. Cyanide leaching was the main reagent used for precious metals. The reaction is selective and leads to stable dicyanoaurate or dicyanoargentate complexes (Wang et al., 2021). Due to its toxic nature, cyanide has recently been replaced by aqua regia, thiosulfate, and thiourea. Table 2

shows the different leaching agents used to recover precious metals from waste mobile phones (Ding et al., 2019).

#### 4.2.2 Recovery of copper from PCBs

Copper is the main component used in printed circuit boards. It accounts for about 25–30% of the total metals used, which is much higher than copper ore, representing 20–40 fold (Xiu et al., 2017). Several techniques for recovering and reusing copper from PCB waste have been proposed (Xiu et al., 2017). Pyrometallurgy (Flandinet et al., 2012), hydrometallurgy (Fogarasi et al., 2015), and mechanical methods (Guo et al., 2011) are among the techniques proposed. Among these technologies, hydrometallurgical processes mainly focused on the leaching of copper with high metal selectivity, no dust/gas formation, relatively low capital costs, functional selectivity, and suitability for small-scale applications are alternatives for the treatment of PCBs waste (Birloaga et al., 2013). In previous reports, different lixiviant systems, including hydrochloric acid, sulfuric acid, nitric acid, ammonia, iodide, cyanide, thiosulphate, thiourea, and microbes, were investigated.

Metallic nanoparticles have unique structures, large surface area, high thermal and mechanical stability, and unusual chemical, optical, magnetic, and catalytic properties, making them the focus of many investigations. Cu NPs have been used in electronic, pharmaceutical, cosmetic energy, catalytic (Wang et al., 2016), solar energy conversion (Sahai et al., 2016), material additives (Jiao et al., 2016), negative electrode material of lithium-ion batteries (Poizot et al., 2000), and microelectronics (Li & Chen, 2014). Several research groups have recently proposed different methods for recover ultrafine copper materials. It is a promising strategy for increasing the added value of copper products derived from waste PCBs. Chemical reduction (Yang et al., 2012), electrochemical process (Chu et al., 2015), and electrokinetic process (Xiu & Zhang, 2009) are among the methods proposed.

Surfactants, reductants, and stabilizers must be used in the proposed processes, among other chemical reagents. Conductive pastes made of copper nanopowder have been used to form thick-film conducting electrodes or patterns in PCBs and multilayered electronic parts (Hai et al., 2007). A current trend in the electronic industry is the replacement of precious metals, such as Ag, Au, or Pd, with Cu nanopowder to produce conductive paste for hybrid integrated circuits and the metallization of multilayer ceramic capacitors (MLCC) (Hai et al., 2007). For example, Cu nanopowder is a potential raw material for the future additive manufacturing industry.

Nowadays, electrospinning is an economical and industrially scalable technique for producing nanofibers (Khalil et al., 2014; Mohamed et al., 2017). Electrospinning was used to create Cu-NPs using a precursor composed of copper acetate and polyvinyl alcohol at 20–29 kV (Khalil et al., 2014). The results showed that Cu NPs had an average diameter between 30 and 70 nm, while demonstrating a good yield and size distribution. Table 3 shows different hydrometallurgical processes for copper recovery from electronic waste.

#### 4.2.3 Recycling of lithium-ion batteries (LIB).

The global lithium-ion battery (LIB) market is projected to grow from \$ 41.1 billion in 2021 to \$ 116.6 billion in 2030, with a 12.3% CAGR (Zheng et al., 2018). As a result, the global mining production of cobalt for LIBs fabrication has exceeded 140,000 metric tons per year [98]. Furthermore, cobalt is produced as a byproduct of copper and nickel mining,

**Table 2** Different processes for recovering precious metals (Ding et al., 2019) with permission from Elsevier

Leaching agent	Process conditions	Metals recovered	References
DMF-CuCl <sub>2</sub> -CaCl <sub>2</sub> (DMF: dimethylformamide) system in mild aqua regia	Temp. 75 °C, leaching time 120 min., L/S ratio 500, CuCl <sub>2</sub> content 0.75 mol/L	Au 99%	(Wang et al., 2021)
Na <sub>2</sub> S <sub>2</sub> O <sub>8</sub> -KI leaching process combined with H <sub>2</sub> SO <sub>4</sub> -H <sub>2</sub> O <sub>2</sub>	0.02 M Na <sub>2</sub> S <sub>2</sub> O <sub>8</sub> , 0.15 M KI, 40 °C, a solid-liquid ratio of 1: 20 (g/mL), and stirring speed = 200 rpm, 120 min leaching time	Au	(Pan et al., 2022)
7 g e-waste, 0.2 mol SC(NH <sub>2</sub> ) <sub>2</sub> , 0.5 mol HCl, 0.1 mol FeCl <sub>3</sub>	Temp 25 °C, Time 2 h, L/S ratio 40	Au 54.81%, Ag 20.72%, Pd 29.6%	(Diaz et al., 2016)
Ag iodine/iodide 1:6	Temp 25 °C, Time 1 h and 30 min, S/L ratio 1/8	Ag 99%	(Xiu et al., 2015)
Pd, Au iodine/iodide 1:5; pH=9,	Temp. 25 °C, Time 2 h, S/L ratio 1/10	Pd 97.2%, Au 98.5%	(Xiu et al., 2015)
100 g/L H <sub>2</sub> SO <sub>4</sub> , 75 g/L NaCl, 25 g/L NaClO <sub>3</sub>	Temp 40 °C, Time 2 h, S/L ratio 1:8	Au 99.6%	(He & Xu, 2015)
72.71 mmol Thiosulfate, 10.0 mmol Cu <sup>2+</sup> , 0.266 mol NH <sub>3</sub>	Temp 40 °C, Time 5 min	Au 91%	(Ha et al., 2014)
Copper was removed before the experiment. Iodine 3%, H <sub>2</sub> O <sub>2</sub> 1%, pH=7	Temp 35 °C, Time 4 S/L 3:20	Au 99.98%	(Sahin et al., 2015)
0.13 M ammonium thiosulfate, 0.02 M Cu <sup>2+</sup>	Temp 20 °C, S/L 50, ratio (g L <sup>-1</sup> ) 50, pH= 10, Stirring (rpm) 180, Duration (min) 120	Au (70.5%)	(Camelino et al., 2015)
0.12 M thiosulfate, 0.2 M ammonium, 20 mM Cu <sup>2+</sup>	Temp 30 °C, S/L, ratio (g L <sup>-1</sup> ) 25, pH= 10, Stirring (rpm) 180, Duration (min) 240	Au (75%)	(Kasper et al., 2018)
0.65 M thiourea, 1.5 M Fe <sup>3+</sup> , H <sub>2</sub> O <sub>2</sub>	Temp 70 °C, S/L, ratio (g L <sup>-1</sup> ) 200, pH= 1	Au (95%), Ag (93%) Pd (99%)	(Quinet et al., 2005)
0.5 mol/L HNO <sub>3</sub> , potential 0.35 V, electrodeposition	Time 5 h, current efficiency 63.48%	Ag 97.72%, Pd 98.05%	(Liu et al., 2022)
Sulfuric acid; thiourea	(1) copper removing: 5% H <sub>2</sub> O <sub>2</sub> ; 2 M H <sub>2</sub> SO <sub>4</sub> ; 25 and 30 °C, 200 rpm for 3 h (2) gold leaching: 20 g/L thiourea; 1/10 S/L ratio; 0.5 M H <sub>2</sub> SO <sub>4</sub> ; and 6 g/L ferric ion, pH = 1; 500 rpm; room temperature	79.1 mg/L Au, 121.1 mg/L Ag	(Birloaga et al., 2014)

**Table 2** (continued)

Leaching agent	Process conditions	Metals recovered	References
Thiourea – ferric sulfate leaching	Leaching in thiourea with ferric sulfate, followed by filtration	Au (69.36%), Cu (100%), Ag (100%)	(Lee et al., 2011)
HNO <sub>3</sub> & Aqua Regia	Dissolving the powder in HNO <sub>3</sub> then aqua regia, followed by precipitation in hydrazine and oxalic acid	Au 99.9%	(Sahan, 2016)

accounting for 98 % of total cobalt production. However, the current rise in demand for electric vehicles (EVs) has resulted in an extreme shortage of cobalt supply, resulting in a 311% price increase from \$12.01/lb (2016) to \$37.43/lb (2018) (Raj et al., 2022). Industrially, various Lithium-ion-based metal oxides, such as  $\text{Li Ni}_{1-x-y}\text{Co}_x\text{Mn}_y\text{O}_2$  (NCM), are rapidly being used in electric vehicles to produce high-energy electrode material ( $> 600 \text{ Wh kg}^{-1}$ ) (Pender et al., 2020). LIBs must go through several processes before they can be reused or recycled due to their various compositions and complex structure. The LIBs must first be classified before they can be discharged or deactivated, disassembled, and separated. Then, as shown in Fig. 6 (Baum et al. 2022), LIBs can be recycled using pyrometallurgy, hydrometallurgy, or a combination of methods. The direct process of removing cathode material for reuse or reprocessing requires disassembling the LIB to obtain usable battery material (Baum et al. 2022). Heating is used in pyrometallurgy to convert the metal oxides used in battery materials into their metal compounds or metal counterparts (Zhou et al., 2021). After pretreatment, the battery materials are heated in a vacuum or inert atmosphere to prepare mixed metal alloys containing Co, Ni, Cu, Fe, and slag containing Li and Al, depending on the battery composition. Pyrometallurgical methods require simpler pretreatment protocols, such as shredding or crushing, to prepare batteries for recycling and require fewer different processes to recycle LIB of various compositions, shapes, and sizes.

Hydrometallurgical methods mainly use aqueous solutions to extract and separate metals from LIBs. The pretreated battery materials with previously removed Al and Cu current collectors are typically extracted with  $\text{H}_2\text{SO}_4$  and  $\text{H}_2\text{O}_2$ . HCl,  $\text{HNO}_3$ , and oxalic or citric acids. Metals are extracted into a solution and selectively precipitated as salts via pH control or extracted using organic solvents containing extractants such as dialkyl phosphates or phosphinate (Baum et al. 2022).

A LIB is typically made of an anode, a separator, a cathode, an electrolyte, an outer case, and sealing parts. Spent LIBs typically contain 5–20% cobalt (Co), 5–10% nickel (Ni), and 5–7% lithium (Li), which are higher than those found in natural ores, 5–10% other metals such as copper, aluminum, and iron. In addition, 15% organic compounds, 7% plastic, with slight variation depending on the manufacturer (Zheng et al., 2018). The recovered metals from spent LIBs, such as Li, Ni, Co, and Mn, have a significant economic impact (Zheng et al., 2018). LIB cathode materials are mostly Li intercalation oxides, such as  $\text{LiMn}_2\text{O}_4$ ,  $\text{LiNiO}_2$ ,  $\text{LiFePO}_4$ ,  $\text{LiCoO}_2$ , and  $\text{Li Ni}_x\text{Co}_y\text{Mn}_{1-x-y}\text{O}_2$  (Wang & Sun, 2015). Also,  $\text{Li Ni}_x\text{Co}_y\text{Mn}_{1-x-y}\text{O}_2$  has emerged as the most prominent LIB cathode material. This is due to its large discharge capacity, low cost, stable structure, and good cyclic performance (Wang & Sun, 2015). On the other hand, the anode (negative active material) contains graphite as an active material with a copper foil coating; an electrolyte is required for ion transfer. It acts as a medium through which ions are moved from one electrode to the other, converting chemical energy into electrical energy (J. Baum et al. 2022).  $\text{LiPF}_6$ ,  $\text{LiBF}_4$ ,  $\text{LiCF}_3\text{SO}_3$ , or  $\text{Li}(\text{SO}_2\text{CF}_3)_2$  are the electrolytes used in LIBs (Ren YH, Wu BR, Yang CW, Wu F). Many studies have discussed the leaching of spent LIBs using inorganic acids, electrochemical leaching, organic leaching, and ammonia leaching. Table 4 lists some of these reports and the corresponding experimental conditions for recovering materials from Lithium-ion batteries.

**Table 3** Different processes for the recovery of copper from E-waste

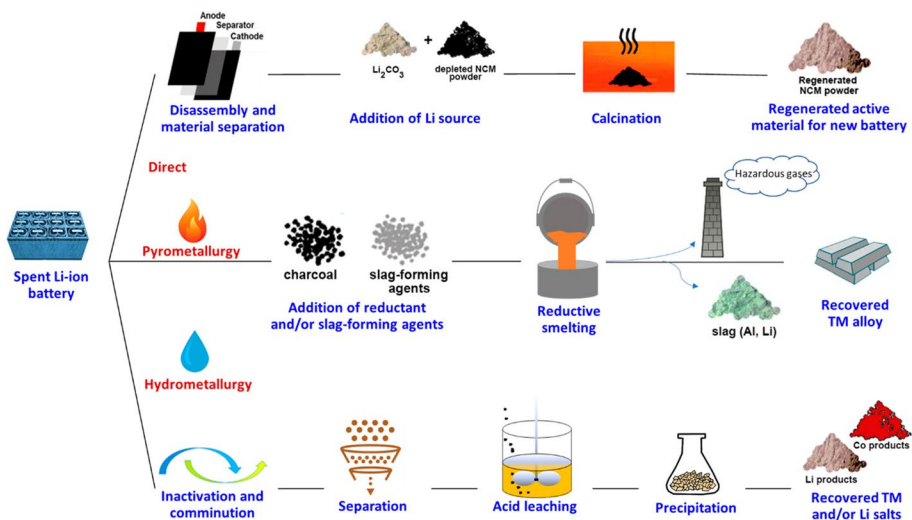
Leaching agent	Process conditions	Metals recovered	References
50 ml con. HCl (37%), 50 ml con. $\text{HNO}_3$ (63%), 0.2 M $\text{H}_2\text{O}_2$ and 2 M $\text{H}_2\text{SO}_4$ $\text{H}_2\text{SO}_4$ leach solution Ammonia-ammonium leach Solution Ammoniacal ammonium salts leaching	30 ml of 3 M NaOH added dropwise, black precipitate drying for 6 h at 80 °C, then calcination for 4 h at 400 °C S/L 1/100, time 150 min, temp at 25, 30, 35, and 45 °C Extractant LIX 84 IC, Con. 10%, Diluent Kerosene, pH 2.5 Extractant LIX 84, Con. 50%, Diluent Kerosene, pH 10 Temp 25 °C, S/L 1/10, ascorbic acid as a reducing agent, CTAP	CuO Nanoparticles Cu Cu 99.99% Cu 99.6% Cu 99.99%	(Rajkumar et al., 2022) (Dávila-Pulido et al., 2021) (Kumari et al., 2016) (Yang et al., 2012) (Seif El-Nasr et al., 2020)
Digested metal powders of WPCBs by microwave aided $\text{HNO}_3$ — $\text{H}_2\text{O}_2$ —HF system $\text{H}_2\text{SO}_4$ , $\text{H}_2\text{SO}_4$ + HCl, HCl, HCl + $\text{HNO}_3$	Slurry electrolysis $\text{HNO}_3$ + HCl leaches Cu with high percentage while $\text{H}_2\text{SO}_4$ showed the lowest leaching after 120 min	Cu 99.3% Cu 92.7%	(Zhang et al., 2017) (Vijayaram R et al. 2013)
Copper foil liberation by chemical-ultrasonic treatment and dissolution in $\text{H}_2\text{SO}_4$ acid Using six ionic liquids to leach Cu from WPCBs	Ascorbic acid reduction in the presence of cyclodextrin Leaching experiments were carried out in 250-mL glass conical flasks. Parameters examined: WPCBs particle size, $\text{H}_2\text{O}_2$ amount, acid concentration, and time at 40–70 °C (250 rpm)	Cu 90% Cu 99.99%	(Tatarants et al., 2018) (Chen et al., 2015)
(i) $\text{H}_2\text{SO}_4$ ; (ii) $\text{H}_2\text{SO}_4$ + $\text{H}_2\text{O}_2$ $\text{H}_2\text{SO}_4$ Mechanical treatment, 3 mol/L ammonia water, 2 mol/L ammonium chloride were used as leaching agents	Temp. (75 °C), time (4 h) and solid/liquid rate (1:10) 70 °C, S/L = 1:20, air flux = 3 L/min, 400 rpm, 4.5 h Temp 45 °C, and the leaching time was set at 20, 40, 60, 80, 100, 120, 140, 160, 180, 200 min. 10 mL of leaching solution was used, CTAB, glucose was used for the pre-reduction process at 85 °C. Ascorbic acid reducing agent, and copper was placed in a vacuum drying oven for 24 h at 60 °C to avoid oxidation	Cu 98.46% Cu 95.72% Cu 99.9%	(Silvas et al., 2015) (Guo et al., 2020) (Zhu et al., 2021)
Potassium persulfate ( $\text{K}_2\text{S}_2\text{O}_8$ )	Variation in Temp. leaching 25, 35, 45, and 55 °C, S/L 1/100, constant magnetic stirring (300 rpm), Cooling recrystallization	Cu 99.9%	(Liu et al., 2019)

## 5 Application of materials extracted from electronic waste in green technologies

One main challenge that currently faces scientists is the sustainable e-waste management. The annual global amount of generated e-waste is expected to increase by 2030, reaching 74.4 by 2030 (Forti et al., 2020). Landfilling, a technique used to get rid of the e-waste, generates vast amounts of methane that contributed to the global warming problem over 100 years by 21 times more than that of CO<sub>2</sub> (Pariatamby et al., 2015). Landfilling is responsible for almost 14% of global methane greenhouse gas emissions (Das et al., 2019). Due to the rigorous environmental regulations, the traditional approaches used for e-waste disposals, such as exporting abroad, burning using incinerators or landfilling disposal, are no longer valid options (Das et al., 2019).

Accordingly, the precious elements in the e-waste and the rising demand for the materials, along with the complications of the presently attainable raw materials, make the extraction of the valuable metals recycled from the e-waste an attractive alternative both economically and environmentally in diverse energy conversion and storage technologies. The metals extracted from the e-waste can be used as a water-splitting catalyst to generate hydrogen under specific conditions. Sustainable recycling of e-waste addresses the shortage of raw materials and minimizes energy consumption during the production of the raw materials while handling environmental concerns associated with hazardous materials generated from electronic waste streams (Das et al., 2019). Energy consumption predominantly contributes to greenhouse gas emissions since the recorded CO<sub>2</sub> emissions from fossil fuel combustion in 2018 was 33.1 Gt in 2018 (Zedalis, 2017). Therefore, replacing fossil fuels with an alternative clean energy source will be vital in lessening global CO<sub>2</sub> emissions. The following section of the review elaborates on the recovered metals from e-waste and their application in energy conversion and storage technologies.

### a Hydrogen production



**Fig. 6** Typical direct, pyrometallurgical, and hydrometallurgical recycling methods for recovering Li-ion battery active materials (Baum et al. 2022). With permission from the American Chemical Society



Waste-to-Hydrogen is the process that emphasizes producing hydrogen from recycling waste materials. Recently, there has been high interest from both governments and industry sides for utilizing hydrogen as a replacement for fossil fuels due to its unique properties (Lui et al., 2020). Hydrogen produces zero greenhouse gas emissions when combusted since it produces only water in the vapor phase, which could significantly enhance the main energy sector decarbonization problem. Nevertheless, the currently used methods for hydrogen production are around 96% depend on fossil fuels, while almost 0.04% comes from renewable energy sources. In addition, 96% of hydrogen obtained from natural gas, petroleum oil, and coal leads to an annual production of CO<sub>2</sub> emissions of 560 million tons, representing 1.7% of the global CO<sub>2</sub> emissions (Zedalis, 2017). Thus, renewable energy, such as wind and solar energy, is used to attain the advantages of using hydrogen as a clean, efficient, and versatile energy source. Hydrogen production from electrochemical water splitting is an example of producing hydrogen from a green energy source. This method includes running electricity through water using an appropriate catalyst to produce hydrogen and oxygen.

## 5.1 Green technologies for green hydrogen production

Water electrolysis is an efficient, promising, and simple technique for the production of pure hydrogen (Anantharaj et al., 2018). Nonetheless, external power is required to recognize the water-splitting process, rendering the water-splitting process economically inefficient. Instead, capturing and storing renewable energy from the surrounding environment, for instance, wind, solar, tidal or thermal energy, can be used for the electrolysis that could eliminate or reduce the need to utilize the external power supply (Wang and Li and Kazunari Domen 2019a and 2019b). Solar energy is an inexhaustible clean energy source that can significantly decrease the overall energy utilization required for water splitting (Haiqing et al. 2018).

For instance, external energy consumption can be minimized using solar cells that directly absorb the sunlight and yield voltage as an alternative to external power supply. Moreover, sunlight can be used as a heating source to generate the power needed in the water-splitting process using thermoelectrical (TE) devices (Haiqing et al. 2018). On the other hand, the natural vast availability of tidal and wind energy that can be harvested by triboelectric nanogenerators (TENGs) to generate electricity that in turn can efficiently decrease the need for external energy demand. Thus, hydrogen production via the water-splitting process can be driven using solar cells, photoelectrode, TE, TENG, along with other devices such as pyroelectric, as illustrated in Fig. 7 (Li et al., 2020).

## 5.2 Electrocatalysts for water splitting

Ni, Cu and Fe are the common elements recovered from the electronic board and have shown excellent electrocatalytic activity in several electrochemical reactions in the application of energy conversions. Particularly, water electrochemical splitting reactions outperformed all other approaches upon using the appropriate catalyst (Karthik et al., 2022). Among the non-noble metal catalysts, Ni and Mo revealed a hydrogen evolution activity that is on par with the activities of the hydrogen evolution of noble metal catalysts. Those metals are also widely utilized in the electronics manufacturing industry and have been classified by the IUPAC as endangered (Karthik et al., 2022).

**Table 4** Various Methods for leaching Lithium-ion batteries (Yang et al., 2021) with permission from Elsevier

Recovered Materials	Reducing and leaching agents	Conditions	Recovery efficiency	References
<i>1 Electrochemical Leaching</i>				
Li Ni Mn Co Hydroxide	3 M HCl and H <sub>2</sub> O <sub>2</sub> , 35% agitation	80 °C, 2 h, pH 6–7, electrochemically deposited onto nickel foam	100% recovery of complex composed of Li Ni Mn Co Hydroxide has great efficiency in Supercapacitor	(Mesbah et al., 2020)
LiCoO <sub>2</sub>	1.25 M malic acid	70 °C, 3 h, and pulp density of 8 V, 0.1 g	Co 90%, Li 94%	(Meng et al., 2018)
<i>2 Inorganic acid leaching</i>				
Li, Co	1.0 M maleic acid and 0.3 M SnCl <sub>2</sub> , H <sub>2</sub> O <sub>2</sub>	20 g·L <sup>-1</sup> , 60 °C, 40 min	Li 98.67%, Co 97.5%	(Sun et al., 2021)
Li, Co	1.0 M HNO <sub>3</sub>	75 °C, S/L ratio 1/50, 1 h, and reducing agent 1.7% (v/v) H <sub>2</sub> O <sub>2</sub>	85% Li, Co	(Lee & Rhee, 2002)
LiCoO <sub>2</sub>	5 vol% H <sub>2</sub> O <sub>2</sub> + 2 M H <sub>2</sub> SO <sub>4</sub> as reducing agent	75 °C, 1 h, 100 g·L <sup>-1</sup>	Co 99.1%, Li 70%	(Jha et al., 2013)
	0.02 mol/L glucose + 1.5 M H <sub>3</sub> PO <sub>4</sub> as a reducing agent	80 °C, 2 h, pulp density 2 g·L <sup>-1</sup>	Co 98%, Li ~100%	(Meng et al., 2017)
Li Ni <sub>x</sub> Co <sub>y</sub> Mn <sub>2</sub> O <sub>2</sub>	1 vol% H <sub>2</sub> O <sub>2</sub> + 1 M H <sub>2</sub> SO <sub>4</sub> , 4 M HCl	40 °C, 1 h, 40 g·L <sup>-1</sup> 25 °C, 120 g·L <sup>-1</sup>	Li, Ni, Co, Mn ~ 100% 81%Co, 98.0% Li, 75.5%Mn, 98% Ni	(He et al., 2017) (Xuan et al., 2019)
LiFePO <sub>4</sub>	0.4 M Citric acid + 0.2 M H <sub>3</sub> PO <sub>4</sub>	90 °C, 30 min, pulp density 20 g·L <sup>-1</sup>	91.63% Co, 100% Li, 93.38% Ni, 92% Mn	(Zhuang et al., 2019)
	H <sub>2</sub> O <sub>2</sub> + 0.3 M H <sub>2</sub> SO <sub>4</sub> (H <sub>2</sub> O <sub>2</sub> /Li molar (2.07)	2 h, 60 °C	96.85% Li, 1.95%P, 0.027% Fe,	(Li et al., 2017)
Li (NiCoAl)O <sub>2</sub>	4 M HCl	90 °C, 50 g·L <sup>-1</sup> , 18 h	Li, Co, Ni, Al ~ 100%	(Joulié et al., 2014)
Li, Co	5% NaOH 4 mol/L H <sub>2</sub> SO <sub>4</sub> , 1.0% H <sub>2</sub> O <sub>2</sub>	85 °C, 10 g L <sup>-1</sup> , 4	95% Co, 96% Li	(Xiao et al., 2017)
<i>3 Organic acid leaching</i>				

Table 4 (continued)

Recovered Materials	Reducing and leaching agents	Conditions	Recovery efficiency	References
LiCoO <sub>2</sub>	4 vol% H <sub>2</sub> O <sub>2</sub> + 1.5 M succinic acid	70 °C, 15 g•L <sup>-1</sup> , 0.67 h	Li > 96, Co ~100	(Li et al., 2015)
	0.75 M 3 vol% H <sub>2</sub> O <sub>2</sub> + Benzenesulfonic acid	90 °C, 15 g•L <sup>-1</sup> , 80 min	Li 99.58%, Co 96.53%	(Fu et al., 2019b)
	6 vol% H <sub>2</sub> O <sub>2</sub> + 2 M DL-malic acid	95 °C, 20 g•L <sup>-1</sup> , 60 min	Li 93.22%, Co 90.57% Mn 99.53%	(de Oliveira Demarco et al. 2019)
	1.5 M formic acid + 1.3 M Benzene-sulfonic acid	50 °C, 30 g•L <sup>-1</sup> , 40 min	Li 99%, Co 97%	(Fu et al., 2019a)
LiNi <sub>x</sub> Co <sub>y</sub> Mn <sub>1-x-y</sub> O <sub>2</sub>	0.02 M ascorbic acid + 0.5 M glycine	80 °C, 2 g•L <sup>-1</sup> , 6 h	Co > 95	(Nayaka et al., 2016)
	0.5 M Citric acid	90 °C, 80 min, 80 g•L <sup>-1</sup>	91% Li, 94% Ni, 89% Mn, 90% Co	(Meng et al., 2020)
	1 M Acetic acid + 3 mL H <sub>2</sub> O <sub>2</sub>	70 °C, 20 g•L <sup>-1</sup> , 60 min	98.83% Li, 97.93 Ni, 97.85% Co, 97.74% Mn	(Li et al., 2018)
	10 mL/L <sup>-1</sup> formic acid + 0.2 mol L <sup>-1</sup> ) H <sub>2</sub> O <sub>2</sub>	80 °C, S/L ratio 50 g L <sup>-1</sup> , 3 h	99% Li 98% Ni 99%Mn	(Zeba et al., 2022)
4 Ammonia leaching				
Li(Ni <sub>1/3</sub> Co <sub>1/3</sub> Mn <sub>1/3</sub> )O <sub>2</sub>	1.5 M (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> , 4 M NH <sub>3</sub> , 0.5 M Na <sub>2</sub> SO <sub>3</sub>	80 °C, 10 g•L <sup>-1</sup> , 5 h	Mn 1.36%; Co, Ni, Li > 98%; Al 0.02%	(Zheng et al., 2017)
Li, Ni, Co and Mn	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> , NHS), sucrose, H <sub>2</sub> SO <sub>4</sub>	30 min, pH=2.0, 25 °C, S/L =25 g/L	Li 97.1% Ni 94.0% Co 87.6% Mn 93.8%	(Liang et al., 2022)
Co, Ni, Mn	1.5 M ammonium citrate, 3 M ethylenediamine	2 h, 30 °C, 50:1 L/S	Ni 99.5% Co 99.4% Mn 99.9%	(Su et al., 2022)

Hence, in order to obtain an industrial profit-oriented water-splitting process, they need catalysts that can be recycled from electronic waste. Recently, a study reported the recycling of the e-waste to obtain a catalyst for HER with an appreciable overpotential at  $10 \text{ mA cm}^{-2}$  of 178 mV for H and overpotential for OER of 220 mV with stability up to 36 h (Jothi et al., 2018). According to the recent IUPAC conference, the elements are classified by researchers according to their usage and availability (Karthik et al., 2022). They unveiled elements extensively used as raw materials in the fabrication of electronic devices. For instant, In, Ag, Zn, Ga, Te, As, and Ge are expected to extend in the coming 100 years and are classified as a serious threat. Co and Cr are experiencing a rising threat due to extensive use, and Cu, Mg, Ni, Li, and Mn are classified as future supply risks due to limited availability. These declared endangered elements possess outstanding electrocatalytic water-splitting activities, as indicated in Fig. 8a and b (Karthik et al., 2022).

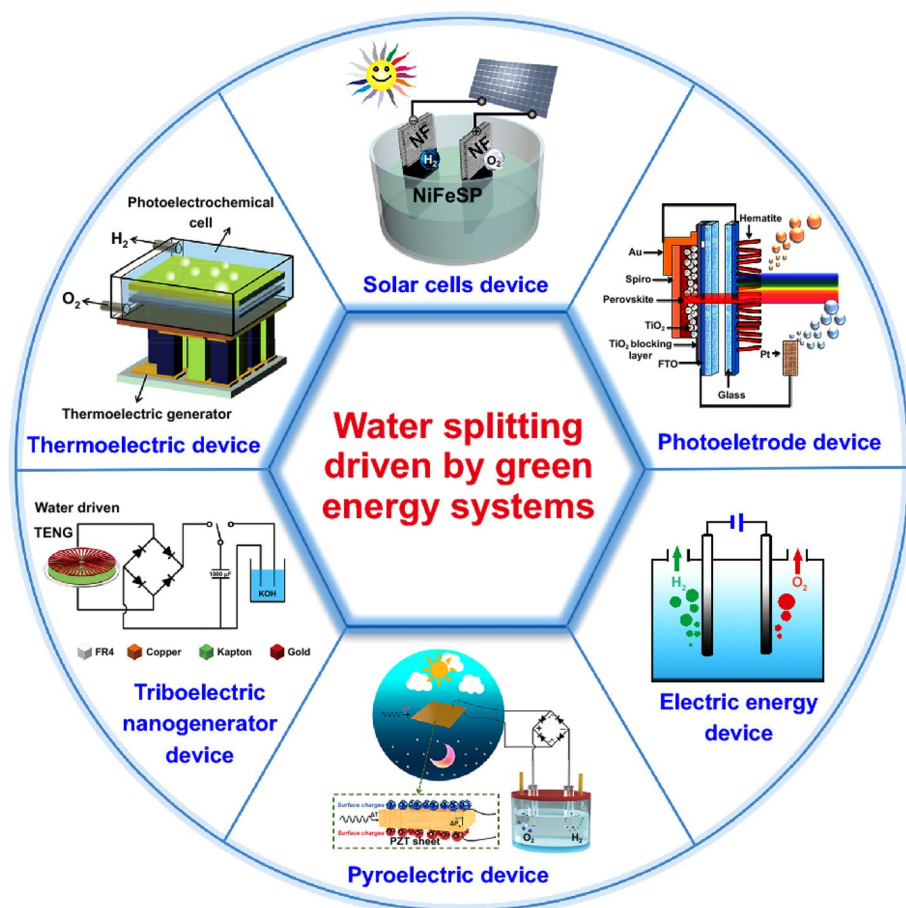
### 5.3 Metals extracted from e-waste as catalysts for hydrogen production

Yi et al. (Jothi et al., 2018) reported the utilization of Cu recovered from waste electric cables as a practical and cost-effective potential current collector for overall water splitting reaction. They reached superior electrochemical performance toward both HER and OER with high replicability and stability using a facile electrodeposition process, where an efficient nickel–cobalt phosphide (NiCoP) electrocatalyst that was formed on the scrap Cu wire (SCW). Therefore, the integration of the non-noble catalyst on the SCW enhanced both the OER and the HER activities in alkaline media at  $10 \text{ mA cm}^{-2}$ , reaching 220 mV and 178 mV, respectively, exceeding the activity of the state-of-the-art electrocatalyst for OER and HER ( $\text{IrO}_2/\text{RuO}_2$  and Pt, respectively). Additionally, an alkaline electrolyzer was stimulated by monitoring the electrocatalytic activity of the prepared electrodes at a current density of  $10 \text{ mA cm}^{-2}$  and a low voltage of 1.59 V for one day.

Slabon et al. (Lee et al., 2012) prepared a mixed graphene support cobalt aluminum borate ( $\text{AlBCoO}_3^{2+}$ ) electrocatalyst from waste Li-ion battery cathodes. The specimens were supported on carbon (named as sample 1), and the other was supported on copper tape (named as 1C). The 1C sample was directly green prepared using the treated decomposed battery with HCl, then neutralizing the recovered materials with the extract with  $\text{Na}_2\text{CO}_3$ . Finally, the reaction was reduced in the presence of graphene using sodium borohydride. The prepared catalyst achieved a hydrogen production rate of  $49.3 \text{ L (H}_2\text{) min}^{-1} \text{ g}^{-1} \text{ Co}$  at  $70^\circ\text{C}$  with a minimum turnover number of  $1.2 \times 10^7$  molecules of hydrogen per Co atom. The other catalyst prepared without the C support (Sample 1) exhibited a low turnover number and showed poor electrocatalyst activity. The STEM and SEM analysis of both prepared samples concluded that the presence of carbon enhances the mass activity. Table 5 surveys the electrocatalysts derived from e-waste used in hydrogen production (Karthik et al., 2022).

### 5.4 The use of recovered materials from e-waste for energy storage

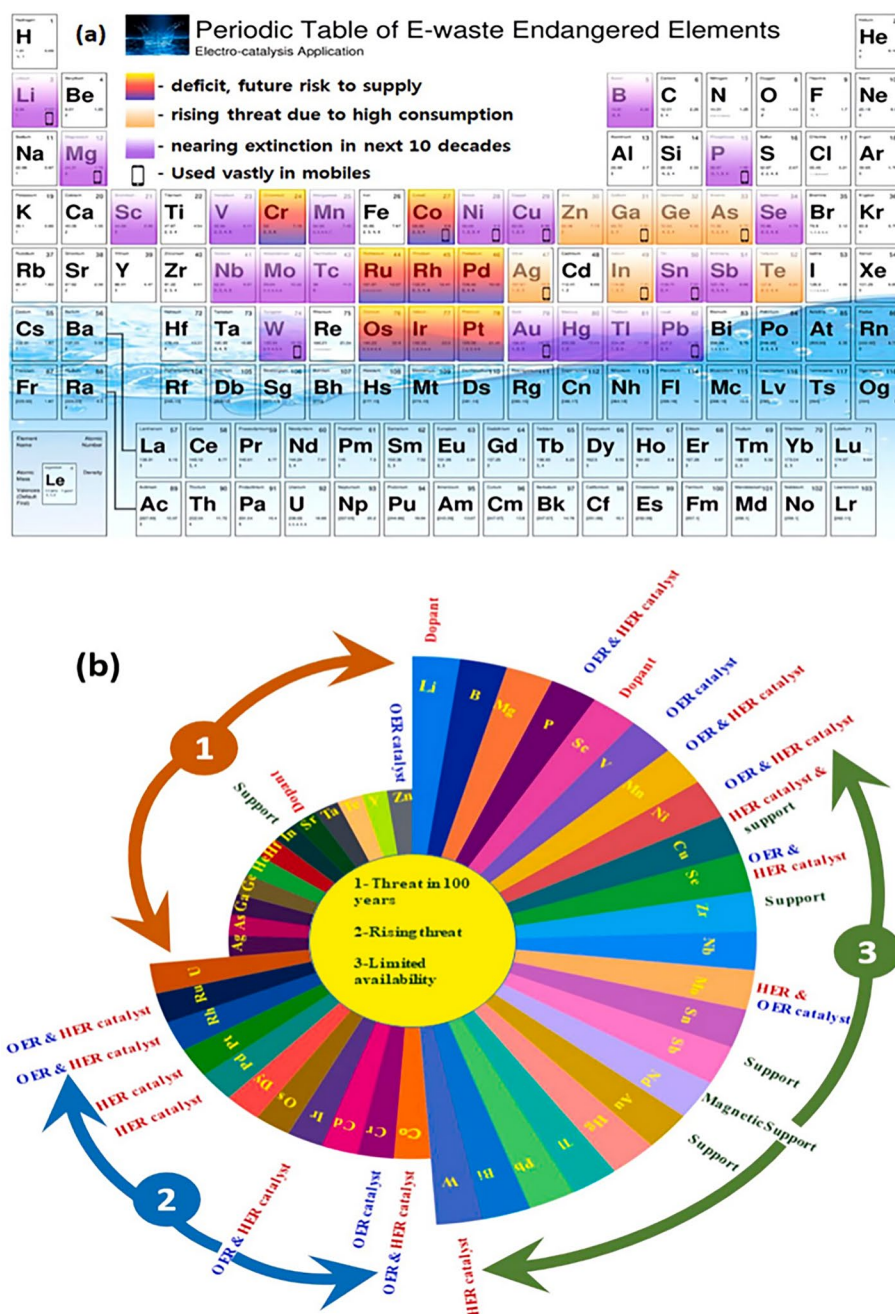
The enduring improvement of nanomaterials to obtain more advanced nanotechnology requires a continuous raw materials supply (Klaine et al., 2012). Consequently, the nanomaterial recovery from any application of nanotechnology is essential to achieve sustainable waste management that maintains the supply of the continuous raw material demand.



**Fig. 7** Water splitting driven by different green energy systems (Li et al., 2020)

Energy storage applications such as supercapacitors and rechargeable batteries rely on nanomaterials. The used materials in the super capacitive application are expensive. For instant, the cost of cobalt oxide increased from 20 \$/Kg in 1998 to 60 \$/Kg in 2017 (Freitas & Garcia, 2007). In electrical storage devices, metal oxides are used as they have a high capacitance value which makes them good candidates. Ruthenium oxide was the first material studied due to its high surface area and conductivity (Aboelazm et al., 2021), showing an excellent capacitance of  $1340 \text{ F g}^{-1}$  that is very close to its optimum theoretical capacitance of  $1400 \text{ F g}^{-1}$  (Hu et al., 2004).

Various transition metal sulfides, oxides, hydroxides, and their respective composites have been investigated as supercapacitor materials, such as  $\text{CuO}$ ,  $\text{Co}_3\text{O}_4$ ,  $\text{V}_2\text{O}_5$ ,  $\text{MnO}_2$ ,  $\text{MoS}_2$ ,  $\text{Fe}_3\text{O}_4$ , and  $\text{NiO}$  (Atef et al., 2018; Nathan et al., 2008).  $\text{Co}_3\text{O}_4$  and  $\text{MnO}_2$  showed significant theoretical capacitance among all the investigated transition metal oxides (TMOs) exhibiting capacitances of  $3560 \text{ F g}^{-1}$  and  $1360 \text{ F g}^{-1}$ , respectively, besides they have multivalence states (Gomaa et al., 2018). The ultra-layered  $\text{Co}_3\text{O}_4$  catalyst has a capacitance of  $548 \text{ F g}^{-1}$  (Sumanta et al. 2011). Subsequently, recovering cost-effective



**Fig. 8** a IUPAC enlarged periodic table of elements (Karthik et al., 2022) and b the corresponding Aster plot showing the plausible water splitting properties. Reproduced with permission from Elsevier

nanomaterials as catalysts from e-waste management has made waste recycling an indispensable necessity.  $\text{MnO}_2$  is a recognized excellent pseudocapacitive nanomaterial that can



substitute expensive and toxic candidates, particularly  $\text{RuO}_2$ . Despite the Mn high abundance in nature, it is crucial to prevent abusing the natural resources to develop the technologies. On the contrary, the best way to obtain  $\text{MnO}_2$  is through the Mn recovery from waste materials.

United States Environmental Protection Agency (USEPA) reported that about 160,000 tons of batteries are generated, and the annual Mn recovery could reach up to 20,000 tons (María et al. 2013). Moreover, a great amount of Mn in waste batteries can be used as a supercapacitor electrode (Sayilgan et al., 2009). Gam et al. reported the use of  $\text{MnO}_2$  nanoflowers recovered from Zn–C Batteries (Gomaa et al. 2014). The recovered  $\text{MnO}_2$  electrocatalyst exhibited a great capacitance of  $294 \text{ F g}^{-1}$ , exhibited high performance in  $1.0 \text{ M Na}_2\text{SO}_4$  electrolyte and showed high stability up to cycles of 88% (Gomaa et al. 2014). The same group used cyclic voltammetry conversion as an alternative electrochemical technique for porous  $\text{MnO}_2$  nanoflowers recovery using spent Zn–C batteries. The process includes thermal treatment of  $900^\circ\text{C}$  powder by cyclic voltammetry for 1000 cycles at  $50 \text{ mV s}^{-1}$  in the potential window— $0.1$ — $0.9 \text{ V}$ . They stated that the capacitance reached  $309 \text{ F g}^{-1}$  with high stability of 93% was reported (Gomaa et al. 2017).

$\text{Co}_3\text{O}_4$  has been extensively examined in the application of the electrode design of supercapacitors since it has multiple oxidation states and high conductivity. Aboelazm et al. managed to recover  $\text{Co}_3\text{O}_4$  nanomaterials with high active surface area from discarded Li-ion batteries using a magnetic field. The recovered cobalt oxide showed a superior capacitance of  $1273 \text{ F g}^{-1}$  with 96% cycling stability (Eslam et al. 2018). Furthermore, Rajkumar et al. reported the recovery of copper oxide nanoparticles from spent circuit boards though the leaching of the powdered circuit boards with a mixture of 37%  $\text{HCl}$  and 63%  $\text{HNO}_3$ , followed by the addition while stirring of  $\text{NaOH}$ . The precipitate was then filtered, purified and dried for 6 h at  $80^\circ\text{C}$ . The performance of the recovered Cu–O supercapacitor was elucidated. The fabricated electrocatalyst electrode exhibited a capacitance of  $408 \text{ F. g}^{-1}$  at  $1 \text{ Ag}^{-1}$  and retaining a capacitance that is 93.1% of its initial value after three thousand GCD cycles (Rajkumar et al., 2022) (Table 6).

## 5.5 E-waste recycling for sustainable development goals

During the last two decades, sustainability has become a principal part of a principal global agenda. Key events such as Brundtland Commission's report, Kyoto Protocol, the Millennium Development Goals in 2000, and recently the Paris Climate Treaty in 2015 showed the significance of sustainable practices. Consequently, businesses have considered serious action inside and outside their companies regarding sustainability issues hence augmenting attention in associating the business responses to sustainability. Sustainability initiatives by companies are on the rise, as an evidence by recent reports. Companies have recently tried to identify numerous ways to move toward a sustainable management system, such as cost-reduction profits, waste minimization, and improved resource management to sustain the raw materials for the coming generation (Bhaskar, 2018).

In 2015, the United Nations members embraced the sustainable development agenda for 2030 agenda which contains 17 goals with 169 targets for achieving this plan for sustainable development strategy (Kumar et al., 2017b). Firms worldwide are directed to align their business to meet a minimum of one of the recent sustainable design goals. The definition of sustainability is broad and challenging for establishments to comprehend and implement (Dao et al., 2011). The accumulative consumption rates of electronic devices,



**Table 5** A survey of recovered electrocatalysts from e-waste recovered for water splitting. Permission from Elsevier

Source	Electrocatalyst		Endangered elements	References
	Activity	Stability		
Waste Cu cable wires	OER ( $\eta = 390$ mV @ $100 \text{ mA/cm}^2$ and $275$ mV @ $20 \text{ mA/cm}^2$ )	—	Cu	(Jothi et al., 2018)
Spent Li-ion Battery (LiCoPO <sub>4</sub> & LiCoO <sub>2</sub> )	OER ( $\eta = 330$ mV)	C.A. @ $2.5$ and $1.7 \text{ V Ag}^{-1}$ for $2$ h	Co and Li, P	(Lee et al., 2012)
Dry cell battery (MnO <sub>2</sub> )	OER ( $\eta = 525$ mV @ $\text{mA/cm}^2$ )	—	Mn	(Karthik et al.)
PCB board and wire (Cu and Ni)	HER ( $\eta = 178$ mV) and OER ( $\eta = 220$ mV) @ $210 \text{ mA/cm}^2$	C.A. @ $1.46 \text{ V}$ and $15 \text{ mA/cm}$ for $36$ h	Ni, Cu	(Jothi et al., 2018)
PCB	HER current density as high as $2.6 \text{ mA/cm}^2$ at $-0.6 \text{ V}_{\text{Ag/AgCl}}$	—	Cu	(Nekouei et al., 2021)
Waste multilayer ceramic capacitors containing BaTiO <sub>3</sub> , Ag, Pd, Ni and Sn	HER ( $156.7 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$ )	—	Ag, Pd, Ni, and Sn	(Niu & Xu, 2019)
Waste tantalum capacitors	HER ( $200.8 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$ )	—	Ta	(Niu et al., 2020)
Waste ceramic capacitor	Z-scheme enhanced H <sub>2</sub> evolution rate, which was $22.2$ times higher than that of $\text{g-C}_3\text{N}_4$	—	Ag, Pd, Ni, and Sn	(Babar et al., 2019)
MEMS (AlScN)	OER ( $\eta = 40$ mV)	C.P @ $10 \text{ mA/cm}$ for $2$ h with $\eta = 430$ mV	Sc	(Wygant et al., 2016)
Memory device (VO <sub>x</sub> )	VO <sub>x</sub> /NiS/NF; OER ( $\eta = 330$ mV @ $50 \text{ mA/cm}^2$ )	$E = 1.2\text{--}1.7 \text{ V}$	V	(Gonçalves & Araki, 2020)
Power electronics (GaN)	HER ( $9.4 \times 10^4 \text{ s}^{-1}$ )	CP electrolysis, stable for $8$ h	Ga	(Ni et al. 2019)
Photocell, rectifier and xerography (Se -Te, Se on SS)	OER ( $\eta = 270$ mV @ $10 \text{ mA/cm}^2$ )	C.A. @ $10 \text{ mA/cm}^2$ for $3$ h and $\eta = 290$ mV	Se	(Qian et al., 2019)
Dielectric in gates and laser device (Y <sub>2</sub> O <sub>3</sub> )	OER ( $\eta = 190$ mV)	C.A. @ $1 \text{ mA/cm}^2$ for $8$ h & $1.5 \text{ V}$	Y	(Kim et al., 2017)
FET (MoS <sub>2</sub> )	HER ( $\eta = 110\text{--}254 \text{ mV}$ @ $10 \text{ mA/cm}^2$ )	$E = +0.2$ to $-0.3 \text{ V}$	Mo	(Benck et al., 2014)
Ag contact in solar cells	HER ( $k_0 = 6 \times 10^{-12} \text{ cm s}^{-1}$ )	—	Ag	(Campbell et al., 2009)

**Table 5** (continued)

Source	Electrocatalyst		Endangered elements	References
	Activity	Stability		
Ni–Cd battery	OER ( $\eta$ = 266 mV @ 10 mA/cm <sup>2</sup> )	C.P for 100 h @ 20 mA/cm <sup>2</sup> and $\eta$ = 300 mV	Ni and Cd	(Chen et al., 2020)
IC, chips, and processors (Sb)	HER (starts at 90 mV)	Electrolysis at −1.1 vs Fe/Fe <sup>+</sup> for 2 h	Sb	(Jiang et al., 2017)

low lifetime, little availability of repairing options, and high remote working consequences increase demands for vigorous practical infrastructure and digital renovation across the firm's models (Rautela et al., 2021). Electronic waste is anticipated to experience a sudden increase due to the recent COVID-19 pandemic (Rautela et al., 2021). The irregular disposal methods of electronic waste lead to several health and environmental hazards since it contains hazardous and toxic elements (Rautela et al., 2021). From an economic point of view, E-waste is considered an 'urban mine' as it includes several precious metals, such as Fe, Au, and Cu, that can be recovered and reused as secondary raw materials, as illustrated in Fig. 9 (Sharma et al., 2021).

Globally, recycled e-waste was approximately \$57 billion in 2019 (Forti et al., 2020). Thus, capturing the remaining cost or utility of the e-waste is essential to reach a circular economy in the electric and electronics production industry. Therefore, recycling e-waste materials significantly increases the sustainability of primary raw materials and reduces greenhouse gas emissions (Sustainable Development Goals 13). The total equivalent amount of CO<sub>2</sub> emitted only from discarded air conditioners and fridges to the atmosphere is 98 Mt, which was not handled according to an environmentally sound manner (Sustainable Development Goals 3, 11, 12, 13). This amount of CO<sub>2</sub> emissions is almost 0.3% of global emissions reported in 2019 (Forti et al., 2020).

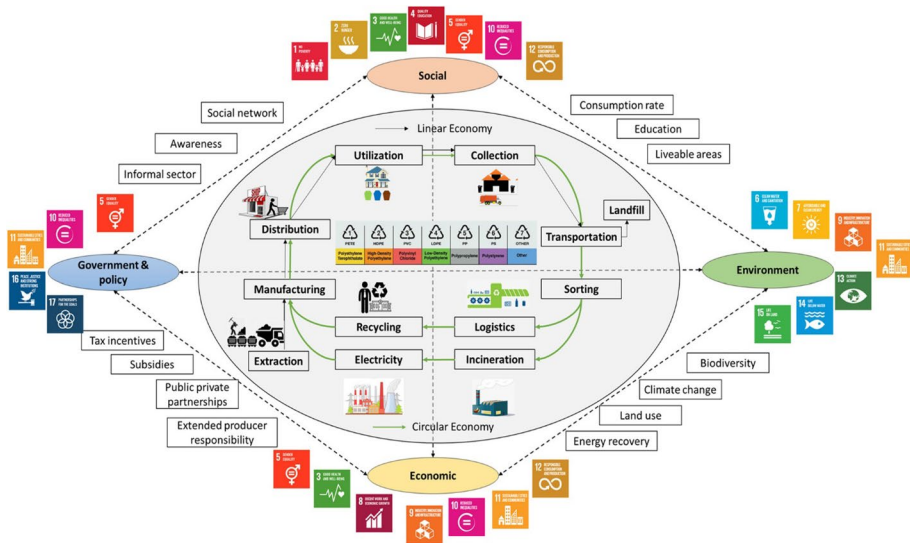
Electronic waste management thoroughly narrates various sustainable development goals. For instants, Goal 3: Health and well-being. This goal covers illness and death rates associated with hazardous materials exposure from air, soil and water. Goal 6: Sanitation and clean water. This goal pursues attaining nontoxic clean drinking water as well as the removal of hazardous materials. Goal 8: Economic growth and decent work that targets entrepreneurship and innovation. Goal 11: Sustainable cities and communities emphasizing per-capita environmental impact. Goal 12: Responsible production and consumption that focuses on the life cycle assessment of each product and its impact on the environment, besides the waste prevention and reduction techniques for individual products (Sharma et al., 2021).

In contrast, a more precise sub-indicator must be performed to monitor the growth of the electronic waste such as firms' models through which the producer preserves the responsibility of their products, enhancing the recovery rate (Morsetto, 2020). Adapting these models could increase the amount of captured materials used in electronic applications while emerging a new relationship with the customers and increasing sustainability for the coming generations.

Global energy consumption increases as a result of the worldwide increase in the population. Consequently, the energy demand increased from  $5.52 \times 10^{20}$  to  $6.07 \times 10^{20}$  J in 2010–2015 and is expected to be  $6.97 \times 10^{20}$  J by 2030 (IRENA, 2018). The current population relies on supplying the energy demand depending on fossil fuels, resulting in drastic climate problems (Acheampong et al., 2016). Consequently, it was a must to inspire clean energy to substitute fossil fuels. It was planned to supply 20% of the global energy demand from clean renewable energy resources in 2014 (Acheampong et al., 2016). Investment in clean renewable energy sources such as solar, wind, hydro and thermal energy has been considered essential to obtaining affordable electricity by 2030 (Barasa et al., 2018). To attain this goal, a reduction in the global domestic and industrial consumption of electricity is required to be 14% and adapting a cost-effective technology. The developing countries are encouraged to surge their infrastructure and develop energy conversion and storage technologies to offer clean energy, which can encourage political growth, and socio-economic and environmental improvement. Besides, renewable energy can increase employment opportunities to reach 24 M by 2030 (IRENA, 2018; Sen & Ganguly, 2016).

**Table 6** A survey of recovered electrocatalysts from e-waste recovered for supercapacitor

Waste	Recovered Material	Preparation Method	Morphology	Specific capacitance (F g <sup>-1</sup> )	Stability (%) @ cycles	References
Zn-C Batteries	MnO <sub>2</sub>	Leaching and electro-winning	Nano-flower	208.5 @ 0.1 A g <sup>-1</sup> 294 @ 10 mV s <sup>-1</sup>	88 @ 900	(Gomaa et al. 2014)
	MnO <sub>2</sub>	Cyclic voltammetry conversion	Nano-flower	09 @ 0.1 A g <sup>-1</sup>	93 @ 1650	(Gomaa et al. 2017)
	MnO <sub>2</sub>	thermal treatment	Spherical & cubic shape	125 Fg <sup>-1</sup> at 5 mV s <sup>-1</sup>	80% @ 2100	(Farzana et al., 2019)
	MnO <sub>2</sub> /rGO	Cyclic voltammetry conversion	Nano-flower/nanosheets	473 Fg <sup>-1</sup> @ 0.25 A g <sup>-1</sup>	95 @ 2000	(Gomaa et al., 2018)
Spent alkaline battery cathode	MnO <sub>2</sub>	Electrodeposition	spherical cluster shape	549 Fg <sup>-1</sup> @ 5 mV s <sup>-1</sup>	87.2 @ 5000	(Thomas et al. 2019)
LIB	Co <sub>3</sub> O <sub>4</sub>	Chemical precipitation and heat-treatment	Agglomerated crystals	13 Fg <sup>-1</sup> @ 1 mV s <sup>-1</sup>		(E.M.S. Barbieri, et al., 2014)
	Co <sub>3</sub> O <sub>4</sub>	Magnetic electrodeposition	Well-defined hierarchical Nanostructure	1273 Fg <sup>-1</sup> @ 1 A g <sup>-1</sup>	96 @ 5000	(Eslam et al. 2018)
	Reduced graphene oxide (rGO)	Simple chemical method	intrinsic flake-like morphology	112 Fg <sup>-1</sup> @ 0.5 Ag <sup>-1</sup>	108 @ 20,000	(Subramaniaet al. 2018)
Printed circuit boards	LiCoO <sub>2</sub>	Chemical precipitation	Crystal structure	654 F g <sup>-1</sup>	86.9% @ 4000	(Xu et al., 2015)
	MnCo <sub>2</sub> O <sub>4</sub>	Chemical precipitation		122.6 F g <sup>-1</sup> @ 5 mV s <sup>-1</sup>	94.4% @ 8000	(Natarajan et al., 2022)
	Li-Ni-Mn-Co hydroxide	Electrodeposition	Nanoflowers-like structure	951 F g <sup>-1</sup> @ 1 Ag	90% @ 10,000	(Mesbah et al., 2020)
SIM card	CuO	Simple chemical method		408 F g <sup>-1</sup> @ 1 Ag <sup>-1</sup>	93.1% @ 3000	(Rajkumar et al., 2022)
	CuO	Simple chemical method	Cauliflower-like structure	542 Fg <sup>-1</sup> @ 1 Ag <sup>-1</sup>	95.3% @ 5000	(Rajkumar et al., 2020)
Waste Toner	Derived Carbon/Fe <sub>3</sub> O <sub>4</sub>	thermal treatment	Sphere in shape	536 Fg <sup>-1</sup> @ 3 Ag <sup>-1</sup>	97% @ 5000	(Kaipannan et al., 2019)



**Fig. 9** Circular economy approaches in the management of electronic waste (Sharma et al., 2021) with permission from Elsevier

The global sustainability goals have three key pillars: renewable energy sources, increasing energy access, and enhancing energy efficiency, as well as addressing the five following targets (Acheampong et al., 2016; Bishoge et al., 2018): 1. Equality in the accessibility of reliable, cheap, and new energy facilities. 2. Augmented stake of global renewable energy compared to non-renewable energy. 3. Doubling the global population rate while maintaining appropriate energy efficiency. 4. Elevation of international collaboration to license investment in different renewable energy technologies. 5. Green energy technologies improvement to enrich the supply of feasible and modern energy facilities to all communities.

## 6 Conclusion and outlook

The world market for electrical and electronic equipment (EEE) has grown exponentially in recent years while the lifespan of these products has been decreasing. The end-of-life of these products has been in landfills and recycling centers, creating new challenges among stakeholders. Government entities and politicians are attempting to provide solutions for the hazardous components disposed off in landfills. Furthermore, scientists and international organizations are working to develop various processes for recycling valuable materials for use in renewable energy technologies. Electronic devices contain many valuable materials and, when appropriately extracted, can be more valuable than those present in the ore. Policymakers have begun implementing e-waste management policies that allow technology transfer to recover high-quality materials from different types of e-waste. This would help them to meet the sustainable development and Paris Agreement goals. This review described the various hydrometallurgical methods used to extract materials from printed circuit boards and lithium-ion batteries.

Structural changes in the world's energy system, primarily relying on renewable energy, can start with the important role of renewable energy in combination with energy efficiency. Technology development beyond research creates an enabling environment that includes education and awareness-raising. The appropriate and reliable mix of the materials extracted from electronic waste as an eco-design catalyst in different renewable energy technologies has emerged as a hot topic. As explained in the review, some researchers started by recovering copper from printed circuit boards and its use for supercapacitors and water-splitting techniques. However, further research is needed to recover other materials such as Cobalt, Iron, Manganese, and Lithium and use them in various renewable energy technologies. From the presented analysis, future directions may include:

The use of precious metals, copper, and other materials extracted from electronic waste as catalysts for CO<sub>2</sub> reduction, ammonia production, and green hydrogen production.

The use of the extracted materials in renewable energy technologies, such as green biogas production, due to its high methane production efficiency.

The use of recovered materials from e-waste for water treatment and desalination.

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**Data availability** The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that they do not have any potential conflicts of interest.

**Consent to publish** The authors hereby give their consent for submitting this manuscript to this journal. All authors read and approved the final manuscript.

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## References

- Abbas, J., Mahmood, S., Ali, H., et al. (2019). The effects of corporate social responsibility practices and environmental factors through a moderating role of social media marketing on sustainable performance of business firms. *Sustain.* <https://doi.org/10.3390/SU11123434>
- Abbasi, K. R., Hussain, K., Abbas, J., et al. (2020). Analyzing the role of industrial sector's electricity consumption, prices, and GDP: A modified empirical evidence from Pakistan. *AIMS Energy*, 9, 29–49. <https://doi.org/10.3934/ENERGY.2021003>

- Abdelbasir, S. M., Hassan, S. S. M., Kamel, A. H., & El-Nasr, R. S. (2018). Status of electronic waste recycling techniques: A review. *Environmental Science and Pollution Research*, 25, 16533–16547. <https://doi.org/10.1007/s11356-018-2136-6>
- Aboelazm, E. A., Mohamed, N., & Ali, G. A. (2021). Makhlof AS CK recycling of cobalt oxides electrodes from spent lithium-ion batteries by electrochemical method. *Waste Recycling Technologies for Nanomater Manufacturing*. [https://doi.org/10.1007/978-3-030-68031-2\\_4](https://doi.org/10.1007/978-3-030-68031-2_4)
- Acheampong, M., Cansu, F., Kappeler, B., & Neubauer, P. (2016). In pursuit of sustainable development goal (SDG) number 7: Will biofuels be reliable? *Renewable and Sustainable Energy Reviews*. <https://doi.org/10.1016/j.rser.2016.11.074>
- Al Halbusi, H., Al-Sulaiti, K., Abbas, J., & Al-Sulaiti, I. (2022). Assessing factors influencing technology adoption for online purchasing amid COVID-19 in qatar: Moderating role of word of mouth. *Frontiers in Environmental Science*, 10, 1–17. <https://doi.org/10.3389/fenvs.2022.942527>
- Ali, G. A. M., Tan, L. L., Jose, R., Yusoff, M. M., & KFC., (2014). Electrochemical performance studies of MnO<sub>2</sub> nano flowers recovered from spent battery. *Materials Research Bulletin*, 60, 5–9. <https://doi.org/10.1016/j.materresbull.2014.08.008>
- Ali, G. A., Yusoff, M. M., Algarni, H., & Chong, K. F. (2018). One-step electrosynthesis of MnO<sub>2</sub>/rGO nanocomposite and its enhanced electrochemical performance. *Ceramics International*, 44, 7799–7807. <https://doi.org/10.1016/j.ceramint.2018.01.212>
- Anantharaj, S., Ede, S. R., Karthick, K., et al. (2018). Precision and correctness in the evaluation of electrocatalytic water splitting: Revisiting activity parameters with a critical assessment. *Energy & Environmental Science*, 11, 744–771. <https://doi.org/10.1039/c7ee03457a>
- Atef, E., Aboelazm, A., Abdelgawad, G., et al. (2018). Flakes size-dependent optical and electrochemical properties of MoS<sub>2</sub>. *Current Nanoscience*, 14, 416–420. <https://doi.org/10.2174/1573413714666180228152602>
- Atia, T. A., Elia, G., Hahn, R., et al. (2019). Closed-loop hydrometallurgical treatment of end-of-life lithium ion batteries: Towards zero-waste process and metal recycling in advanced batteries. *Journal of Energy Chemistry*, 35, 220–227. <https://doi.org/10.1016/j.jechem.2019.03.022>
- Babar, P., Lokhande, A., Karade, V., et al. (2019). Towards highly efficient and low-cost oxygen evolution reaction electrocatalysts: An effective method of electronic waste management by utilizing waste Cu cable wires. *Journal of Colloid and Interface Science*, 537, 43–49. <https://doi.org/10.1016/j.jcis.2018.10.079>
- Barasa, M., Bogdanov, D., Oyewo, A. S., & Breyer, C. (2018). A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030. *Renewable and Sustainable Energy Reviews*, 92, 440–457. <https://doi.org/10.1016/j.rser.2018.04.110>
- Barbieri, E. M. S., Lima, E. P. C., & Lelis, M. F. F. (2014). Recycling of cobalt from spent Li-ion batteries as b-Co (OH)<sub>2</sub> and the application of Co<sub>3</sub>O<sub>4</sub> as a pseudocapacitor. *Journal of Power Sources*, 270, 158–165. <https://doi.org/10.1016/j.jpowsour.2014.07.108>
- Baum, Z. J., Bird, R. E., Yu, X., & Ma, J. (2022). Lithium-ion battery recycling—overview of techniques and trends. *ACS Energy Letter*, 7, 712–719. <https://doi.org/10.1021/acsenenergylett.1c02602>
- Benck, J. D., Hellstern, T. R., Kibsgaard, J., et al. (2014). Catalyzing the hydrogen evolution reaction (HER) with molybdenum sulfide nanomaterials. *Acs Catalysis*. <https://doi.org/10.1021/cs500923c>
- Bhaskar, K. B. K. (2018). Electronic waste management and sustainable development goals is there a business case for linking the two? *Journal of Indian Business Research*. <https://doi.org/10.1108/JIBR-01-2018-0051>
- Bhuie, A. K., Ogunseitan, O. A., Saphores, J. D. M., Shapiro, A. A (2004) Environmental and economic trade-offs in consumer electronic products recycling: A case study of cell phones and computers. In *IEEE International Symposium on Electronics and the Environment* 74–79. doi:<https://doi.org/10.1109/isee.2004.1299691>
- Birloaga, I., Coman, V., Kopacek, B., & Vegliò, F. (2014). An advanced study on the hydrometallurgical processing of waste computer printed circuit boards to extract their valuable content of metals. *Waste Management*, 34, 2581–2586. <https://doi.org/10.1016/j.wasman.2014.08.028>
- Birloaga, I., De Michelis, I., Ferella, F., et al. (2013). Study on the influence of various factors in the hydrometallurgical processing of waste printed circuit boards for copper and gold recovery. *Waste Management*, 33, 935–941. <https://doi.org/10.1016/j.wasman.2013.01.003>
- Bishoge, O., Zhang, L., & Mushi, W. (2018). The potential renewable energy for sustainable development in Tanzania: A review. *Cleaning Technology*, 1, 70–88. <https://doi.org/10.3390/cleantechnol1010006>
- Camelino, S., Rao, J., Padilla, R. L., & Lucci, R. (2015). Initial studies about gold leaching from printed circuit boards (PCB's) of waste cell phones. *Procedia Materials Science*, 9, 105–112. <https://doi.org/10.1016/j.mspro.2015.04.013>



- Campbell, F. W., Belding, S. R., Baron, R., et al. (2009). The hydrogen evolution reaction at a silver nanoparticle array and a silver macroelectrode compared: Changed electrode kinetics between the macro- and nanoscales. *The Journal of Physical Chemistry C*, 33, 14852–14857.
- Chancerel, P., Meskers, C. E. M., Hagelüken, C., & Rotter, V. S. (2009). Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. *Journal of Industrial Ecology*, 13, 791–810.
- Chen, M., Huang, J., Ogunseitan, O. A., et al. (2015). Comparative study on copper leaching from waste printed circuit boards by typical ionic liquid acids. *Waste Management*, 41, 142–147. <https://doi.org/10.1016/j.wasman.2015.03.037>
- Chen, X., Wang, H., Meng, R., et al. (2020). Cadmium hydroxide: A missing non-noble metal hydroxide electrocatalyst for the oxygen evolution reaction. *ACS Applied Energy Materials*. <https://doi.org/10.1021/acsaeam.9b02352>
- Chu, Y., Chen, M., Chen, S., et al. (2015). Micro-copper powders recovered from waste printed circuit boards by electrolysis. *Hydrometallurgy*, 156, 152–157. <https://doi.org/10.1016/j.hydromet.2015.06.006>
- Chung, S. S., Lau, K. Y., & Zhang, C. (2011). Generation of and control measures for, e-waste in Hong Kong. *Waste Management*, 31, 544–554. <https://doi.org/10.1016/j.wasman.2010.10.003>
- COP26 (2021) COP26: EU helps deliver outcome to keep the Paris Agreement targets alive. 2020–2021
- Cui, J., & Forssberg, E. (2003). Mechanical recycling of waste electric and electronic equipment: A review. *Journal of Hazardous Materials*, 99, 243–263. [https://doi.org/10.1016/S0304-3894\(03\)00061-X](https://doi.org/10.1016/S0304-3894(03)00061-X)
- Cui, J., & Forssberg, E. (2007). Characterization of shredded television scrap and implications for materials recovery. *Waste Management*, 27, 415–424. <https://doi.org/10.1016/j.wasman.2006.02.003>
- Dao, V., Langella, I., & Carbo, J. (2011). From green to sustainability: Information Technology and an integrated sustainability framework. *The Journal of Strategic Information Systems*, 20, 63–79. <https://doi.org/10.1016/j.jsis.2011.01.002>
- Das, S., Lee, S. H., Kumar, P., et al. (2019). Solid waste management: Scope and the challenge of sustainability. *Journal of Cleaner Production*, 228, 658–678. <https://doi.org/10.1016/j.jclepro.2019.04.323>
- Dávila-Pulido, G. I., Salinas-Rodríguez, A., Carrillo-Pedroza, F. R., et al. (2021). Leaching kinetics of electronic waste for the recovery of copper: Rate-controlling step and rate process in a multisize particle system. *International Journal of Chemical Kinetics*, 53, 379–389. <https://doi.org/10.1002/kin.21450>
- de Oliveira Demarco, J., Stefanello Cadore, J., da de Silveira Oliveira, F., et al. (2019). Recovery of metals from spent lithium-ion batteries using organic acids. *Hydrometallurgy*, 190, 105169. <https://doi.org/10.1016/j.hydromet.2019.105169>
- Deng, H., Su, Y., Liao, Z., & Wu, J. (2022). Proposal of implementation framework of cooperative approaches and sustainable development mechanism. *Sustain*. <https://doi.org/10.3390/su14020655>
- Diaz, L. A., Lister, T. E., Parkman, J. A., & Clark, G. G. (2016). Comprehensive process for the recovery of value and critical materials from electronic waste. *Journal of Cleaner Production*, 125, 236–244. <https://doi.org/10.1016/j.jclepro.2016.03.061>
- Ding, Y., Zhang, S., Liu, B., et al. (2019). Recovery of precious metals from electronic waste and spent catalysts: A review. *Resources, Conservation and Recycling*, 141, 284–298. <https://doi.org/10.1016/j.resconrec.2018.10.041>
- Directive EC (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment WOEJ of the EUL 2012;197:38-71. Directive EC. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment, WEEE. Official Journal of the European Union L. 197:38-71.
- Farzana, R., Hassan, K., & Sahajwalla, V. (2019). Manganese oxide synthesized from spent Zn–C battery for supercapacitor electrode application. *Science and Reports*, 9, 8982. <https://doi.org/10.1038/s41598-019-44778-z>
- Flandinet, L., Tedjar, F., Ghetta, V., & Fouletier, J. (2012). Metals recovering from waste printed circuit boards (WPCBs) using molten salts. *Journal of Hazardous Materials*, 213–214, 485–490. <https://doi.org/10.1016/j.jhazmat.2012.02.037>
- Fogarasi, S., Imre-Lucaci, F., Egedy, A., et al. (2015). Eco-friendly copper recovery process from waste printed circuit boards using  $\text{Fe}^{3+}/\text{Fe}^{2+}$  redox system. *Waste Management*, 40, 136–143. <https://doi.org/10.1016/j.wasman.2015.02.030>
- Forti, V., Baldé, C. P., Kuehr, R., Bel, G. (2020) The global e-waste monitor. Quantities, flows and the circular economy potential. [https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM\\_2020\\_def.pdf](https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf)
- Freitas, M. B. J. G., & Garcia, E. M. (2007). Electrochemical recycling of cobalt from cathodes of spent lithium–ion batteries. *Journal of Power Sources*, 171, 953–959. <https://doi.org/10.1016/j.jpowsour.2007.07.002>

- Fu, Y., He, Y., Chen, H., et al. (2019a). Effective leaching and extraction of valuable metals from electrode material of spent lithium-ion batteries using mixed organic acids leachant. *Journal of Industrial and Engineering Chemistry*, 79, 154–162. <https://doi.org/10.1016/j.jiec.2019.06.023>
- Fu, Y., He, Y., Qu, L., et al. (2019b). Enhancement in leaching process of lithium and cobalt from spent lithium-ion batteries using benzenesulfonic acid system. *Waste Management*, 88, 191–199. <https://doi.org/10.1016/j.wasman.2019.03.044>
- Gao, Y., Gao, X., & Zhang, X. (2017). The 2 °C global temperature target and the evolution of the long-term goal of addressing climate change—from the united nations framework convention on climate change to the Paris agreement. *Engineering*, 3, 272–278. <https://doi.org/10.1016/J.ENG.2017.01.022>
- Gautam, P., Behera, C. K., Sinha, I., et al. (2022). High added-value materials recovery using electronic scrap-transforming waste to valuable products. *Journal of Cleaner Production*, 330, 129836. <https://doi.org/10.1016/j.jclepro.2021.129836>
- Gonçalves, J. M., & Araki, K. (2020). Vanadium-containing electro and photocatalysts for the oxygen evolution reaction: a review. *Journal of Materials Chemistry A*. <https://doi.org/10.1039/c9ta10857b>
- Guo, C., Wang, H., Liang, W., et al. (2011). Liberation characteristic and physical separation of printed circuit board (PCB). *Waste Management*, 31, 2161–2166. <https://doi.org/10.1016/j.wasman.2011.05.011>
- Guo, X., Qin, H., Tian, Q., & Li, D. (2020). Recovery of metals from waste printed circuit boards by selective leaching combined with cyclone electrowinning process. *Journal of Hazard Materials*, 384, 121355. <https://doi.org/10.1016/j.jhazmat.2019.121355>
- Guo, X., & Yan, K. (2017). Estimation of obsolete cellular phones generation: A case study of China. *Science of the Total Environment*, 575, 321–329. <https://doi.org/10.1016/j.scitotenv.2016.10.054>
- Gurgul, A., Szczepaniak, W., & Zabłocka-Malicka, M. (2018). Incineration and pyrolysis vs. steam gasification of electronic waste. *Science of the Total Environment*, 624, 1119–1124. <https://doi.org/10.1016/j.scitotenv.2017.12.151>
- Ha, V. H., Lee, J. C., Huynh, T. H., et al. (2014). Optimizing the thiosulfate leaching of gold from printed circuit boards of discarded mobile phone. *Hydrometallurgy*, 149, 118–126. <https://doi.org/10.1016/j.hydromet.2014.07.007>
- Hagelūken, C. (2006) Improving metal returns and eco-efficiency in electronics recycling - a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining. In *Proceedings of 2006 IEEE International Symposium of Electronics and the Environment* 218–223
- Hai, H. T., Gwan, A. J., Jin, K. D., et al. (2007). Growth process of copper particles in the cuprous oxide-water system. *Materials Transactions*, 48, 1137–1142. <https://doi.org/10.2320/matertrans.48.1137>
- Hazra, A., Das, S., Ganguly, A., et al. (2019). *Waste valorisation and recycling*. Singapore: Springer.
- He, L. P., Sun, S. Y., Song, X. F., & Yu, J. G. (2017). Leaching process for recovering valuable metals from the LiNi<sub>1/3</sub>Co<sub>1/3</sub>Mn<sub>1/3</sub>O<sub>2</sub> cathode of lithium-ion batteries. *Waste Management*, 64, 171–181. <https://doi.org/10.1016/j.wasman.2017.02.011>
- He, P., Wang, C., & Zuo, L. (2018). The present and future availability of high-tech minerals in waste mobile phones: Evidence from China. *Journal of Cleaner Production*, 192, 940–949. <https://doi.org/10.1016/j.jclepro.2018.04.222>
- He, Y., & Xu, Z. (2015). Recycling gold and copper from waste printed circuit boards using chlorination process. *RSC Advances*, 5, 8957–8964. <https://doi.org/10.1039/c4ra16231e>
- Holgerson, S., Steenari, B. M., Björkman, M., & Cullbrand, K. (2018). Analysis of the metal content of small-size waste electric and electronic equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. *Resources, Conservation and Recycling*, 133, 300–308. <https://doi.org/10.1016/j.resconrec.2017.02.011>
- Hu, C., Electrochem, J., Soc, A., et al. (2004). How to achieve maximum utilization of hydrous ruthenium oxide for supercapacitors how to achieve maximum utilization of hydrous ruthenium oxide for supercapacitors. *Journal of the Electrochemical Society*. <https://doi.org/10.1149/1.1639020>
- IRENA (2018) Renewable Energy Outlook: Egypt
- İşildar, A., van de Vossenberg, J., Rene, E. R., et al. (2016). Two-step bioleaching of copper and gold from discarded printed circuit boards (PCB). *Waste Management*, 57, 149–157. <https://doi.org/10.1016/j.wasman.2015.11.033>
- Islam, M. T., & Huda, N. (2018). Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment (WEEE)/E-waste: A comprehensive literature review. *Resources, Conservation and Recycling*, 137, 48–75. <https://doi.org/10.1016/j.resconrec.2018.05.026>
- Jha, M. K., Kumari, A., Jha, A. K., et al. (2013). Recovery of lithium and cobalt from waste lithium ion batteries of mobile phone. *Waste Management*, 33, 1890–1897. <https://doi.org/10.1016/j.wasman.2013.05.008>

- Jiang, J., Materna, K. L., Hedström, S., et al. (2017). Antimony complexes for electrocatalysis: Activity of a main-group element in proton reduction. *Angewandte Chemie International Edition*. <https://doi.org/10.1002/anie.201704700>
- Jiao, Z. B., Luan, J. H., Guo, W., et al. (2016). Effects of welding and post-weld heat treatments on nanoscale precipitation and mechanical properties of an ultra-high strength steel hardened by NiAl and Cu nanoparticles. *Acta Materialia*, 120, 216–227. <https://doi.org/10.1016/j.actamat.2016.08.066>
- Jothi, V. R., Bose, R., Rajan, H., et al. (2018). Harvesting electronic waste for the development of highly efficient eco-design electrodes for electrocatalytic water splitting. *Advanced Energy Materials*, 8, 1–11. <https://doi.org/10.1002/aenm.201802615>
- Joulié, M., Laucournet, R., & Billy, E. (2014). Hydrometallurgical process for the recovery of high value metals from spent lithium nickel cobalt aluminum oxide based lithium-ion batteries. *Journal of Power Sources*, 247, 551–555. <https://doi.org/10.1016/j.jpowsour.2013.08.128>
- Kaipannan, S., Govindarajan, K., Sundaramoorthy, S., & Marappan, S. (2019). Waste toner-derived carbon/Fe<sub>3</sub>O<sub>4</sub> nanocomposite for high-performance supercapacitor. *ACS Omega*, 4, 15798–15805. <https://doi.org/10.1021/acsomega.9b01337>
- Kaliyavaradhan, S. K., Prem, P. R., Ambily, P. S., & Mo, K. H. (2022). Effective utilization of e-waste plastics and glasses in construction products—a review and future research directions. *Resources, Conservation and Recycling*. <https://doi.org/10.1016/j.resconrec.2021.105936>
- Karthik, P. E., Mondal, S., Sahoo, L., & Gautam, U. K. (2018). Exploring discharged dry cell as an electrocatalyst for oxygen evolution reaction. *The Royal Society of Chemistry*, 1–8. <https://doi.org/10.1039/b000000x/a>
- Karthik, P. E., Rajan, H., Jothi, V. R., et al. (2022). Electronic wastes: A near inexhaustible and an unimaginably wealthy resource for water splitting electrocatalysts. *Journal of Hazardous Materials*, 421, 126687. <https://doi.org/10.1016/j.jhazmat.2021.126687>
- Kasper, A. C., Berselli, G. B. T., Freitas, B. D., et al. (2011). Printed wiring boards for mobile phones: Characterization and recycling of copper. *Waste Management*, 31, 2536–2545. <https://doi.org/10.1016/j.wasman.2011.08.013>
- Kasper, A. C., Veit, H. M., García-Gabaldón, M., & Herranz, V. P. (2018). Electrochemical study of gold recovery from ammoniacal thiosulfate, simulating the PCBs leaching of mobile phones. *Electrochimica Acta*, 259, 500–509. <https://doi.org/10.1016/j.electacta.2017.10.161>
- Khalil, A., Jouiad, M., Khraisheh, M., & Hashaiekh, R. (2014). Facile synthesis of copper oxide nanoparticles via electrosynthesis. *Journal of Nanomater.* <https://doi.org/10.1155/2014/438407>
- Khetriwal, D. S., Kraeuchi, P., & Widmer, R. (2009). Producer responsibility for e-waste management: Key issues for consideration - Learning from the Swiss experience. *Journal of Environmental Management*, 90, 153–165. <https://doi.org/10.1016/j.jenvman.2007.08.019>
- Kim, J., Shih, P., Tsao, K., et al. (2017). High-performance pyrochlore-type yttrium ruthenate electrocatalyst for oxygen evolution reaction in acidic media high-performance pyrochlore-type yttrium ruthenate electrocatalyst for oxygen evolution reaction in acidic media. *Journal of the American Chemical Society*. <https://doi.org/10.1021/jacs.7b06808>
- Klaine, S. J., Koelmans, A. A., Horne, N., et al. (2012). Paradigms to assess the environmental impact of manufactured nanomaterials Stephen. *Environmental Toxicology and Chemistry*, 31, 3–14. <https://doi.org/10.1002/etc.733>
- Kumar, A., Holuszko, M., & Espinosa, D. C. R. (2017a). E-waste: An overview on generation, collection, legislation and recycling practices. *Resources, Conservation and Recycling*, 122, 32–42. <https://doi.org/10.1016/j.resconrec.2017.01.018>
- Kumar, B., Manrai, A. K., & Manrai, L. A. (2017b). Purchasing behaviour for environmentally sustainable products: A conceptual framework and empirical study. *Journal of Retailing and Consumer Services*, 34, 1–9. <https://doi.org/10.1016/j.jretconser.2016.09.004>
- Kumari, A., Jha, M. K., Lee, J. C., & Singh, R. P. (2016). Clean process for recovery of metals and recycling of acid from the leach liquor of PCBs. *Journal of Cleaner Production*, 112, 4826–4834. <https://doi.org/10.1016/j.jclepro.2015.08.018>
- Lahti, J., Vazquez, S., Virolainen, S., et al. (2020). Membrane filtration enhanced hydrometallurgical recovery process of indium from waste LCD panels. *Journal of Sustainable Metallurgy*, 6, 576–588. <https://doi.org/10.1007/s40831-020-00293-4>
- Landsiedel, R., Ma-Hock, L., Kroll, A., et al. (2010). Testing metal-oxide nanomaterials for human safety. *Advanced Materials*, 22, 2601–2627. <https://doi.org/10.1002/adma.200902658>
- Lee, C. K., & Rhee, K. I. (2002). Preparation of LiCoO<sub>2</sub> from spent lithium-ion batteries. *Journal of Power Sources*, 109, 17–21. [https://doi.org/10.1016/S0378-7753\(02\)00037-X](https://doi.org/10.1016/S0378-7753(02)00037-X)
- Lee, C. H., Tang, L. W., & Popuri, S. R. (2011). A study on the recycling of scrap integrated circuits by leaching. *Waste Management Research*, 29, 677–685. <https://doi.org/10.1177/0734242X10380995>

- Lee, S. W., Carlton, C., Risch, M., et al. (2012). The nature of lithium battery materials under oxygen evolution reaction conditions. *Journal of the American Chemical Society*, 136, 3–6.
- Li, C. W., & Kanan, M. W. (2012). CO<sub>2</sub> reduction at low overpotential on Cu electrodes resulting from the reduction of thick Cu<sub>2</sub>O films. *Journal of the American Chemical Society*, 134, 7231–7234. <https://doi.org/10.1021/ja3010978>
- Li, H., Xing, S., Liu, Y., et al. (2017). Recovery of lithium, iron, and phosphorus from spent LiFePO<sub>4</sub> batteries using stoichiometric sulfuric acid leaching system. *ACS Sustainable Chemistry and Engineering*, 5, 8017–8024. <https://doi.org/10.1021/acssuschemeng.7b01594>
- Li, L., Bian, Y., Zhang, X., et al. (2018). Economical recycling process for spent lithium-ion batteries and macro- and micro-scale mechanistic study. *Journal of Power Sources*, 377, 70–79. <https://doi.org/10.1016/j.jpowsour.2017.12.006>
- Li, L., Qu, W., Zhang, X., et al. (2015). Succinic acid-based leaching system: A sustainable process for recovery of valuable metals from spent Li-ion batteries. *Journal of Power Sources*, 282, 544–551. <https://doi.org/10.1016/j.jpowsour.2015.02.073>
- Li, W., & Chen, M. (2014). Synthesis of stable ultra-small Cu nanoparticles for direct writing flexible electronics. *Applied Surface Science*, 290, 240–245. <https://doi.org/10.1016/j.apsusc.2013.11.057>
- Li, X., Zhao, L., Yu, J., et al. (2020). Water splitting: From electrode to green energy system. *Nano-Micro Lett*, 12, 1–29. <https://doi.org/10.1007/s40820-020-00469-3>
- Liang, Z., Peng, G., Hu, J., et al. (2022). Mechanochemically assisted persulfate activation for the facile recovery of metals from spent lithium ion batteries. *Waste Management*, 150, 290–300. <https://doi.org/10.1016/j.wasman.2022.07.014>
- Liu, K., Yang, J., Hou, H., et al. (2019). Facile and cost-effective approach for copper recovery from waste printed circuit boards via a sequential mechanochemical/leaching/recrystallization process. *Environmental Science & Technology*, 53(5), 2748–2757. <https://doi.org/10.1021/acs.est.8b06081>
- Liu, Q., Li, K. Q., Zhao, H., et al. (2009). The global challenge of electronic waste management. *Environmental Science and Pollution Research*, 16, 248–249. <https://doi.org/10.1007/s11356-009-0131-7>
- Liu, Y., Song, Q., Zhang, L., & Xu, Z. (2022). Targeted recovery of Ag–Pd alloy from polymetallic electronic waste leaching solution via green electrodeposition technology and its mechanism. *Separation and Purification Technology*, 280, 118944. <https://doi.org/10.1016/j.seppur.2021.118944>
- Lui, J., Chen, W. H., Tsang, D. C. W., & You, S. (2020). A critical review on the principles, applications, and challenges of waste-to-hydrogen technologies. *Renewable and Sustainable Energy Reviews*, 134, 110365. <https://doi.org/10.1016/j.rser.2020.110365>
- Matsukami, H., Tue, N. M., Suzuki, G., et al. (2015). Flame retardant emission from e-waste recycling operation in northern Vietnam: Environmental occurrence of emerging organophosphorus esters used as alternatives for PBDEs. *Science of the Total Environment*, 514, 492–499. <https://doi.org/10.1016/j.scitotenv.2015.02.008>
- Meng, F., Liu, Q., Kim, R., et al. (2020). Selective recovery of valuable metals from industrial waste lithium-ion batteries using citric acid under reductive conditions: Leaching optimization and kinetic analysis. *Hydrometallurgy*, 191, 105160. <https://doi.org/10.1016/j.hydromet.2019.105160>
- Meng, Q., Zhang, Y., & Dong, P. (2017). Use of glucose as reductant to recover Co from spent lithium ions batteries. *Waste Management*, 64, 214–218. <https://doi.org/10.1016/j.wasman.2017.03.017>
- Meng, Q., Zhang, Y., & Dong, P. (2018). Use of electrochemical cathode-reduction method for leaching of cobalt from spent lithium-ion batteries. *Journal of Cleaner Production*, 180, 64–70. <https://doi.org/10.1016/j.jclepro.2018.01.101>
- Mesbah, Y. I., Ahmed, N., Ali, B. A., & Allam, N. K. (2020). Recycling of Li–Ni–Mn–Co hydroxide from spent batteries to produce high-performance supercapacitors with exceptional stability. *ChemElectroChem*, 7, 975–982. <https://doi.org/10.1002/celec.202000081>
- Mohamed, A., Yousef, S., Ali Abdelnaby, M., et al. (2017). Photocatalytic degradation of organic dyes and enhanced mechanical properties of PAN/CNTs composite nanofibers. *Separation and Purification Technology*, 182, 219–223. <https://doi.org/10.1016/j.seppur.2017.03.051>
- Mohammadi, E., Singh, S. J., & Habib, K. (2021). Electronic waste in the Caribbean: An impending environmental disaster or an opportunity for a circular economy? *Resources Conservation and Recycling*, 164, 105106. <https://doi.org/10.1016/j.resconrec.2020.105106>
- Morseletto, P. (2020). Targets for a circular economy. *Resources Conservation and Recycling*, 153, 104553. <https://doi.org/10.1016/j.resconrec.2019.104553>
- Mubeen, R., Han, D., Abbas, J., et al. (2022). Examining the relationship between product market competition and Chinese firms performance: the mediating impact of capital structure and moderating influence of firm size. *Frontiers in Psychology*, 12, 1–13. <https://doi.org/10.3389/fpsyg.2021.709678>

- Natarajan, S., Krishnamoorthy, K., & Kim, S.-J. (2022). Effective regeneration of mixed composition of spent lithium-ion batteries electrodes towards building supercapacitor. *Journal of Hazard Materials*, 430, 128496. <https://doi.org/10.1016/J.JHAZMAT.2022.128496>
- Nathan, T., Aziz, A., Noor, A. F., & Prabakaran, S. R. S. (2008). Nanostructured NiO for electrochemical capacitors : Synthesis and electrochemical properties. *Journal of Solid State Electrochemistry*. <https://doi.org/10.1007/s10008-007-0465-3>
- Nayaka, G. P., Pai, K. V., Santhosh, G., & Manjanna, J. (2016). Recovery of cobalt as cobalt oxalate from spent lithium ion batteries by using glycine as leaching agent. *Journal of Environmental Chemical Engineering*, 4, 2378–2383. <https://doi.org/10.1016/j.jece.2016.04.016>
- Nekouei, R. K., Tudela, I., Mofarah, S. S., et al. (2021). Dual functionality of mixed Cu-based two-dimensional (2D) heterostructures derived from electronic waste. *Green Chemistry*. <https://doi.org/10.1039/d1gc00354b>
- Nguyen, R. T., Diaz, L. A., Imholte, D. D., & Lister, T. E. (2017). Economic assessment for recycling critical metals from hard disk drives using a comprehensive recovery process. *JOM Journal of the Minerals Metals and Materials Society*, 69, 1546–1552. <https://doi.org/10.1007/s11837-017-2399-2>
- Nithya, R., Sivasankari, C., & Thirunavukkarasu, A. (2021). Electronic waste generation, regulation and metal recovery: A review. *Environmental Chemistry Letters*, 19, 1347–1368. <https://doi.org/10.1007/s10311-020-01111-9>
- Niu, B., Chen, Z., & Xu, Z. (2020). Recycling waste tantalum capacitors to synthesize high value-added Ta<sub>2</sub>O<sub>5</sub> and polyaniline-decorated Ta<sub>2</sub>O<sub>5</sub> photocatalyst by an integrated chlorination-sintering-chemisorption process. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2019.06.037>
- Niu, B., & Xu, Z. (2019). Innovating e-waste recycling : From waste multi-layer ceramic capacitors to Nb/Pb codoped and ag-Pd-Sn-Ni loaded BaTiO<sub>3</sub> nano-photocatalyst through one-step ball milling process. *Sustainable Materials and Technologies*, 21, e00101. <https://doi.org/10.1016/j.susmat.2019.e00101>
- Pan, L., Zhang, X., He, S., et al. (2022). Eco-friendly and efficient extraction of AU from waste mobile phones using a sodium persulfate–potassium iodide system. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4013267>
- Pariatamby, A., Cheah, W. Y., Shrizal, R., et al. (2015). Enhancement of landfill methane oxidation using different types of organic wastes. *Environment and Earth Science*, 73, 2489–2496. <https://doi.org/10.1007/s12665-014-3600-3>
- Pender, J. P., Jha, G., Youn, D. H., et al. (2020). Electrode degradation in lithium-ion batteries. *ACS Nano*, 14, 1243–1295. <https://doi.org/10.1021/acsnano.9b04365>
- Poizot, P., Laruelle, S., Grugnon, S., et al. (2000). Nano-sized transition-metal oxides as negative-electrode materials for lithium-ion batteries. *Nature*, 407, 496–499. <https://doi.org/10.1038/35035045>
- Qian, J., Wang, T., Xia, B., et al. (2019). Zn-doped MoSe<sub>2</sub> nanosheets as high-performance electrocatalysts for hydrogen evolution reaction in acid media. *Electrochimica Acta*, 296, 701–708. <https://doi.org/10.1016/j.electacta.2018.10.089>
- Quinet, P., Proost, J., & Van Lierde, A. (2005). Recovery of precious metals from electronic scrap by hydrometallurgical processing routes. *Mining, Metallurgy & Exploration*, 22(1), 17–22. <https://doi.org/10.1007/BF03403191>
- Raj, T., Chandrasekhar, K., Kumar, A. N., et al. (2022). Recycling of cathode material from spent lithium-ion batteries: Challenges and future perspectives. *Journal of Hazard Materials*, 429, 128312. <https://doi.org/10.1016/j.jhazmat.2022.128312>
- Rajkumar, S., Elanthamilan, E., Balaji, T. E., et al. (2020). Recovery of copper oxide nanoparticles from waste SIM cards for supercapacitor electrode material. *Journal of Alloys Compounds*, 849, 156582. <https://doi.org/10.1016/j.jallcom.2020.156582>
- Rajkumar, S., Elanthamilan, E., Wang, S. F., et al. (2022). One-pot green recovery of copper oxide nanoparticles from discarded printed circuit boards for electrode material in supercapacitor application. *Resources Conservation and Recycling*, 180, 106180. <https://doi.org/10.1016/j.resconrec.2022.106180>
- Rautela, R., Arya, S., Vishwakarma, S., et al. (2021). E-waste management and its effects on the environment and human health. *Science of Total Environment*, 773, 145623. <https://doi.org/10.1016/j.scitotenv.2021.145623>
- Sahai, A., Goswami, N., Kaushik, S. D., & Tripathi, S. (2016). Cu/Cu<sub>2</sub>O/CuO nanoparticles: Novel synthesis by exploding wire technique and extensive characterization. *Applied Surface Science*, 390, 974–983. <https://doi.org/10.1016/j.apsusc.2016.09.005>
- Sahan, Y. (2016) Gold separation of handphone circuit board scraps (PCBs) by leaching process. *International Journal of Environmental Research & Clean Energy*, 3. <https://isomase.org/IJERCE1.php>



- Sahin, M., Akcil, A., Erust, C., et al. (2015). A potential alternative for precious metal recovery from e-waste: iodine leaching. *Separation Science and Technology*, 50, 2587–2595. <https://doi.org/10.1080/01496395.2015.1061005>
- Sayilgan, E., Kukrer, T., Civelekoglu, G., Ferella, F., & AkcilVeglio, A. F. M. K. (2009). Hydrometallurgy a review of technologies for the recovery of metals from spent alkaline and zinc-carbon batteries. *Hydrometallurgy*, 97, 158–166. <https://doi.org/10.1016/j.hydromet.2009.02.008>
- Seif El-Nasr, R., Abdelbasir, S. M., Kamel, A. H., & Hassan, S. S. M. (2020). Environmentally friendly synthesis of copper nanoparticles from waste printed circuit boards. *Separation and Purification Technology*, 230, 115860. <https://doi.org/10.1016/j.seppur.2019.115860>
- Sen, S., & Ganguly, S. (2016). Opportunities, barriers and issues with renewable energy development – A discussion. *Renewable and Sustainable Energy Reviews*, 69, 1170–1181. <https://doi.org/10.1016/j.rser.2016.09.137>
- Sharma, H. B., Vanapalli, K. R., Samal, B., et al. (2021). Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery. *Science of the Total Environment*, 800, 149605. <https://doi.org/10.1016/j.scitotenv.2021.149605>
- Silvas, F. P. C., Jiménez Correa, M. M., Caldas, M. P. K., et al. (2015). Printed circuit board recycling: Physical processing and copper extraction by selective leaching. *Waste Management*, 46, 503–510. <https://doi.org/10.1016/j.wasman.2015.08.030>
- Su, F., Zhou, X., Liu, X., et al. (2022). Recovery of valuable metals from spent lithium-ion batteries by complexation-assisted ammonia leaching from reductive roasting residue. *SSRN Electron Journal*, 312, 137230. <https://doi.org/10.2139/ssrn.4196427>
- Sun, L. Y., Liu, B. R., Wu, T., Wang, G. G., Huang, Q., Su, Y. F., & Wu, F. (2021). Hydrometallurgical recycling of valuable metals from spent lithium-ion batteries by reductive leaching with stannous chloride. *International Journal of Minerals Metallurgy and Materials*, 28, 991–1000. <https://doi.org/10.1007/s12613-020-2115-z>
- Tan, Q., Duan, H., Liu, L., et al. (2018). Rethinking residential consumers' behavior in discarding obsolete mobile phones in China. *Journal of Cleaner Production*, 195, 1228–1236. <https://doi.org/10.1016/j.jclepro.2018.05.244>
- Tatariants, M., Yousef, S., Sakalauskaitė, S., et al. (2018). Antimicrobial copper nanoparticles synthesized from waste printed circuit boards using advanced chemical technology. *Waste Management*, 78, 521–531. <https://doi.org/10.1016/j.wasman.2018.06.016>
- United Nations Development Programme (2015) E-Waste Assessment Report- EEAA report.
- US EPA (2017) Overview of Greenhouse Gases | US EPA. Us Epa Al-Homoud, M. S. (2001). Computer-aided building e.
- Valero Navazo, J. M., Villalba Méndez, G., & Talens Peiró, L. (2014). Material flow analysis and energy requirements of mobile phone material recovery processes. *International Journal of Life Cycle Assessment*, 19, 567–579. <https://doi.org/10.1007/s11367-013-0653-6>
- Wang, J., & Sun, X. (2015). Olivine LiFePO<sub>4</sub>: The remaining challenges for future energy storage. *Energy & Environmental Science*, 8, 1110–1138. <https://doi.org/10.1039/c4ee04016c>
- Wang, J., Zhu, H., Chen, J. D., et al. (2016). Small and well-dispersed Cu nanoparticles on carbon nanofibers: Self-supported electrode materials for efficient hydrogen evolution reaction. *International Journal of Hydrogen Energy*, 41, 18044–18049. <https://doi.org/10.1016/j.ijhydene.2016.08.058>
- Wang, Ni., Lei, H., Zhang, Z., Jianfeng Li, W., & Zhang, R. C. (2019a). Electrocatalytic hydrogen evolution with gallium hydride and ligand-centered reduction. *Chemical Science*, 10, 2308–2314. <https://doi.org/10.1039/c8sc05247f>
- Wang, R., Zhang, C., Zhao, Y., et al. (2021). Recycling gold from printed circuit boards gold-plated layer of waste mobile phones in “mild aqua regia” system. *Journal of Cleaning Production*. <https://doi.org/10.1016/j.jclepro.2020.123597>
- Wang, Z., Li, C., & Domen, K. (2019b). Recent developments in heterogeneous photocatalysts for solar-driven overall water splitting. *Chemical Society Reviews*, 48, 2109–2125. <https://doi.org/10.1039/c8cs00542g>
- Wilson, G. T., Smalley, G., Suckling, J. R., et al. (2017). The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery. *Waste Management*, 60, 521–533. <https://doi.org/10.1016/j.wasman.2016.12.023>
- Wygant, B. R., Jarvis, K. A., Chemelewski, W. D., et al. (2016). Structural and catalytic Effects of iron- and scandium-doping on a strontium cobalt oxide electrocatalyst for water oxidation. *ACS Catalysis*. <https://doi.org/10.1021/acscatal.5b02429>

- Xiao, J., Li, J., & Xu, Z. (2017). Recycling metals from lithium ion battery by mechanical separation and vacuum metallurgy. *Journal of Hazardous Materials*, 338, 124–131. <https://doi.org/10.1016/j.jhazmat.2017.05.024>
- Xiu, F. R., Qi, Y., & Zhang, F. S. (2015). Leaching of Au, Ag, and Pd from waste printed circuit boards of mobile phone by iodide lixiviant after supercritical water pre-treatment. *Waste Management*, 41, 134–141. <https://doi.org/10.1016/j.wasman.2015.02.020>
- Xiu, F. R., Weng, H., Qi, Y., et al. (2017). A novel recovery method of copper from waste printed circuit boards by supercritical methanol process: Preparation of ultrafine copper materials. *Waste Management*, 60, 643–651. <https://doi.org/10.1016/j.wasman.2016.11.001>
- Xiu, F.-R., & Zhang, F.-S. (2009). Preparation of nano-Cu<sub>2</sub>O/TiO<sub>2</sub> photocatalyst from waste printed circuit boards by electrokinetic process. *Journal of Hazardous Materials*, 172, 1458–1463. <https://doi.org/10.1016/j.jhazmat.2009.08.012>
- Xu, Y., Dong, Y., Han, X., et al. (2015). Novel application for simply recovered LiCoO<sub>2</sub> material : As a high- performance candidate for supercapacitor in aqueous system. *ACS Sustainable Chemical and Engineering*, 3, 2435–2442. <https://doi.org/10.1021/acssuschemeng.5b00455>
- Xuan, W., Otsuki, A., & Chagnes, A. (2019). Investigation of the leaching mechanism of NMC 811 (LiNi<sub>0.8</sub>Mn<sub>0.1</sub>Co<sub>0.1</sub>O<sub>2</sub>) by hydrochloric acid for recycling lithium ion battery cathodes. *RSC Advances*, 9, 38612–38618. <https://doi.org/10.1039/c9ra06686a>
- Yang, J. G., Wu, Y. T., & Li, J. (2012). Recovery of ultrafine copper particles from metal components of waste printed circuit boards. *Hydrometallurgy*, 121–124, 1–6. <https://doi.org/10.1016/j.hydromet.2012.04.015>
- Yang, Y., Okonkwo, E. G., Huang, G., et al. (2021). On the sustainability of lithium ion battery industry—A review and perspective. *Energy Storage Mater*, 36, 186–212. <https://doi.org/10.1016/j.ensm.2020.12.019>
- Yoo, J. M., Jeong, J., Yoo, K., et al. (2009). Enrichment of the metallic components from waste printed circuit boards by a mechanical separation process using a stamp mill. *Waste Management*, 29, 1132–1137. <https://doi.org/10.1016/j.wasman.2008.06.035>
- Yu, S., Abbas, J., Draghici, A., et al. (2022). Social media application as a new paradigm for business communication: The role of Covid-19 knowledge, social distancing, and preventive attitudes. *Frontiers in Psychology*, 13, 1–17. <https://doi.org/10.3389/fpsyg.2022.903082>
- Zeba, G. T. C., Paulino, J. F., & Afonso, J. C. (2022). Recovery of metals from electroactive components of spent Li-ion batteries after leaching with formic acid. *Brazilian Journal of Chemical and Engineering*, 39, 147–158. <https://doi.org/10.1007/s43153-021-00095-5>
- Zedalis RJ (2017) *International energy law: Rules governing future exploration, exploitation and use of renewable resources*. <https://doi.org/10.4324/9781315252056>
- Zeng, X., Gong, R., Chen, W. Q., & Li, J. (2016). Uncovering the recycling potential of “new” WEEE in China. *Environmental Science and Technology*, 50, 1347–1358. <https://doi.org/10.1021/acs.est.5b05446>
- Zhang, S., Li, Y., Wang, R., et al. (2017). Superfine copper powders recycled from concentrated metal scraps of waste printed circuit boards by slurry electrolysis. *Journal of Cleaner Production*, 152, 1–6. <https://doi.org/10.1016/j.jclepro.2017.03.087>
- Zheng, X., Gao, W., Zhang, X., et al. (2017). Spent lithium-ion battery recycling – Reductive ammonia leaching of metals from cathode scrap by sodium sulphite. *Waste Management*, 60, 680–688. <https://doi.org/10.1016/j.wasman.2016.12.007>
- Zheng, X., Zhu, Z., Lin, X., et al. (2018). A mini-review on metal recycling from spent lithium ion batteries. *Engineering*, 4, 361–370. <https://doi.org/10.1016/j.eng.2018.05.018>
- Zhou, M., Li, B., Li, J., & Xu, Z. (2021). Pyrometallurgical technology in the recycling of a spent lithium ion battery: Evolution and the challenge. *ACS ES&T Engineering*, 1, 1369–1382. <https://doi.org/10.1021/acsestengg.1c00067>
- Zhu, X. N., Nie, C. C., Ni, Y., Zhang, T., Li, B., Wang, D. Z., Qu, S. J., Qiao, F. M., Lyu, X. J., Qiu, J., & Li, L. (2021). Advanced utilization of copper in waste printed circuit boards: Synthesis of nano-copper assisted by physical enrichment. *Journal of Hazard Materials*, 401, 123294. <https://doi.org/10.1016/j.jhazmat.2020.123294>
- Zhuang, L., Sun, C., Zhou, T., et al. (2019). Recovery of valuable metals from LiNi<sub>0.5</sub>Co<sub>0.2</sub>Mn<sub>0.3</sub>O<sub>2</sub> cathode materials of spent Li-ion batteries using mild mixed acid as leachant. *Waste Management*, 85, 175–185. <https://doi.org/10.1016/j.wasman.2018.12.034>