



Process intensification for sustainable extraction of metals from e-waste: challenges and opportunities

Aaliya Javed¹ · Jogender Singh¹

Received: 22 December 2022 / Accepted: 9 March 2023 / Published online: 30 March 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

The electrical and electronic waste is expected to increase up to 74.7 million metric tons by 2030 due to the unparalleled replacement rate of electronic devices, depleting the conventional sources of valuable metals such as rare earth elements, platinum group metals, Co, Sb, Mo, Li, Ni, Cu, Ag, Sn, Au, and Cr. Most of the current techniques for recycling, recovering, and disposing of e-waste are inappropriate and therefore contaminate the land, air, and water due to the release of hazardous compounds into the environment. Hydrometallurgy and pyrometallurgy are two such conventional methods used extensively for metal recovery from waste electrical and electronic equipment (WEEE). However, environmental repercussions and higher energy requirements are the key drawbacks that prevent their widespread application. Thus, to ensure the environment and elemental sustainability, novel processes and technologies must be developed for e-waste management with enhanced recovery and reuse of the valued elements. Therefore, the goal of the current work is to examine the batch and continuous processes of metal extraction from e-waste. In addition to the conventional devices, microfluidic devices have been also analyzed for microflow metal extraction. In microfluidic devices, it has been observed that the large specific surface area and short diffusion distance of microfluidic devices are advantageous for the efficient extraction of metals. Additionally, cutting-edge technologies have been proposed to enhance the recovery, reusability, and recycling of e-waste. The current study may support decision-making by researchers in deciding the direction of future research and moving toward sustainable development.

Keywords Sustainability · Environment · Process intensification · Microfluidic device · Microflow extraction

Introduction

In the last two decades, millions of electronic devices have been sold around the world due to rapid technological breakthroughs and market penetration. In 2019, the annual amount of waste electrical and electronic equipment (WEEE) has reached up to 53.6 million metric tons (MMT) worldwide (excluding PV panels), or 7.3 kg per inhabitant. As a result, the global amount of e-waste has been expanding at an alarming rate of about 2.5 million tons per year (Forti et al.

2020). It has been also estimated that the global e-waste generation will exceed 74.7 MMT in 2030, as shown in Fig. 1. In India, the alarming amount of e-waste generation has been significantly impacted by the rising average annual growth rate from 0.56% in 1991 to 1.62% in 2011. In 2019, India has been ranked third for e-waste generation with 3.2 MMT, after China (10.1 MMT) and the USA (6.9 MMT) as shown in Fig. 2 (Forti et al. 2020). Unfortunately, conventional supplies such as mines of ores for valuable metals are “running out,” posing new challenges in the form of a resource shortfall. For metal sustainability, the use of the metals in present must not restrict the ability to use the same element by future generations (Hunt et al. 2013). Within these restrictions, it is also critical to examine the triple bottom line of sustainability, i.e., environment, society, and economy. Therefore, the metal sustainability should be of great concern due to the known availability of the metals and their demands in future (Hunt et al. 2013).

Responsible Editor: George Z. Kyzas

✉ Jogender Singh
jogender.iitd@gmail.com; jogendersingh@ched.svnit.ac.in

¹ Department of Chemical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat 395007, India

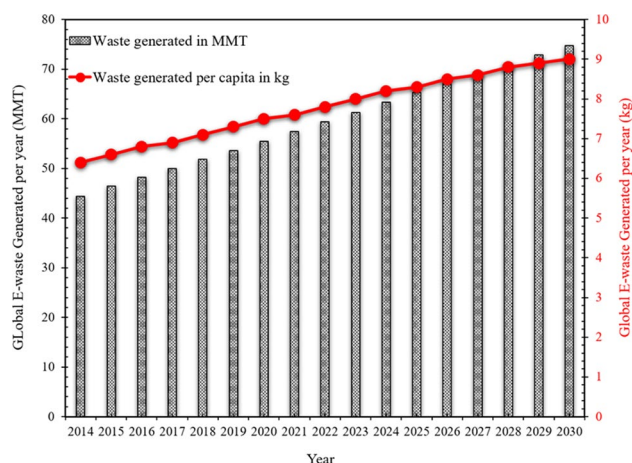


Fig. 1 Trends of the global e-waste generation (Forti et al. 2020)

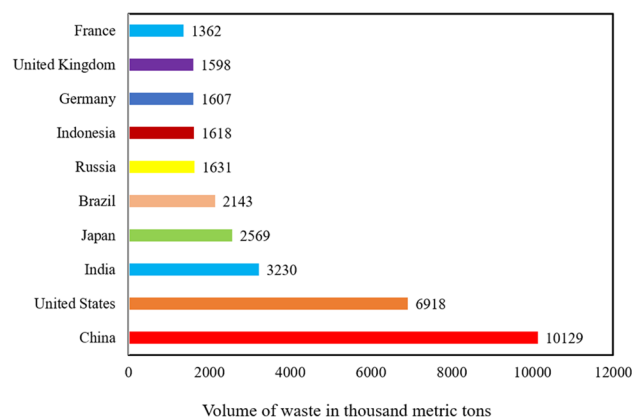


Fig. 2 Country-wise generation of electronic waste in 2019 (Forti et al. 2020)

It has been noted that a very few studies were published on e-waste till twenty-first century. However, subsequently, the publications increased exponentially realizing the importance of e-waste management as shown in Fig. 3. This exponential growth in research on e-waste is caused by the significant increase in e-waste and the ban on hazardous waste export to underdeveloped countries by force of an international accord, known as the Basel Convention, which has urged the scientist to focus their research on e-waste management rather than only focusing on air, land, and water pollution. A maximum number of research papers have been published from 2019 to 2021, respectively. The number of studies rose sharply after 2014, with a maximum amount of research published in 2021 (Yang et al. 2021; Rao et al. 2021; Jadhao et al. 2021; Panda et al. 2021; Asrami et al. 2021). With growing environmental concerns, numerous countries and scholars have initiated e-waste research, resulting in a significant amount of

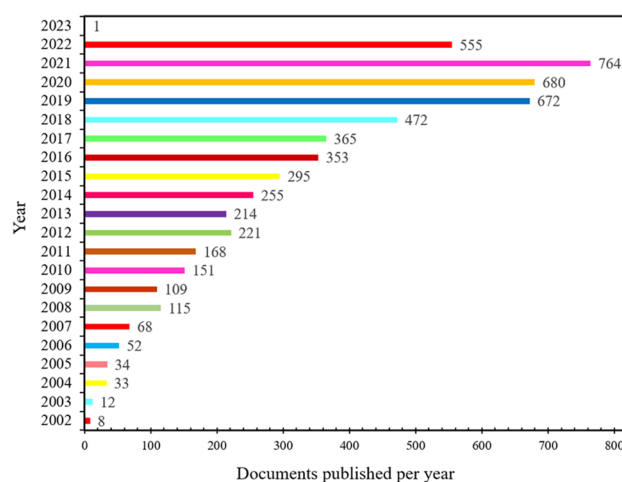


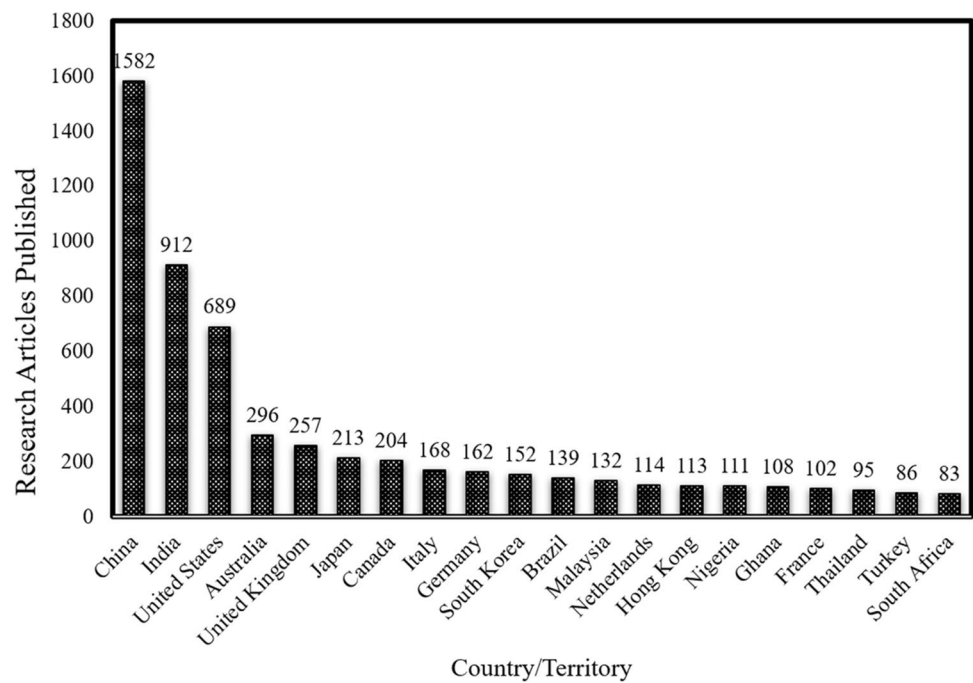
Fig. 3 Articles published on e-waste management, recovery, and recycle (Scopus analysis, 2022)

electronic waste research over the last decade and raised public awareness of e-waste as a serious environmental health hazard (Heacock et al. 2016). Some of the most effective e-waste management system case studies have been identified in countries like Switzerland and the Netherlands (Bhutta et al. 2011). In addition, China (Ding et al. 2019; Yang et al. 2019; Liu et al. 2021) has published the most research articles on WEEE with India being the second in ranking of the top 10 countries and territories, including four other Asian countries as shown in Fig. 4.

Metal recovery from e-waste is a tricky process proven significantly more challenging by the complexity of the material. Therefore, the main focus of scientific community is on sustainable processes using green solvents, which are the critical components for a sustainable planet. Metal separation via liquid–liquid extraction is an important scientific topic with significant economic implications. Solvent extraction, which is part of hydrometallurgical processing, is currently one of the most used industrial-scale processes for metal separation and recovery (Asrami et al. 2021). The most prevalent types of metal extraction equipment such as mixer settler and batch extractor have certain drawbacks such as longer mixing time and big plant footprint for multiphase coalescence. As a result, process intensification (PI) comes into play for metal recovery since PI technologies drastically improve mixing at the molecular level, hence improving mass and heat transfer, reaction kinetics, and yields. Also, PI can reduce the number of equipment, size of the facility, complexity of the processes, cost, carbon footprint, and risk and increases the throughput of the plant (Wang et al. 2017).

Process intensification employing microfluidics has caused a lot of interest in both the industry and academia. Microfluidics is a relatively young field that combines

Fig. 4 Country-wise research articles published on e-waste (Scopus analysis, 2022)



physics, chemistry, biology, fluid dynamics, microelectronics, and the principles of material science (Erickson and Li 2004). The intensified design of microfluidic devices can improve heat and mass transfer rates, while also permit operation at high concentrations due to downsizing (Singh et al. 2013, 2014b, a, 2016, 2019b, a; Singh and Nigam 2016; Ramirez-Tijerina et al. 2018). Thus, the microfluidic devices can be a better prospect for solvent extraction due to their smaller footprint and higher efficiency (Santana et al. 2020; Asrami et al. 2021). PI for metal recovery from e-waste can be achieved via two approaches: (i) by developing novel devices and technologies or (ii) by using eco-friendly, non-toxic, cheaper, and recoverable greener solvents to develop the zero-waste process (Jadhao et al. 2016; Gande et al. 2021). The microflow devices also offer significant advantages over conventional batch reactors, including enhanced heat and mass transfer, operational safety, precise control over residence time, isolation of delicate processes from air and moisture, and simplicity of scaling up (Vural Gürsel et al. 2016).

Therefore, the present study provides a comprehensive review of e-waste recycling and its potential role in the circular economy. The most recent advance technologies for recovery of the e-waste have been also discussed along with few viable alternatives such as microfluidic metal extraction processes. Additionally, a critical evaluation of various microflow extraction devices is presented from an economic, ecological, and technological perspective. The overall goal of this study is to offer the updated data on e-waste generation and to provide the detailed analysis for metal extraction from e-waste. The present work not only

offers the updated information on e-waste generation but also discusses the novel avenues to aid the metal extraction from e-waste via application of the process intensification. Recently, solvent-based microflow extraction has been demonstrated as an efficient metal extraction technique from different waste streams. However, microflow extraction has not been explored yet to extract metal from any kind of e-waste. Therefore, one of the objectives of this work is to explore the applicability of various novel microflow extraction devices for the recovery of the metals from various types of electronic waste using greener solvents.

Current scenario of e-waste

E-waste, frequently known as the WEEE (waste electrical and electronic equipment), refers to all electrical and electronic devices and their discarded parts with no intention of being recycled. The e-waste contains both the valuable and hazardous materials, necessitating unique handling and recycling techniques. The e-waste was divided into 54 distinct product-centric groups based on their different properties (Zhang et al. 2013; Nakamura et al. 2015; Forti et al. 2020). Also, based on the type of equipment and waste management features, EEE product types can further be classified into six broad categories as shown in Fig. 5. The positive and negative signs indicate the growth and decline of waste generation for that specific category in 2019 respectively as compared to the year 2014.

The majority of the world's electronic waste in 2019 as shown in Fig. 5 was composed of small (17.4 Mt), large (13.1 Mt), and temperature exchange (10.8 Mt) equipment. In 2019,



Fig. 5 Growth of e-waste generated from various categories of EEE from 2014 to 2019 respectively (Forti et al. 2020)

screens and monitors, small IT and telecommunication equipment, and lamps accounted for 6.7 Mt, 4.7 Mt, and 0.9 Mt of e-waste, respectively. Lamps and small equipment (+4%), large equipment (+5%), and heat exchange equipment (+7%) have all shown the significant weight increases since 2014. This trend is fueled by the higher living standards provided by these products in the under developed countries. Compared to small information technology (IT) and telecom equipment, screens and monitors have increased more slowly (−1%).

Composition of e-waste

E-waste is basically the heterogeneous mixture of complex compounds that contains various valuable and precious metals as well as plastics and other components. As shown in Fig. 6, the major components of e-waste are metals (63%) and plastics (21%). According to various analyses, approximately 69 different metals are present in e-waste, the majority of which can be extracted from PCBs, subscriber identification module (SIM) waste and waste memory modules (WMM). The material composition of (a) typical computer, (b) typical television (TV), (c) typical mobile

phone, and (d) typical solar photovoltaic panel is shown in Fig. 7. PCBs are the most complicated fraction of e-waste containing base metals (copper, iron, aluminum, tin, zinc, titanium, antimony, nickel, magnesium, sodium, manganese, strontium, bismuth, cobalt, lithium, gallium, beryllium, etc.), platinum group metals (PGMs) (silver, gold, platinum, palladium, iridium), rare earth elements (REE) (lanthanum, cerium, dysprosium, europium, terbium, etc.), heavy metals (lead, chromium, arsenic, cadmium, mercury), and non-metals (silicon, carbon, chlorine, boron, bromine, sulfur, phosphorous, fluorine, iodine) (Chauhan et al. 2018; van Yken et al. 2021).

Polymers, ceramics, and metals are used to make mobile phone PCBs. Copper (Cu), tin (Sn), zinc (Zn), nickel (Ni), gold (Au), silver (Ag), and palladium (Pd) are among the metals found in the metallic fraction (Yamane et al., 2011). Due to European rules-WEEE and Restriction of Hazardous Substances (RoHS), the amount of silver in each cell phone will most likely increase in the coming years, replacing the lead found in welds. The elemental composition of defunct SIM waste shows 75.84 wt% Cu, 0.42 wt% Au, and 0.01 wt% Ag. According to

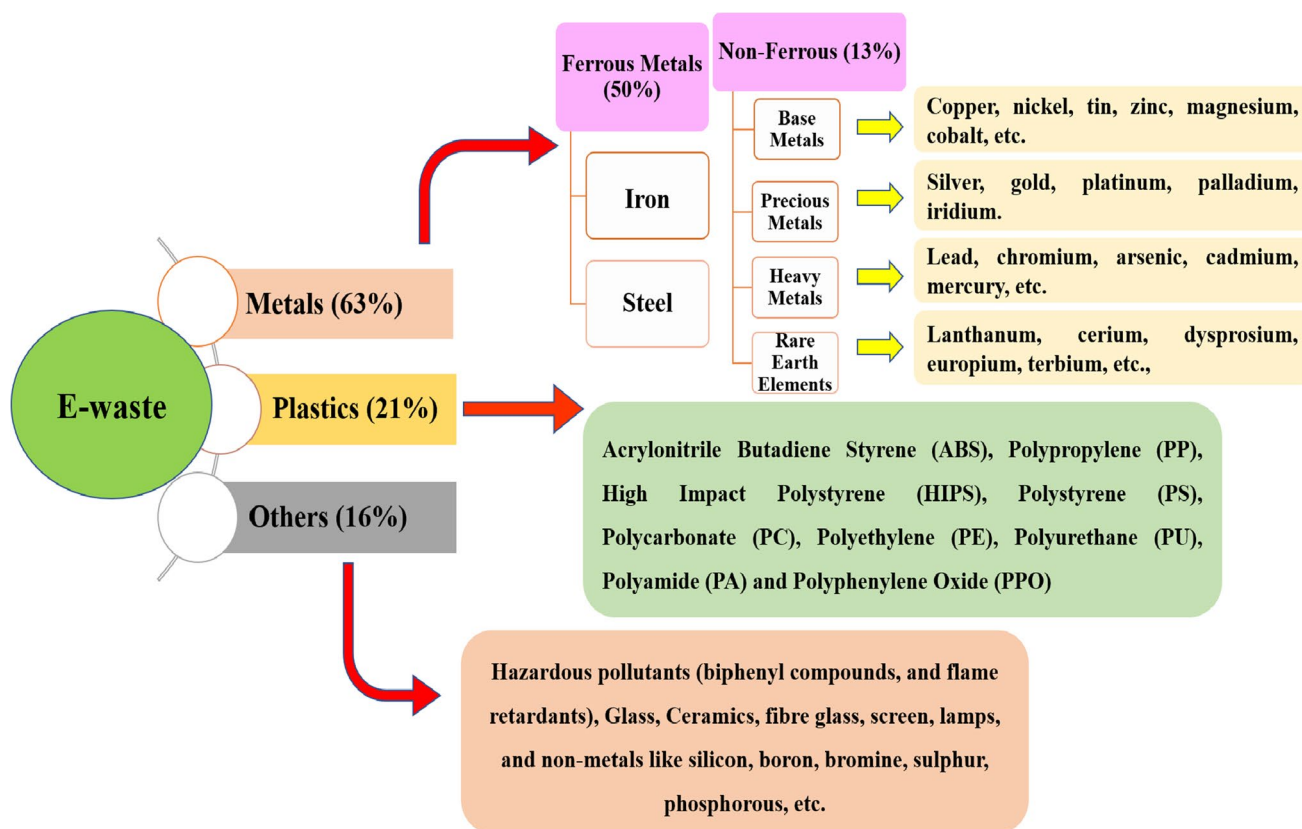
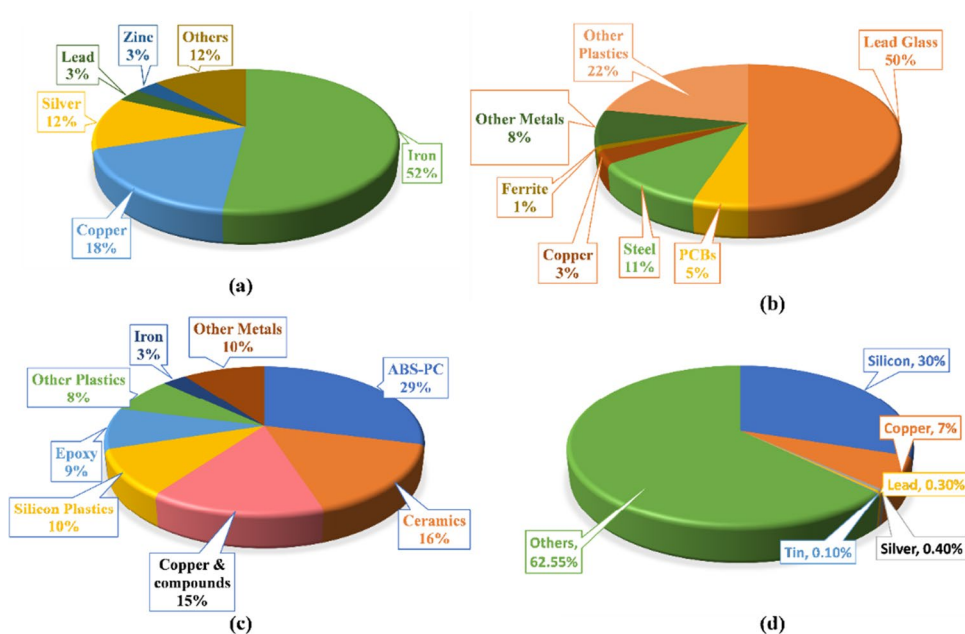


Fig. 6 Composition of metals, plastics, and other components in e-waste

Fig. 7 Material composition of **a** typical computer, **b** TV, **c** mobile phone, and **d** solar photovoltaic panel



chemical analysis, SIMW had a greater metal concentration than waste CPCBs (Dias et al. 2016; Sahni et al. 2016; Ardente et al. 2019).

End-of-life solar panels are another type of e-waste, and the amount of waste photovoltaic panels is expected to grow exponentially in the coming decades. Based on 25 years of

average panel lifetime, global solar photovoltaic PV waste is expected to reach 4–14% of total e-waste generation by 2030 with further increment over 80% (approximately 78 million tons) by 2050. Typical waste PV panels include silicon solar cells, a metal frame (mainly aluminum), glass sheet, and wire. But due to recent advancement in technology, a number of materials can be used for the PV panel construction including gallium, indium, arsenic, phosphorous, cadmium, telluride, zinc, sulfur, copper, tin, perovskite, organic dyes, and fluorinated plastics (Dias et al. 2016; Ardenete et al. 2019). WMMs, a type of discarded printed circuit board, also have lot of brominated epoxy resin (BER), fiber glass, and higher purity metal content (copper 10 wt%, gold 0.7 wt%) (Li and Xu 2015).

The other components in e-waste include flame retardants (FR), thermosetting resins, reinforcing materials, additives, polychlorinated biphenyls (PCB), tetrabromobisphenol A (TBBA), polybrominated biphenyls (PBB), polybrominated diphenyl ethers (PBDE), chlorofluorocarbon (CFC), and polyvinylchloride (PVC). These compounds are toxic and if recycled in improper way can jeopardize the health of workers and the people around them (Li et al. 2018).

Hazardous pollutants in e-waste

Electronics in landfills release toxic chemicals that harm air, soil, and water and human health. E-waste contains mercury, brominated flame retardants (BFR), and chlorofluorocarbons (CFCs), or hydrochlorofluorocarbons (HFCs). E-waste rising volume, poor collection rates, and unsustainable disposal and treatment pose serious environmental and health risks. Fifty tons of mercury and 71 kt of BFR plastics are discovered in undocumented e-waste flows around the world in 2019 (as shown in Fig. 8), which is mostly released into the environment emitting greenhouse gases and has an influence on the health of those

exposed. To begin, reducing the greenhouse gas emissions caused by the extraction and refining of primary raw materials depends on recycling the materials in e-waste. It should be noted that some refrigerants used in temperature exchange systems are greenhouse gases themselves. A net amount of 98 MMT of CO₂ equivalents were emitted into the atmosphere in 2019 as a result of improperly managed discarded refrigerators and air conditioners (Forti et al. 2020). In 2019, this represents about 0.3% of worldwide energy-related emissions (International Energy Agency, IEA). Solar panels that are not properly disposed of become hazardous waste. Photovoltaic panels must be incinerated to recycle silver and silicon, but fluorinated polymers may release harmful HF fumes (N. Perkins et al. 2014).

Disassembling, shredding, or melting electronic waste releases dust and chemicals, including dioxins, into the air, polluting and harming respiratory health. Although informal e-waste recycling emits pollutants far from recycling facilities, those who handle it are most at risk. E-waste improperly disposed of in authorized or illegal dumping sites leaches heavy metals and flame retardants into the soil, contaminating groundwater and future crops. Pollutants can damage soil microbes and plants for years. Animals and wildlife that depend on nature will eat the afflicted plants, causing internal health issues. Mercury, lithium, lead, and barium from e-waste can leak into groundwater and eventually enter ponds, streams, rivers, and lakes. Clean drinking water acidification harms freshwater and marine life, disrupts biodiversity, and damages ecosystems beyond repair.

Health hazards on human beings

Consequently, e-waste has been related to negative health effects as described briefly in Table 1. Since the previous e-waste monitor was published in 2017, the number of studies on the detrimental health effects of e-waste has increased.

Fig. 8 Potential of e-waste in the circular economy

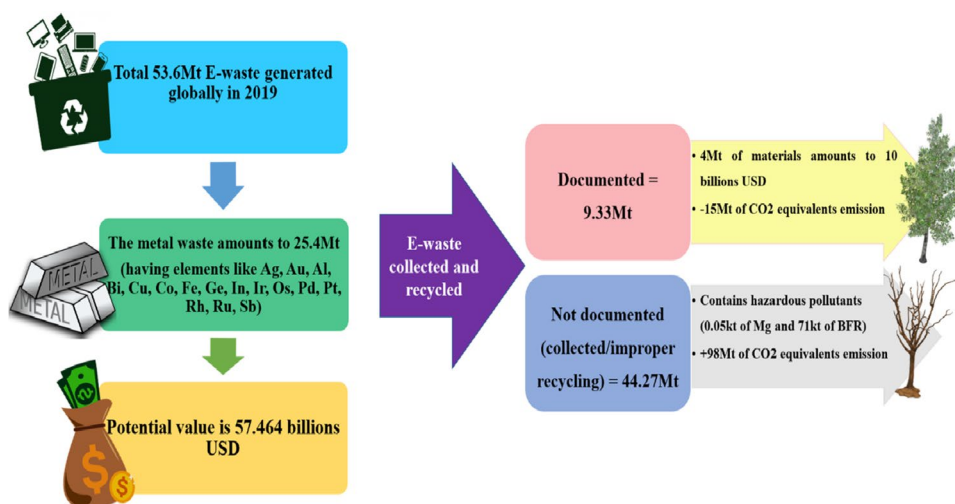


Table 1 Health hazards on children and co-workers due to pollutants present in e-waste

Pollutant	Source of exposure	Route of exposure	Health consequences	References
Lead (Pb)	E-waste recycling site, tinfoil manufacturing	Inhalation, ingestion, dermal, and placental	Increased lymphocytic micro-nucleated binucleated cells (MNBNCs), elevated BLLs (blood lead levels) in children, hematological disorders, renal impairment, altered neurodevelopment especially in children, fetal growth restriction (FGR), hearing loss, cancer, atherosclerosis, nervous disorders, and cardiovascular disorders, alteration of inborn immune cells, olfactory memory loss, abnormality of coagulation, still birth	Wang et al. (2011, 2012); Xu et al. (2015b, 2016, 2020); Zhang et al. (2016, 2017a); Zeng et al. (2017, 2018)
Perfluorooctanoic acid (PFOA)	E-waste recycling site	Maternal exposure	Lung infection, reproduction toxicity, immunotoxicity, hepatotoxicity mainly in newborns, carcinogenic, hormonal changes, genetic toxicity	Wu et al. (2012); Perkins et al. (2014); Xu et al. (2015c)
Cadmium (Cd)	E-waste recycling site	Inhalation and ingestion	Fetal growth restriction (FGR), hearing loss, cancer, atherosclerosis, nervous disorders, cardiovascular diseases, alteration of inborn immune cells, adverse birth outcomes, lung malfunctioning, decrease in IQ	Wu et al. (2012); N. Perkins et al. (2014); Xu et al. (2016, 2020); Zeng et al. (2017, 2019)
Chromium or hexavalent chromium (Cr)	E-waste recycling site	Inhalation and ingestion	Lung infection, toxicities in humans, decrease in IQ, reproductive developmental, anomalies, skin abnormalities, carcinogenic, mutation	Noel-Brune et al. (2013); Zheng et al. (2013); Xu et al. (2015c); Zhang et al. (2017c); Zeng et al. (2019); Choi et al. (2022)
Mercury (Hg)	E-waste recycling site	Inhalation, ingestion, and dermal	Lung infection, toxicities in humans, decrease in IQ, fertility decline, skin problems, nephrotoxic, memory loss, immune system toxicity, gene toxicity, inflammation	Perkins et al. (2014); Xu et al. (2015c); Debnath et al. (2018); Zeng et al. (2019)
Polyaromatic hydrocarbons (PAHs)			Lung infection, cardiovascular diseases, peripheral arterial disease, altered growth of children and development, kidney failures, hematological disorders, lymphocyte proliferation, DNA damage	Xu et al. (2015c, b)

Table 1 (continued)

Pollutant	Source of exposure	Route of exposure	Health consequences	References
Polybrominated diphenyl ethers (PBDEs), polybrominated biphenyls (PBBs), polychlorinated biphenyls (PCBs)	E-waste recycling site	Inhalation, ingestion, dermal, and placental	Lung infection, alters newborn physiological system, carcinogenic, developmental toxicity, genotoxic, health deterioration of pregnant women and infants, immunotoxicity, hepatotoxicity, reproduction toxicity, altered thyroid hormone, affects endocrine system, decrease fertility in women, decrease in IQ of children	Xu et al. (2014, 2015a)

These researches have continued to underline the negative health effects of exposure to well-studied toxins such as lead. According to a new study, unauthorized e-waste recycling is linked to an increasing number of detrimental health effects due to release of harmful products in environment such as lead, mercury, cadmium, and brominated flame retardants. Adverse perinatal results, abnormal neurodevelopment, poor learning outcomes, DNA damage, adverse respiratory consequences, immune system repercussions, skin disorders, hearing impairment, and cancer are only a few examples (shown in Table 1) (Frazzoli et al. 2010; Noel-Brune et al. 2013; Sheffield et al. 2014; Ceballos and Dong 2016).

E-waste recycling for sustainable environment

Potential of e-waste in the circular economy

Electronic garbage (e-waste) can be considered as a two-edged sword: it has high recycling value but also causes adverse effects on the environment. Metals can be recovered as secondary materials from e-waste, effectively transforming these dumps into an “urban mine.” Compared to conventional metal ore mines, urban mining has become a trend resulting in high minerals per ton since metals are found in greater abundance in these wastes than in original sources. Industrialized metropolitan regions account for 75% of global e-waste, generating it on a continual basis.

In 2019, a total of 1,335,848 tons of technology and precious metal ores were mined. Also, 207,478,486 tons of industrial metals and 3,040,000,000 tons of iron ore were mined, totaling 3,248,814,334 tons. In 2019, 347 million tons of bauxite ore was mined, but only 62.9 million tons of pure aluminum was recovered (Maus et al. 2020). The most crucial part of sustainability for organizations is significant financial sustainability. Metal recovery seems to be the most crucial aspect of e-waste optimum utilization. In order to recover valuable metal, it is necessary to apply the “3R” rules (reduce, reuse, and recycle) while also using the additional “R” known as “redesign” (Debnath et al. 2018). According to the Norwegian research institute, extracting the metals via urban mining uses 17 times less energy than collecting them from conventional sources. The cost of extracting huge amounts of gold and copper from garbage television has been discovered to be lower than the cost of obtaining the metal from a mine site. Some significant social and health issues, as well as technical challenges, stand in the way of full-scale urban mining and a sustainable economy. Metals cannot be recycled continuously, which is one of these technical issues. Also, ore availability in e-waste mine is difficult to access (N. Perkins et al. 2014).

Potential of e-waste in circular economy is shown in Fig. 8. The value of raw materials in global e-waste generated in 2019 was estimated to be around \$57 billion USD (as shown in Fig. 8), with iron, copper, and gold being the most valuable metals. According to Global E-waste Monitor 2020, 17.4% of total e-waste collected have been recycled, recovering raw materials worth of \$10 billion USD are collected. The recycling of iron, aluminum, and copper led to an overall CO₂ savings of 15 MMT, which is comparable to emissions from the recycling of secondary raw materials that might otherwise be used for primary materials (Forti et al. 2020). For every 1 million cell phones that are recycled, 35,274 lbs of copper, 772 lbs of silver, 75 lbs of gold, and 33 lbs of palladium can be recovered.

Technologies for the recovery of e-waste

Recycling is defined as the recovery of waste materials for the original or additional purposes. Electronic trash recycling entails not only the disassembly and/or destruction of obsolete equipment in order to recover materials but it involves certain physical and chemical treatments for the recovery of precious metals as their quantity is very negligible in comparison to other base metals and plastics. Pretreatment of e-waste includes dismantling, shredding grinding, etc., which has already been explained in detailed in previous literature (Li et al. 2018; Jadhao et al. 2022). Primarily,

the simple and rough processes for precious metals recycling were widely adopted. Later, the researchers developed various efficient recovery procedures, including hydrometallurgy and pyrometallurgy recrystallization, chemical precipitation, ion exchange, and solvent extraction, but recovery of lower concentration metals like gold, silver, palladium, nickel, and zinc remains a global challenge (Jha et al. 2020). Since the main concern is to extract valuable metals from e-waste, this review article is mainly concerned with the technology involved for the same. The conventional e-waste recovery techniques include pyrometallurgy and hydrometallurgy (Li et al. 2018; Jha et al. 2020; Chowdhury et al. 2020).

Pyrometallurgy

Pyrometallurgy is the thermal treatment (at very high temperature) of e-waste using high-energy techniques such as incineration, calcination, roasting, and smelting (Fig. 9). Because e-waste contains contaminants such as lead, mercury, arsenic, flame retardants, CFCs, and other chemicals, burning it to extract metals releases harmful fumes; as a result, a legislature facility is required to prevent the release of harmful gases when processing e-waste, making this process expensive (examples discussed in Table 2). Incinerating e-waste in a conventional municipal solid waste treatment is extremely harmful (Cui and Zhang 2008). Furthermore, the plastic components of e-waste leak dioxin in smelters, and a high volume of slag formation makes it impossible

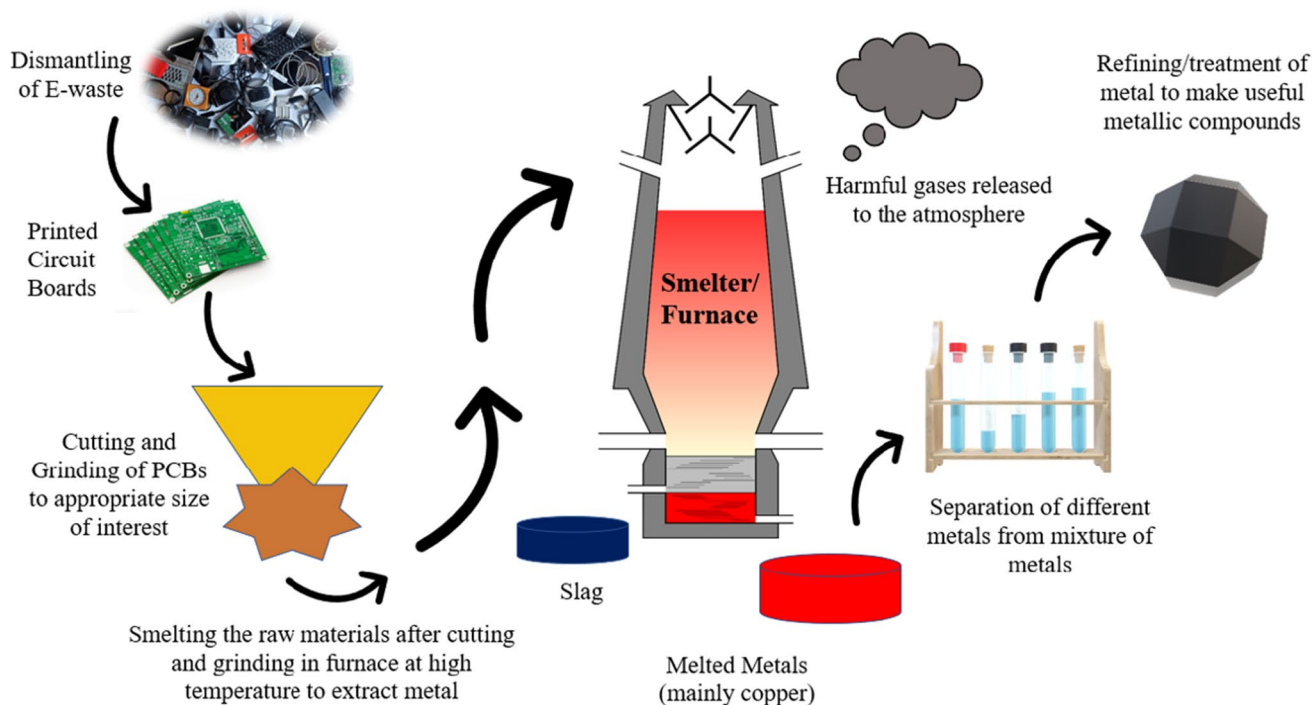


Fig. 9 Pyrometallurgy of e-waste

Table 2 Summary of various techniques used for metal extraction from e-waste

E-waste source	Techniques used	Solvent/organism/treatment used	Targeted metal	Comments	Environmental limitations	Ref.
1. Metal extraction using pyrometallurgy						
WPCBs	Carbonization treatment	Carbonized under a nitrogen atmosphere at 873–1073 K	Nickel, copper	Nickel recovery is 74%, 70% of tantalum grade, and energy consumption for Cu is 3 times higher, 50% higher for tantalum	CO ₂ emission and high energy consumption	Jadhao et al. (2021)
Spent lithium-ion batteries	Multi-vacuum pyrolysis (VP)	First, materials were separated using the VP method from 623 to 823 K. Then, conversion of LiCoO ₂ to Co or CoO and Li ₂ CO ₃ by carbothermic reduction under vacuum and at 873 to 1273 K	Lithium and cobalt	Recovery rates for Li and Co both exceed 93% and 99% respectively	High energy consumption	Tang et al. (2019)
2. Metal extraction using hydrometallurgy						
WPCBs of mobile phones	Two-stage leaching	Nitric acid and extractant ACORGA M5640 and tertiary amide L ³	Copper and gold	Effective to separate and recover all copper and gold from WPCBs	Reagent recovery and economic feasibility	Rao et al. (2021)
Waste PCBs	Acid leaching	Nitric acid	Tin, lead, copper	Tin, lead, and copper are often extracted as tin oxide, lead nitrate and copper nitrate with an efficiency of 77–97%, 51–85%, and 100% respectively	Loss of reagent. Corrosion of equipment due to high usage of nitric acid	Gande et al. (2021)
WPCB	Alkali leaching	Liquid ammonia, ammonium sulfate, and hydrogen peroxide	Copper and nickel	100% copper (with impurity) and 90% nickel	Proper disposal of ammonia and its recovery or recyclability	Jadhao et al. (2021)
PCBs	Bioreaching	<i>Pseudomonas chlororaphis</i> (PC)	Gold, silver, and copper	8.2% of the gold, 12.1% silver, and 52.3% copper are recovered	Short-term shelf life of <i>Pseudomonas chlororaphis</i> (PC) makes the process inefficient	Ruan et al. (2014)
WPCBs of cell phones	Chemical leaching	Thiosulphate leaching (NH ₄) ₂ S ₂ O ₃	Silver	Leaching of silver with sodium thiosulphate and ammonium thiosulphate exhibited a low efficiency	More amount of solvents is required making it uneconomical	Petter et al. (2014)
Scrap TV circuit boards (STVB)	Bioreaching	Mesophilic bacteria	Copper	25–83% copper recovery	Acid consuming process as well as required pyrite to increase metal recovery, thus uneconomical	Bas et al. (2013)

Table 2 (continued)

E-waste source	Techniques used	Solvent/organism/treatment used	Targeted metal	Comments	Environmental limitations	Ref.
3. Metal extraction using alternative technologies						
Spent silver oxide batteries	Deep eutectic solvent extraction and electrolytic bath	AcChCl:U (acetyl choline chloride and urea)	Silver	Waste silver oxide button batteries were successfully recycled to extract silver using DES	Time and temperature control are essential	Sanchez-Ortiz et al. (2021)
Lithium-ion batteries	Deep eutectic solvent extraction	ChCl:EG (choline chloride and ethylene glycol)	Cobalt and lithium	Leaching efficiencies reach upon 99.3%	Duration of leaching is long, and temperature control is required	Tran et al. (2019)
WPCB	Chelation and acid leaching	EDTA (ethylenediaminetetraacetic acid) and sulfuric acid	Copper	83.8% copper recovery by chelation and only 27% Cu was recovered by acid leaching without oxidant	Cost optimization is required while using chelating agents	Jadhao et al. (2016)
Scrap PCBs	Pyro-hydro hybrid metallurgical process	Sulfuric acid	Copper, iron, and nickel	Approximate 99% metal recovery	Pyrolysis at a temperature of 300°C for effective removal of plastics and volatile compounds from the PCBs results in releasing toxic fumes into the environment	Kumari et al. (2016)
Obsolete mobile sim cards	Chemo-biohydrometallurgy	Aqua regia (HCl:HNO ₃ = 3:1) <i>Chromobacterium violaceum</i>	Copper, gold, silver	For gold mobilization from SIMW, chemical treatment with aqua regia found to be an efficient and more suitable process	Metal concentrations above a certain threshold restrict bacterial growth and diminish metal bioleaching	Sahni et al. (2016)

to recover Al, Fe, and other metals, as well as causes the loss of precious metals. A summary of the pyrometallurgical treatment of e-waste to recover metals is shown in Fig. 9. It includes disassembling electronic waste, crushing, grinding, and finally incinerating the resulting powder in a smelter. In the European Union (EU) Community, emissions from waste incineration are expected to account for 36 tons of mercury and 16 tons of cadmium per year. The hierarchy of e-waste treatment advocates the reuse of the entire device first, followed by remanufacturing, material recovery via recycling procedures, and finally, incineration and landfilling as a last choice (Cui and Zhang 2008). As a result, the focus has changed from pyrometallurgy to hydrometallurgy in order to establish a more cost-effective and ecologically acceptable method of extracting metal from e-waste.

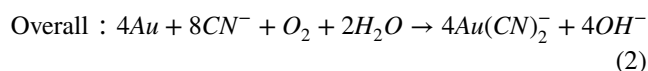
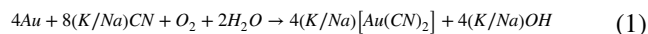
Hydrometallurgy

Metal recovery via hydrometallurgy is done by chemical leaching and acid/alkali leaching and by using hybrid technology, i.e., biohydrometallurgy as show in Fig. 10. The hydrometallurgical process is mostly linked to the use of acid or alkaline solutions to dissolve a solid material, a process known as leaching. Chemical leaching with cyanide, thiourea, thiosulphate, acid, and halide is difficult to handle because these cyanide and non-cyanide reagents are hazardous in nature, necessitating highly corrosive resistant

equipment, which raises the cost of construction materials. When compared to pyrometallurgy, hydrometallurgical processes exhibit higher selectivity for metal recovery, require less energy load, liberate less toxic fumes, are easier to apply in laboratory conditions achieving significant metal recovery (Cui and Zhang 2008; Chauhan et al. 2018; Li et al. 2018). Figure 10 gives the overview of different hydrometallurgical technologies used so far to extract metal from e-waste along with their advantages and disadvantages. The figure is discussed in detail in the proceeding section.

Cyanide leaching

Cyanide is one of the most important reagents used for gold recovery by leaching process as the cyanide ion form complex with gold ion at anode in electrochemical process while reducing oxygen at cathode. The overall anodic and cathodic reaction are given below: -



The absorption of oxygen or cyanide from feed liquid to the solid matrix through natural leaching processes on the

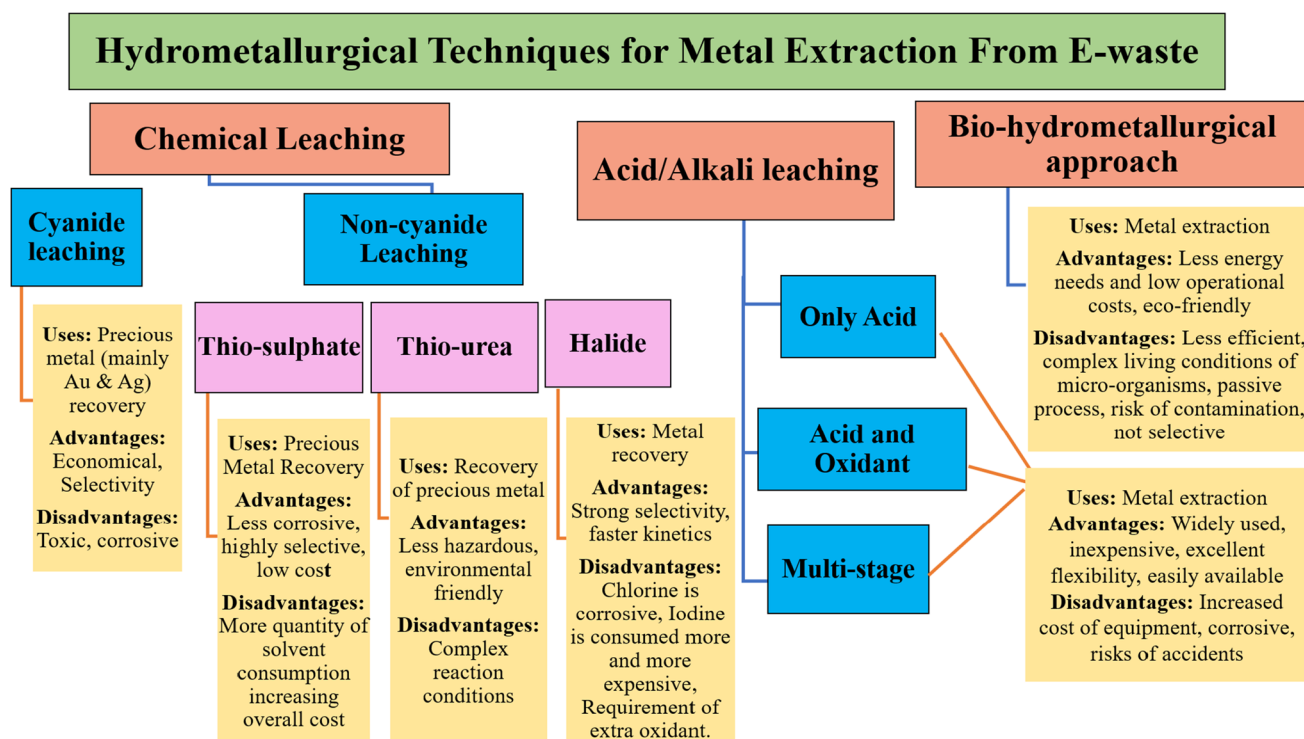
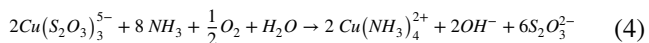
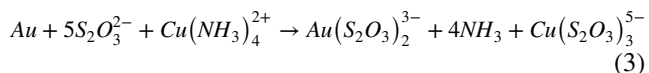


Fig. 10 Hydrometallurgy technologies for metal recovery

particle's surface determines the effectiveness of cyanide leaching of metals from e-waste. As a result, increasing the dissolved oxygen content accelerates the rate of dissolution. To maximize the effectiveness of cyanide leaching for the recovery of Au and Ag, it is critical to recover other base metals, particularly copper, prior to cyanidation, as direct cyanidation results in the recovery of unwanted metals while reducing gold and silver recovery (Cu-77%, reducing Au and Ag recovery from 48 to 52% drastically to lower value). Reaction temperature, solution pH, e-waste surface area, stirring rate, and other anion/cations present in solution are another significant parameter in the efficient cyanidation process. While cyanide is a very economical product in the industry, it is extremely dangerous. As a result, cyanide's use as a leaching agent is a big issue, and numerous studies are being conducted to find a safer alternative (Cui and Zhang 2008).

Thiosulfate leaching

Thiosulfate has been proposed as a viable alternative to cyanide for the leaching of precious metals from minerals due to its low corrosivity, excellent selectivity, and low cost, and several experiments utilizing thiosulfate leaching for WPCB recycling have been conducted. Because thiosulfate is readily destroyed in acid solution, it is carried out in an alkaline environment with a pH range of 9–10.5 (H Li et al.). As per different researches, in the presence of cupric ion (Cu^{2+}) and ammonia (NH_3), the reaction between Au and thiosulfate generates a gold-thiosulfate complex; Cu^{2+} and NH_3 act as a catalyst and form cupric ammonia $[\text{Cu}(\text{NH}_3)_4]^{2+}$ in thiosulfate solution and enhance metal recovery by stabilizing the gold-thiosulphate complex $[\text{Au}(\text{S}_2\text{O}_3)_2]^{3-}$. The equations are as follows:

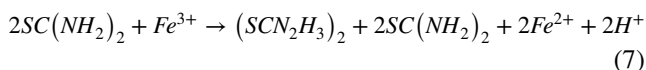
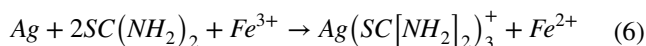
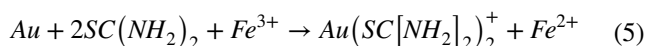


Au leaching has been studied, and it has been discovered that as the concentration of thiosulfate is increased up to 0.1–0.14 M, the amount of Au leaching increases (Chauhan et al. 2018). However, when the concentration of Au increases, the efficiency of Au leaching diminishes. This could occur because greater thiosulfate levels produce undesired compounds such as sulfate, trithionate, and tetrathionate. Negative findings have been demonstrated in various investigations for direct leaching of WPCBs or size-reduced WPCBs using a thiosulfate leaching system, implying that the operational parameters can be further optimized and suitable additives can be considered for a high leaching rate. The leaching systems

of $\text{Na}_2\text{S}_2\text{O}_3$ or $(\text{NH}_4)_2\text{S}_2\text{O}_3$, CuSO_4 or H_2O_2 , and $\text{NH}_2\text{H}_2\text{O}$ did not show a significant leaching effect for both Au and Ag from the whole size of WPCBs, with all rates around 16%. Furthermore, it was discovered that adding H_2O_2 as an oxidant had no significant effect on both Au and Ag leaching. However, for a lengthy leaching duration (approx. 48 h), the size-reduced WPCBs showed > 93% leaching efficiencies for both Au and Ag. The key issues of thiosulfate leaching are the overconsumption of thiosulfate and relatively modest leaching kinetics, which render the procedure prohibitively expensive and inefficient, despite its significant environmental advantages (Cui and Zhang 2008).

Thiourea leaching

Thiourea ($(\text{NH}_2)_2\text{CS}$) employed as a lixiviant for precious metals is less hazardous and more environmentally acceptable than conventional leaching approaches, and it can achieve a high leaching rate (99% for Au) and faster kinetics. The electron pair between the nitrogen and sulfur atoms in thiourea creates an affinity for forming a coordination bond with Ag and Au. Because thiourea is stable in acidic solutions, the acidic condition must be kept during the thiourea leaching process. In thiourea leaching, the use of ferric ion as an oxidizing agent aids the dissolving of Ag and Au. It has been observed that adding Fe^{3+} to Au extraction can boost its efficiency by four times compared to not adding Fe^{3+} . Thiourea, on the other hand, is highly unstable, especially at pH levels above 4.3, and is easily oxidized and destroyed (Ding et al. 2019). Furthermore, keeping Fe^{3+} in solution at pH levels higher than 3.5 is problematic. Fe^{3+} can oxidize thiourea to formamidine disulfide (FDS), which can be further oxidized to undesired sulfur and cyanamide, and the sulfur can cause inactivation for Au dissolution (Birloaga et al. 2014). Furthermore, Fe^{3+} can produce $[\text{FeSO}_4\text{CS}(\text{NH}_3)_2]^+$ with thiourea, lowering leaching efficiency and increasing thiourea consumption.



The Au was not eliminated because Cu and Au were both leached at the same time without any prior oxidative leaching. As a result, prior oxidative leaching is required to increase Au leaching, and after oxidative leaching, Au recovery was around 69% (Birloaga et al. 2014). The recovery of Au and Ag was investigated using one-step and two-step leaching techniques. Thiourea leaching was used in one stage and resulted

in 90% and 100% Au and Ag leaching, respectively. To recover the base metals, H_2SO_4 leaching was used first, followed by thiourea leaching. This two-step technique recovered Au and Ag at 98 and 100%, respectively (Lee et al. 2018). Huang et al. explored using thiourea to recover Au from PCB. Parallel to Au recovery, microwave pyrolysis was used and two-stage Cu recovery. Pyrolysis at 400°C was used in the first phase to transform organic resources into useful products. The pyrolytic PCB was subjected with two-stage acid leaching to recover Cu and other base metals after pyrolysis (Huang et al. 2014). The final stage involved using thiourea to further process the acid leaching residue in order to recover Au. With 20 g/L thiourea, 28.25 g/L ferric sulfate, and 10 g/L sulfuric acid, a process period of 3 h and a stirring speed of 400 rpm at 25°C, an Au recovery of 80% was documented (Huang et al. 2014).

Halide leaching

Chloride, bromide, and iodide leaching are all halide leaching methods. Using various halide lixiviants, several investigations demonstrated considerable metal extraction from e-waste. Chlorine/chloride leaching has been studied for years, with conventional aqua regia leaching as an example, and has been commercialized on a large scale (Cui and Zhang 2008). However, the expensive cost of equipment, such as stainless steel and a rubber-lined reactor, and the possibility for health risks limit its widespread implementation (Cui and Zhang 2008). For Au extraction from e-waste using the iodine leaching approach, the effect of various process parameters such as halide concentration, oxidizing agent concentration, and sludge density were evaluated while keeping other parameters constant, such as pH = 7, ambient temperature = 35°C, leaching time = 240 min, and stirring speed = 170 rpm. Using 3% iodine concentration in the presence of 2% hydrogen peroxide as an oxidant, around 90% Au recovery was obtained; however, no appreciable gold recovery was found in the absence of oxidant. Furthermore, higher pulp density (> 15%) was found to result in lower Au extraction due to increased oxidant consumption. Iodine/iodide leaching is non-corrosive and non-toxic, with a fast kinetics and strong selectivity for valuable metals (Cui and Zhang 2008). Furthermore, the Au-iodide combination is the most stable Au-halogen compound. Iodine/iodide leaching, on the other hand, has a high reagent consumption and iodine is relatively expensive, which are the main drawbacks of this technique (Jadhao et al. 2016; Li et al. 2018).

Acid leaching

The most widely used method for recovering metal from electronic scrap is acid leaching. For metal recovery from WEEE, various acids such as H_2SO_4 , HNO_3 , and HCl and their mixtures have been used due to their inexpensive prices, well-studied leaching mechanism, and greater flexibility in process control and scalability. Base metals such as Zn, Sn, Fe, and Al can usually be dissolved in dilute mineral acids; however, Cu and precious metals such as Au and Pd can only be dissolved substantially in oxidizing acid (e.g., concentrated HNO_3) or non-oxidizing acid in the presence of oxidizing agents (air/ O_2 , H_2O_2 , Cl_2 , Cu^{2+} , Fe^{3+} , etc.), as explained by their basic redox potential. Metals like Ag and Pb generate a wide range of insoluble salts, making it challenging to acid-leach them effectively in most cases. In general, there are three forms of acid leaching: (a) the use of only acid, (b) acid and oxidizing agent usage, and (c) multi-stage acid leaching (Jadhao et al. 2016; Li et al. 2018).

- (a) Leaching done by using only acid: HCl , HNO_3 , H_2SO_4 , acetic acid ($\text{C}_2\text{H}_4\text{O}_2$), and citric acid ($\text{C}_6\text{H}_8\text{O}_7$) were used in a study by Jadhav and Hocheng to extract base and precious metals from PCB. HCl and HNO_3 were the only two acids that were able to extract all of the metals with 100% efficiency in 22 and 96 h, respectively. The extraction efficiency of acid leaching with H_2SO_4 , $\text{C}_2\text{H}_4\text{O}_2$, and $\text{C}_6\text{H}_8\text{O}_7$ was relatively low. Cu recovery was only 8.8% with 1 M H_2SO_4 for 96 h at ambient temperature, 9.89% with $\text{C}_2\text{H}_4\text{O}_2$, and 19.57% with $\text{C}_6\text{H}_8\text{O}_7$, respectively. Aqua regia can leach a wide range of base and precious metals (e.g., Cu, Pb, Zn, Ni, and Au) rapidly (Cui and Zhang 2008). Bas et al. studied the recovery of Cu and Ag using HNO_3 in another research. The findings indicated that at 70°C and 6% sludge density, the concentration of HNO_3 should be higher than 2–3 M to significantly boost Cu recovery (88–99%). At 5 M HNO_3 , Ag extraction was around 68%, which could be owing to Ag's strong standard reduction potential (Bas et al. 2013; Valdés Vergara et al. 2015; Sahni et al. 2016).
- (b) Leaching done by using mineral acid and oxidant: because non-oxidizing acids seldom leach precious metals with large reduction potentials, oxidants are commonly utilized to speed up the leaching process. H_2SO_4 and H_2O_2 are the most commonly used mineral acid and oxidant combination for full Cu leaching. Cu^{2+} as an oxidant works with Cl in sulfate solution exhibiting good leaching of Fe, Ni, Cu, and Ag (> 90%) and partial leaching of Pd (58%) along with the leaching of Cu, according to Yazici and Deveci (Bas

et al. 2013). To avoid the production of CuCl , it is critical to maintain the appropriate concentration of Cl^- .

- (c) Multi-stage acid leaching: multi-stage leaching has been reported to be an effective method for selective metal leaching. Somasundaram et al. employed 0.1 M CuCl_2 and 3.0 M HCl at 25°C to selectively leach Sn (92%) from WPCBs, with only minor leaching of Cu, Pb, and Ni (6.6%). Cu, Pb, and Ni may then be leached out in the second stage by increasing CuCl_2 concentration and temperature to 0.5 M and roughly 50°C, respectively. For the recovery of Au, a three-stage acid leaching method was developed. Nitric acid was used to recover metals in phases I and II. Furthermore, before acid leaching, the residue obtained after the I step was mechanically crushed, allowing for more efficient recovery of base metals and Ag (Ding et al. 2019).

Bioleaching

The growing interest in using the bio hydrometallurgical pathway for recycling wastes is due to the fact that it is eco sustainable and has an immense potential for lowering operational costs and energy demands. *Pseudomonas chlororaphis* (PC) was discovered to dissolve gold, silver, and copper from crushed discarded PCBs. According to the findings, 8.2% of the gold, 12.1% of the silver, and 52.3% of the copper were dissolved in solution as described in Table 2 (Ruan et al. 2014). Because of their ability to promote metal dissolution through a series of bio-oxidation and bioleaching reactions, chemo-lithoautotrophic bacteria are the most widespread used class of microorganisms in bioleaching solutions. Abiotic dissolution, in which protons carry out bio-oxidation and leaching reactions to carry out metal solubilization, might result in bioleaching. Inhibition and other additional processes, on the other hand, may have a detrimental effect on metal dissolution rate, resulting in low metal yields and slow leaching kinetics (Chauhan et al. 2018). Jadhav et al. used *A. niger* in a two-stage bioleaching experiment, in which the fungus was cultured for organic acid generation in the first phase and the culture supernatant without fungal cells was collected and used in the metal leaching process in the second step. Metals were recovered from SIMW using a chemo-biohydrometallurgy method. Within 4 days of incubation, two-step bioleaching of pretreated SIMW at alkaline pH with *Chromobacterium violaceum* solubilized 70.61% of the residual Cu (Table 2). Thus, Cu and other metals can be recovered efficiently from SIMW using a hybrid approach. Despite its several benefits, bioleaching's industrial venture is still in its infancy due to the sluggish nature of the process, the risk of contamination, and the microorganism's sensitivity to pH and temperature. In addition, these techniques are unable to recover most

of the metals included in WEEE (Bas et al. 2013; Sahni et al. 2016). Bioleaching is sometimes preferred for specific metals, whereas chemical leaching is preferred because it extracts the most metals from the feedstock. The responsiveness of microbes to various metal ions that are toxic at high concentrations is the driving force behind selective leaching via bioprocess. As a result, quantitative metal leaching from WEEE is sometimes impossible; thus, chemical leaching is preferable to bioleaching, particularly from WEEE; however, non-toxic chemical compounds should be used instead when possible.

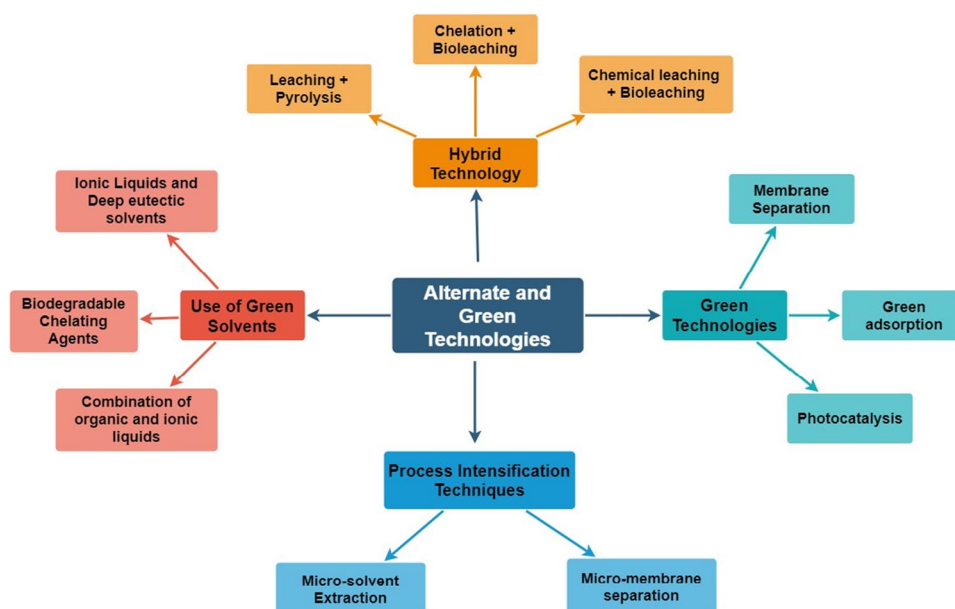
Alternative technologies for WEEE recycling

Researchers have created new, alternative methods for recovering metals from e-waste shown in Fig. 11 in an effort to improve metal recovery in a sustainable way which are discussed below in detail. The block diagram shown in Fig. 11 displays the various methods used to recover metal from waste streams as well as some potential techniques that could be effective for the same.

Green technologies

The discovery of green solvents, such as those with lower toxicity and vapor pressure than conventional solvents, has piqued interest from an environmental standpoint. The use of greener solvents for recovery of metals is one of the greener approaches that has been addressed in the subsequent paragraphs (Fig. 11). Ionic liquids (ILs) have the potential to play a significant role as a future solvent or extractant in the metal extraction process. Ionic liquids are made up of organic cations and different inorganic anions. ILs can be miscible with water and/or nonpolar organic solvents depending on their cationic or anionic structure. Ionic liquids are often hydrophobic, allowing them to extract hydrophobic chemicals in biphasic separations. Because metal ions are hydrated, they prefer to persist in the aqueous phase. Extractants are generally required to remove metal ions from the aqueous phase into hydrophobic ILs by forming complexes, hence enhancing the metal's hydrophobicity. In the extraction of lanthanides and actinides, ILs have proven to be effective (Chauhan et al. 2018; Asrami et al. 2021). Deep eutectic solvents (DESs) have been developed in order to get around the problems of ILs, which include severe toxicity, poor biodegradability, and exorbitant cost. In a DES, two or three reasonably priced and relatively less toxic substances can be combined using hydrogen bonding to act as hydrogen bond donors (HBDs) and acceptors (HBAs), respectively. This results in a eutectic mixture with a melting point that is much lower than the sum of its parts due to large, non-symmetric ions with low lattice energy (Zhang et al. 2012;

Fig. 11 Alternative technologies to extract metal from e-waste



Zhao et al. 2015, 2019). Several academic researchers have explored the use of DES as an extractant for metal recovery; a few examples related to e-waste are mentioned in Table 2 (Filiz 2007; Ola and Matsumoto 2019).

Glycine, the most basic amino acid produced naturally by microbes, is non-toxic, nonvolatile, and stable over a wide pH-Eh range, with high metal affinities (Li et al. 2018). With higher silver content, glycine concentrations, and pH (up to pH 11) values, precious metal dissolution rates rose (Oraby and Eksteen 2015). At ambient conditions and a pH of 10.5–11, the lixiviant system containing glycine and peroxide demonstrated total copper dissolution of 98% in 48 h. The analysis shows that the concentrate contained 100% chalcocite, cuprite, metallic copper, and approximately 80% chalcopyrite. Pyrite remained stable throughout the leaching process, and the iron composition in the final pregnant solution was found to be 12 mg/L when the copper concentration was 4745 mg/L, while the gold concentration was limited to 0.8 mg/L Au (Oraby and Eksteen 2014). In the case of recycling WPCBs, the glycine leaching system has yet to be documented. WPCBs can be extracted of base and precious metals using a glycine leaching system owing to the resemblance between Au-Cu concentrate, foils, and WPCBs. Glycine solution has a relatively low leaching efficiency, lasting 40 to 50 h during ore extraction. Additionally, leaching WPCBs with glycine solution may be difficult due to the intrinsic structure and complex compositions of WPCBs. Therefore, it is important to research and develop more effective oxidants and catalysts (Li et al. 2018).

Chelation technology, a unique greener strategy for heavy metal extraction from soils and industrial waste, has gained popularity in recent years among environmentalists. Biodegradable ligands such as DTPA (diethylene triamine

pentaacetate), NTA (nitrilotriacetic acid), oxalate, citrate, and tartrate, as well as oxalate, citrate, and tartrate, have been employed as chelating agents to remove metals such as Cr, Cu, Zn, and Pb from polluted soils. Chauhan et al. used a biodegradable chelating agent (S, S)-ethylenediaminedisuccinic acid ((S, S)-EDDS) in a batch manner under atmospheric reflux conditions to extract Ni from wasted catalyst and recovered 84% Ni in one cycle under ideal reaction conditions and discovered that (S, S)-EDDS required a shorter pH range for extraction and solvent/chelator regeneration than EDTA. The research on chelating agents and their interactions with the environment suggests a wide range of applications in medicine, soil remediation, microbial growth, and metal recovery from industrial waste, but there have been just handful studies on the chelation process for metal recovery from e-waste. There are many more aspects of this innovative paradigm of chelation-dechelation chemistry that need to be investigated for effective WEEE control (Jadhao et al. 2016; Chauhan et al. 2018).

Green techniques for metal extraction from industrial effluent include membrane filtration, green adsorption, and photocatalysis. Green adsorption is frequently used to remove metals from contaminated locations, which comprises low-cost materials derived from agricultural sources, agricultural by-products, agricultural residues, and agricultural wastes (Akcil et al. 2015; Sahni et al. 2016). For the first time, dyes (MB, MG, and CR) were extracted from aqueous solutions using CLP and ZMC, demonstrating the potential for adsorption of green adsorbents. In comparison to chemically modified adsorbents, low adsorbents are more benign to the environment while still being effective at removing toxic elements from industrial waste water (Singh et al. 2017).

Several researchers have looked into chemo-biohydrometallurgy (Table 2; part 3), leaching with pyrometallurgy, and other combinations of two or more technologies for efficient metal extraction from various contaminated sites. A hybrid strategy combining chelation technology and bioleaching to effectively remove Pb and Zn from industrial carbon sludge in subsequent steps had been proposed (Cheikh et al. 2010). Hong et al. introduces a porous porphyrin polymer that quantitatively collects precious metals from PCB waste even with different elements due to its amazing selectivity as well as a reductive mechanism, allowing for unprecedented levels of precious metal recycling, notably gold, from e-waste (Hong et al. 2020).

Several studies have been conducted in recent years to extract metal ions in microfluidic devices for continuous flow liquid–liquid extraction (Asrami et al. 2021). Zhang et al. used Cyanex 272 to extract Co and Ni using coiled flow inverter (CFI) technology, as microflow systems can also help to improve selectivity for a given metal ion (Zhang et al. 2017b).

Various techniques used for the recycling of e-waste is summarized in Table 2. First part shows two studies on pyrolytic metal extraction from e-waste employing carbonization treatment (Jadhao et al. 2021) and vacuum pyrolysis (Tang et al. 2019) to extract Ni, Cu, and Li at high temperature range 623 K to 1273 K. Although the process provides better purity product and significant recovery, but these processes are highly energy intensive and release toxic fumes into the environment requiring additional scrubbers or electro-precipitators (Table 2; part 1). Second part describes about

some hydrometallurgical techniques using different acids, halides, and microbes to extract metal from various e-waste sources along with their drawbacks. Gande et al. focused on developing a process based on the use of a single acid, i.e., nitric acid, and as a result, created zero discharge technology for sustainable metal extraction. This makes it possible to recycle the acid, significantly reducing any negative environmental effects (Gande et al. 2021). The third part of Table 2 shows that the additional technologies that needed to exploit for better recovery of metals from e-waste green solvents have also been studied for use in metal extraction. Jadhao et al. were able to accomplish substantial metal extraction as well as 96% chelating agent recovery. The suggested green process has several advantages, including the recycling of reactant in the next chelation cycle and practically zero discharge to the environment (Jadhao et al. 2016).

Challenges and opportunities

The conventional method used so far although provides significant recovery of metals (base, precious, and REE), but they have certain limitations (Table 3) like pyrometallurgy method of recycling liberates lots of toxic fume and demands high power consumption, and if not handled properly will ultimately cause loss of precious metals, require complicated metal separation techniques, and also cause harm to the environment causing air pollution which ultimately leads to health hazards to all living beings. Hydrometallurgy

Table 3 Advantages and disadvantages of technologies used for metal extraction

Pyrometallurgy	Hydrometallurgy	Novel technologies
Pros i. Significant metal recovery ii. High purity product Cons i. Highly energy intensive ii. Produce toxic gases iii. High economics iv. Loss of precious metals v. Large amount of slag formation vi. Marine and fresh water toxicity vii. Radiation viii. Carbon deposit ix. Water depletion	Pros i. Less amount of toxic gas emission compared to pyrometallurgical process ii. Less dust generation iii. Better metal recovery due to selectivity for particular metal Cons i. Toxic reagents ii. Hazardous to handle, corrosive, expensive iii. Higher by-product generation iv. Large amount of solvent is required v. Acidification vi. Eutrophication vii. Abiotic depletion	Pros i. Maximum metal recovery due to formation of stable metal complexes ii. Handles hazardous material safely iii. Faster process compared to conventional techniques iv. Minimal risk of casualties v. Considered as greener technologies vi. Approaches toward zero discharge Cons i. At an infancy period ii. Few studies have been reported so far now iii. Need to be explored more in future

technology is the most widely used technology for e-waste recycling so far, but it has its own repercussions such as cyanide leaching releases toxic effluents, acid leaching necessitates expensive corrosive resistant equipment, and thiosulfate, thiourea, halide, and bioleaching are inefficient when compared to cyanide leaching, which necessitates a longer residence time, higher solvent demands, higher operating costs, and greater reagent loss due to improper recovery of solvents used for metal extraction. Table 3 briefly discussed about the advantages and disadvantages of different techniques used for metal recovery from e-waste.

To fulfil the expanding industrial demand, future efforts should concentrate on process sustainability, economics, and environmental impact. Future research should concentrate on microextraction and the use of solvents such as ionic liquids and green solvents. Ionic liquids aid in metal extraction by having a unique solubility capability that can be fine-tuned in ways that ordinary solvents cannot (Chauhan et al. 2018; Asrami et al. 2021). This study summarizes the scope of research on microfluidic devices in metal extraction processes.

Process intensification for metal extraction

Process intensification is a revolutionary concept in chemical reaction engineering and process design which can result in considerable gains in terms of process efficiency, higher product quality, reduced total revenue and total expenses, reduced wastage, and enhanced process safety (Haase et al. 2022). Process intensification enables novel process windows to be formed, allowing for improved process performance in terms of conversion, selectivity, and safety. Thus, here in this review, we are more focused on process intensification via miniaturization of reactors and microfluidics to enhance heat and mass transfer for better metal extraction (Singh et al. 2014b, 2019a).



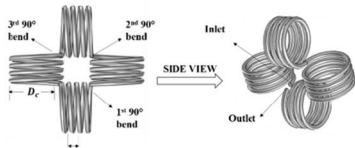
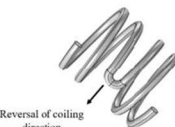
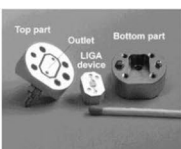

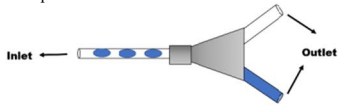
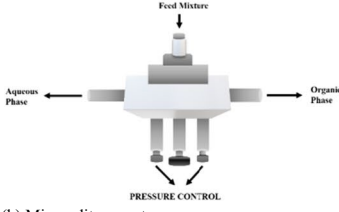
Microfluidics and microscale mixing bring new technical opportunities in better metal extraction (Singh et al. 2020). Obtaining the highest mass transfer rate at the lowest cost is one of the most significant design objectives for the metal extraction process. There are many types of microreactor designs developed by researchers for the same. Polymethyl methacrylate (PMMA) and polydimethylsiloxane (PDMS) are the most common polymeric materials used in microfluidic devices. Curved channels in microfluidic devices accelerate mixing, particularly when they are engineered to induce chaotic flow patterns enhancing the heat and mass transfer rates in curved microchannels. The shape of the microchannel, its width, and the geometry of the channel are parameters influencing extraction performance. The curved microchannel either bent or “C shaped” generates a directional change in the flow, causing chaotic flux and increasing phase interaction to

improve gas bubble or liquid slug break-up. Higher flow rates are used for better phase contacting and mixing, as well as high mass flow rates and greater productivity (Singh et al. 2014b, 2019b; Singh and Nigam 2016). Some of the applications of using microfluidic devices are (i) faster internal recirculation which aids in improving mass transfer between immiscible liquid phases; (ii) by expanding the contact area and lowering the mass transfer resistance, extraction efficiency can be enhanced; (iii) miniaturization allows to overcome the hazardous organic phase and waste materials and has more control over liquid–liquid extraction; (iv) the flow is laminar with lack of turbulence; (v) smaller space occupation on demand and high surface-to-volume ratio; and (vi) efficient and less energy consumption by-products.

Investigation on the slug flow pattern in several residence time units (RTUs) such as straight capillary, micro structured helically coiled tube (MHCT), and micro structured coiled flow inverter (MCFI) (Singh et al. 2013, 2019a; Singh and Nigam 2016) to explore a liquid–liquid (L–L) extraction system was conducted. It was observed that due to enhanced secondary flow and flow inversions, high extraction efficiency was maintained in coiled flow inverter (CFI) (Table 4) around 20% higher than straight tube even at significantly greater flow rates. The findings demonstrate that, compared to straight capillaries, a coiled flow inverter (CFI) offers higher extraction efficiencies of up to 20–25% at constant residence times (Kurt et al. 2016). Higher Reynolds numbers (>100) make these designs more effective (Vural Gürsel et al. 2016). Adjusting $Re = 250$ and varying the tube diameter in MCFI showed that tube with ID 0.5 mm can achieve complete mixing and the mixing efficiency decreases by increasing the tube ID (0.6 mm, 0.8 mm, and 1.0 mm showed 78.9%, 69.6%, and 54.5% mixing respectively) (Zi et al. 2017). The angle of inversion in coiled flow inverter, i.e., α between 90° and 120° , is found to be best to increase mixing rate.

It was observed that mixing rate increases with the increase in Dean number, Schmidt number, and by increasing the number of bends in micro-coiled flow inverter (MCFI) (Mridha and Nigam 2008). Due to the stabilizing effects of Dean vortices in helical tubes generating during the first two turns, Kovats et al. (2020) discovered that the 3-turn CFI can achieve approximately the same mixing efficiency as the 6-turn CFI with double length (Kováts et al. 2020). The coiling orientation is swiftly and completely reversed in the CFR, resulting in a more diverse secondary flow and improved mixing and heat transfer. Additionally, even at high Reynolds numbers, such as $Re=3000$, excellent mixing can be produced with a minor increase in pressure drop of up to 9% higher than in straight helical coils. The coiled flow reverser (CFR) mixing coefficient has been investigated to have more variations, but it is found out systematically better than the CFI for $Re \geq 500$.

Table 4 Summary of miniaturized device

Device	Comments	Ref.
1. Microchips Examples: -  (a) Glass microchip  (b) Silicone microchip	Properties Ψ-Ψ Shaped, Y-shaped or T-shaped, etc., are used to develop stable 3-phase or two-phase flow. May also have narrow zigzag mixing segment, followed by a swirling channel. Photolithography and wet etching were used to make early devices out of silicon and glass, and glass remains a common material. Applications Provides higher $k_L a$ and extraction efficiency. Used in protein separation technology. Used in purification technology combining micro-dialysis. Used for scalability of mass transfer in liquid-liquid system. Helps in achieving phase dispersion and interfacial mass transfer.	Huh et al. (2010) Woitalka et al. (2014)
2. Coiled tube microdevices Examples: -  (a) Coiled Flow Inverter  (b) Coiled Flow Reverser	Properties Also called Tubular miniaturized extractors. Capillary tube (having diameter ≤ 1 mm) with the 90° bends in the square shape (CFI) or reversal of coiling direction (CFR) allow the direction of the centrifugal forces to vary, thus providing efficient mixing. Design specification ranges from ID = 0.1–1 mm; Reynolds No. = 25–1200; Prandtl No. = 0.74–150. Applications Excellent mixing and high heat and mass transfer rates make it useful in both Mass transfer and heat transfer processes. Ability to work on low flow rates is suitable for Solvent extraction process providing possibilities to extract metal from spent catalysts, waste water and E-waste.	Singh et al. (2013, 2014b, 2019b); Singh and Nigam (2016)
3. Micromixers Examples: -  (a) 30 channels static micromixer  (b) Twisted micromixer	Properties Available for low, medium and high-volume flow rates. Static micromixers use multi-lamination principle and comprises of number of interdigital microchannels according to plant specification. Made of various materials like stainless steel, nickel copper, silver, glass, etc. depending upon the type of reagents used. Applications Cascade type of micromixer helps to achieve 100% extraction efficiency due to highly efficient mixing. Helps in forming emulsions, gas liquid dispersions and creams. Provides narrow density distribution emulsions. Used in mini-plants.	Benz et al. (2001); Jafari et al. (2016) Copyright 2016 Elsevier
4. Phase separators Examples: -  (a) Y-shaped phase separator  (b) Micro-slit separator	Properties Also called Flow splitter Teflon, glass and steel are used mostly to fabricate them. We can influence both the capillary pressure and the hydraulic pressure drop in the slits by varying the height. Applications Separation based on wetting properties difference The organic phase is more affluent with Teflon than the aqueous phase is with steel. It is particularly well suited for usage in microscale equipment, where surface tension forces predominate over gravity body forces. Good separation is possible over a broad range of flow rates and phase ratios. Allow for a short contact time and robust performance to allow for minimal pressure gradient between the outlets.	Gaakeer et al. (2012); Assmann et al. (2013); Vural Gürsel et al. (2016)

Abbasi et al. fabricated a microfluidic Y–Y channel employing CO₂-laser technique in a glass microchip to extract gadolinium as depicted in Table 4. Yamamoto et al. (2015) also determines the extraction rate of plutonium (IV) between nitric acid and tri-n-butylphosphate solution using a glass chip microchannel. Different geometrical microchannels exist (rectangular, square, trapezoidal, circular, etc.), each with a different junction design, such as a T-junction or a Y-junction (Fig. 12). The geometry of microchannels is a key design variable for achieving the appropriate mixing performance. Mixing improves when obstructions and wavy channels are included in the channel design as illustrated in Table 4. To enhance mixing performance and reduce mixing time, various configurations of micromixers with obstructions in the channel's center are used. Shorter residence times, from a few seconds to a few minutes, are typically thought to be best suited for applications using microchannels. According to Kashid et al. (2011), mass transfer occurs in the mixing junction, the microchannel, and the downstream capillary which links the microchannel to the sample.

Various designs of microchannel (shown in Fig. 12) have been used in the literature which includes T-shaped, Y-shaped, F-shaped, S-shaped, serpentine, zig-zag shaped, etc. T-square and T-trapezoidal form two stable flow regimes slug and parallel flow, and change in microchannel cross-section does not affect the flow regimes. The transition from slug flow to slug-drop flow occurred in Y-rectangular microchannels at relatively low flow rates for each phase when compared to T microchannels. When flow rates are higher, concentric microchannels produce annular flow. In a caterpillar design, slug-dispersed phase forms at high flow rates. If some internal structure is present, a dispersed phase is created as the flow velocity increases (Kashid et al. 2011).

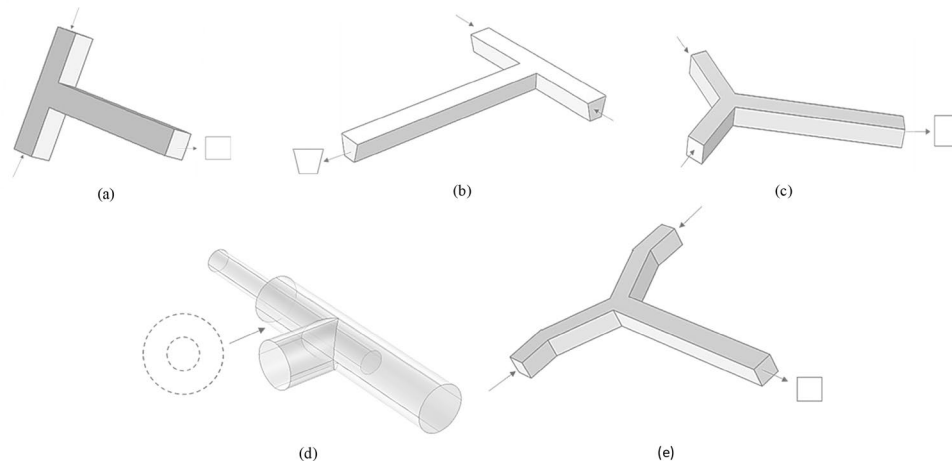
Micromixers are used to make emulsions, gas liquid dispersions, and creams. Fast extraction using nondispersive microdevices has been reported in the literature as shown in Table 4 (Benz et al. 2001; Jafari et al. 2016). In earlier

studies, it was demonstrated that micromixers or micromixer arrays were extremely effective extraction devices. The volume flow dependence of mean droplet size and, consequently, the specific surface area of the intermediately generated dispersions, was found to be a function of the extraction effectiveness (Benz et al. 2001). Jafari et al. investigated that increasing the twist in the micromixer leads in more effective liquid–liquid mass transfer, but at the expense of more energy required to pump fluids into the microchannel. The results show that raising the twist ratio improved both extraction efficiency and pressure reduction (Table 4) (Jafari et al. 2016).

Multiphase microfluidics is gaining popularity due to the continuing interest in using microreactors and micro processing in the chemical and biochemical sectors. Organic/aqueous phase separation can also be performed well on the microscale by utilizing wettability variations between liquids on hydrophilic or hydrophobic surfaces (Table 4). The microscale slit separator separates the aqueous phase from the glass side and the organic phase from the Teflon side (Zhang et al. 2017b). Numerous examples of micro separation devices based on capillary forces and operating at a range of flow rates can be found in the literature. For example, the partially hydrophobic coated conduit maintains a parallel flow of immiscible liquids. Liquids exit the channel independently at the outlets on the coated and uncoated sides. Additionally, it has been demonstrated that membranes work well for microextraction as a separator of immiscible liquids (Gaakeer et al. 2012).

In Table 4, a summary of the most common devices used to investigate the extraction performance of metal ions from the aqueous phase is presented. Y–Y type microchannel, tube reactor, CFI, or T-junction microchannel are the most commonly used devices for the same. Table 4 is divided into four sections based on how microdevices are designed and used. The table lists the various types of microdevices that scientists have used for mixing, extracting, and separating

Fig. 12 Different types of geometry mixing junction microchannel. **a** T-square. **b** T-trapezoidal. **c** Y-rectangular. **d** T-concentric/annular. **e** Y-square caterpillar



processes, which include microchips, coiled tube micro-devices, micromixers, and at last micro separators (Yang et al. 2013; Woitalka et al. 2014; Zhang et al. 2015; Vural et al. 2015; Abbasi et al. 2018). Since none of the mentioned devices and proposed methodologies have been used to extract metals from WEEE, this creates a new domain of novel technologies for researchers to examine their applicability for effective metal extraction from WEEE. Modern computational methods are also thought to contribute to an ongoing revival of research activities, which could aid in the identification of promising biodegradable chelating agents/adsorbents or ionic liquids for metal recovery from WEEE (Chauhan et al. 2018).

Quantitative analysis of microfluidic solvent extraction for metal recovery

To ascertain the applicability of various microdevices in metal recovery, the current study quantitatively analyzes experimental data from the literature (Tsaoulidis et al. 2013; Yang et al. 2013; Yamamoto et al. 2015; Yin et al. 2015; Kriel et al. 2015; Li and Angeli 2016; Zhang et al. 2017b; Jeong et al. 2019; Xie et al. 2019; Angeli et al. 2019). Also, a quantitative comparison between batch and continuous microflow extraction process is presented in the proceeding section based on experimental data from the literature (Zhang et al. 2015; Abbasi et al. 2018; Zhang et al. 2017b; Jeong et al. 2019; Xie et al. 2019).

Effect of residence time on extraction rate

For the analysis of various types of metal extraction using different solvents in microdevices, the experimental data extracted from plots presented in various studies are plotted in Fig. 13 (reference from Table 5) in terms of residence time vs extraction rate (Tsaoulidis et al. 2013; Yang et al. 2013; Yamamoto et al. 2015; Yin et al. 2015; Kriel et al. 2015; Li and Angeli 2016; Zhang et al. 2017b; Jeong et al. 2019; Xie et al. 2019; Angeli et al. 2019). A wide range of tube diameters (0.5 to 2 mm), tube length (2 to 3 m), flow rates (10–500 ml/h) for various solvents, microchannel cross sections, and process conditions like pH, aqueous to organic phase ratio, volume ratio of extractant (%v/v), and inert gas are covered by the experimental data.

The graph shows that the microdevices used in the studies are achieving the higher extraction rates within a range of 50 s of residence time and after reaching certain maximum limit the extraction rate become nearly constant with further increase in residence time. Mass transfer is high at the inlet where both organic and aqueous feed meet with high concentration and mixing is vigorous because the extraction rate first significantly increases with increase in

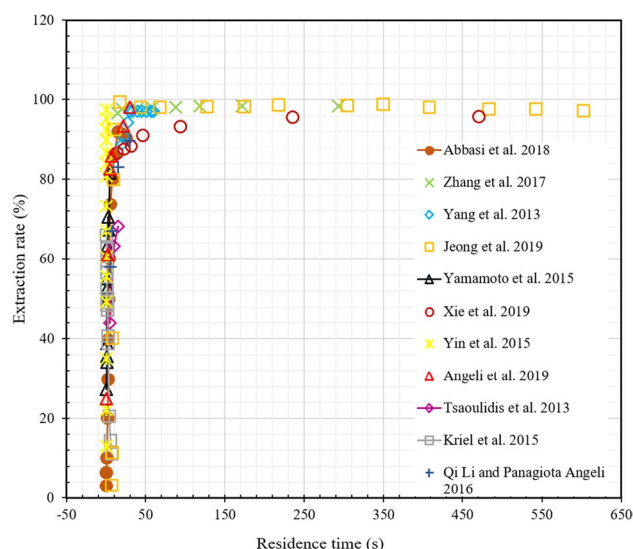


Fig. 13 Residence time (τ) versus extraction rate (E) in different microdevices

residence time due to longer contact time of both phases. Additionally, the increased interfacial area to volume ratio achieved in the present investigations can be attributed to the faster extraction equilibrium. (Yamamoto et al. 2015; Yin et al. 2015; Abbasi et al. 2018) (Angeli et al. 2019) as tabulated in Table 5. However, when the flow pattern develops (mainly slugs or plugs formation), circulation in them will help in mass transfer (diffusion dominant). Xie et al. (2019) shows effect of contact time on extraction by varying the flow rate simultaneously. The intensity of internal circulations within slugs increases as total flow rate increases, boosting the driving force for mass transfer, thus almost 90% extraction rate is reached in < 50 s. Yet, the experimental data indicate that decreasing residence time overcomes increasing flow rate. As a result, at lengthy residence times, high extraction ratios are attained (i.e., low flow rate) as shown in Fig. 13 (Xie et al. 2019). Jeong et al. (2019) investigated that because of the shorter diffusion length, complete extraction can be accomplished in less than 10 s, and oil phase recovery is aided by the low buoyancy of compound bubbles (Jeong et al. 2019). Zhang et al. (2017a) found that 60 s is the optimized contacting time in the microflow as the residence time had little effect on the extraction efficiency in microflow because it is controlled by setting different flow rates in CFI (Zhang et al. 2017b). Tsaoulidis et al. (2013) also carried out various experiments for different channel lengths ranging from 10 to 30 cm to investigate the effect of residence time on dioxouranium (VI) extraction in the microchannel and discovered that increasing the residence time increases dioxouranium (VI) extraction (Tsaoulidis et al. 2013). Yang et al. (2013) observed in their experiment that the

Table 5 Metal extraction using microfluidic device

Ref.	Microdevice used	Metal of interest	Extractant used	Design specification, reaction conditions, and flow properties					Feed concentration	Extractant concentration	Residence time (s)	Mass transfer coefficients $k_L a$ (s^{-1})	Remarks
				w^*h/ID	L_c	d_h	pH	Phase ratio (organic/aqueous)					
Xie et al. (2019)	Slug flow micro-reactor	Zn(II)	D2EHPA	1 mm	0.5 m, 0.75 m, 1 m, and 2 m	1 mm	---	1:1	0.50 mg/L	5–30%v/v	0–500	0.016–0.18	Within a 1 m length, well-defined slugs formed at a flow rate of 0.1–4 mL/min. 2.7–38.9 times higher of $\beta_{Zn/Ni}$ and 3.9–34.9 times higher of $\beta_{Zn/Co}$ then batch and equilibrium experiments. Compared with batch experiments at the same 94 s, the extraction ratio of Zn is 5.1–20.7% higher
Angeli et al. (2019)	Circular quartz micro-channel	Europium(III)	TBP/CMPO	200 μ m	241 mm			0.5–1	1–6 mg/mL	1.2 M/0.2 M	0–60	0.05–3.3	High extraction efficiency ~80% was achieved at short residence times (in the first 6 s). It was discovered that mass transfer was significant at the channel's entrance, near to the inlet, i.e., 1 mm distance

Table 5 (continued)

Ref.	Microde-vice used	Metal of interest	Extractant used	Design specification, reaction conditions, and flow properties					Feed concentration	Extractant concentration	Residence time (s)	Mass transfer coefficients $k_L a$ (s^{-1})	Remarks
				$w * h / ID$	L_c	d_h	pH	Phase ratio (organic/ aqueous)					
Jeong et al. (2019)	Flow focusing generator-FFG parallelized microfluidic device	REE (neodymium)	P507	$w_g * h_g = 40 \mu m * 45 \mu m$ $w_m * h_m = 40 \mu m * 45 \mu m$ $w_c * h_c = 150 \mu m * 90 \mu m$ $w_s * h_s = 2000 \mu m * 1200 \mu m$ $w_d * h_d = 600 \mu m * 1200 \mu m$	$l_g = 1300 \mu m$ $l_m = 5000 \mu m$ $l_c = 700 \mu m$ $l_s = 5750 \mu m$ $l_d = 760 \mu m$	---	----	1:4, 1:6, 1:8, and 1:10	90 mg/L	1% v/v	300	-----	Using 100-FFG device provide rapid extraction ($E > 90\%$) within 10 s as compared to 400-FFG device
Abbasi et al. (2018)	Y-Y microchip	Gadolinium	MDEPHA	400 $\mu m * 400 \mu m$	60 mm	400 μm	1–5	1:1	10–50 mg/L	1–3% v/v	5–25	1.04–0.28	Feed concentration=30 mg/L, extractant concentration=2.9 vol%, pH=2.5, and $\tau = 13.5$ s are optimum conditions providing $k_L a = 3.4 s^{-1}$ and 95.5% gadolinium extraction rate
Zhang et al. (2017b)	CFI	Co and Ni	Cyanex 272	1 mm	2.5 m	1 mm	3–6	1:1	2.578 (Cu) and 66.340 (Ni) g/L	5–25% v/v	15–300	0.26–0.017	Maximum $\beta_{Co/Ni} = 748$ is achieved in $\tau = 60$ s at pH=5.8–5.9 and 4.5 times increase of the k_L value of Co to Ni is observed in CFI

Table 5 (continued)

Ref.	Microde-vice used	Metal of interest	Extractant used	Design specification, reaction conditions, and flow properties					Feed concentration	Extractant concentration	Residence time (s)	Mass transfer coefficients $k_L a$ (s^{-1})	Remarks
				$w \cdot h / ID$	L_c	d_h	pH	Phase ratio (organic/aqueous)					
Li and Angeli (2016)	Micro-chip	Eu(III)	CMPO	0.2 mm and 0.5 mm	5–25 cm	0.2 mm and 0.5 mm	-----	1:1	0.653–21.205 mL/h	-----	0–50	0.005–0.05	Compared to conventional contactors, the interfacial areas and mass transfer coefficients were significantly higher. Thus, $k_L a$ is also higher in the small channel than the large one for the identical mixture velocities
Yamamoto et al. (2015)	Glass chip micro-channel	Plutonium(IV)	TBP	100 $\mu m \cdot 40 \mu m$	80 mm, 120 mm, and 200 mm	57.14 μm	----	1:1	5–20 $\mu L / min$	0.14 mg/L	0.48–4.8	-----	Extraction rate of Pu(IV) increases with increasing contact time of two phases in the microchannel (max. E achieved = 82% in $\tau = 4.8$ s)
Yin et al. (2015)	Micro-reactor	La(III)	P507	160 $\mu m \cdot 40 \mu m$	120 mm	-----	1.5–4.5	1:1	2.98–1.5 $\cdot 10^{+2}$ mL/h	0.2 mol/L	0–0.4	-----	Nearly 100% is the highest extraction efficiency, and as the volumetric flow rate rises, extraction efficiency drops (optimum pH = 4, $\tau = 0.37$) and $J = 3.9 \cdot 10^{-2}$ mol/ $m^2 \cdot s$

Table 5 (continued)

Ref.	Microde-vice used	Metal of interest	Extractant used	Design specification, reaction conditions, and flow properties					Feed concentration	Extractant concentration	Residence time (s)	Mass transfer coefficients $k_L a$ (s^{-1})	Remarks
				w^*h/ID	L_c	d_h	pH	Phase ratio (organic/aqueous)					
Kriel et al. (2015)	Micro-chips (1, extraction, 2, scrubbing; and 3, stripping)	Pt(IV)	Secondary amine	$w_{ad} = 30, 39$, and $40 \mu m$ $w_{org} = 58, 56$, and $40 \mu m$	155 mm, 129, and 129 mm	0.56, 2.38, and 7.82 μm	---	0.6, 2.2, and 5.7	24 mg/L	---	0–14	---	Extraction equilibrium was reached in a matter of seconds (2–6 s). Scrubbing revealed minimal platinum loss in the organic phase. Stripping required longer contact periods (12 s) to reach equilibrium
Tsaoulidis et al. (2013)	Micro-channels	Dioxouranium(VI)	$[C_4mim][NTf_2]$, $[C_{10}mim][NTf_2]$, and $[P_{6,6,6,14}][NTf_2]$	0.5 mm	10–30 cm	0.5 mm	---	1:1	0.1–3 M	30%v/v	0–15	0.07–0.23	Increasing the residence time increases the dioxouranium(VI) extraction and reaches 91% of the equilibrium value within 14.52 s. At an initial nitric acid concentration of 3 M, $k_L a$ is $\approx 0.2 s^{-1}$ for all TBP/ionic liquid systems
Zhang et al. (2015)	Y type micro-channel	Nd(III)	P507	100 $\mu m^*120 \mu m$	140 mm		4	1:1	0.001 mol/L	0.02 mol/L	1.5	---	Within 1.5 s, extraction equilibrium is reached
Yang et al. (2013)	T-junction micro-channel	Cu	AD-100	600 $\mu m^*600 \mu m$	900 mm	600 μm	0.1–3.1	1:1	3 g/L	30%v/v	0–40	0.02–0.2	Extraction efficiency is found to be 0.96, and $k_L a$ increases by increasing the Re_M (ranges 9–200)

extraction efficiency enhanced linearly with the residence time for the copper extraction process as the extraction process in the microchannel is controlled by both reaction-intrinsic kinetics and mass transfer (Yang et al. 2013). Kriel et al. (2015) predicted the diffusion-limited extraction, and the results are found to be in agreement with a diffusion limited model as the extraction is completed within short span of time (Kriel et al. 2015). A summary of various microfluidic devices used for metal extraction is presented in Table 5. From the table, we can clearly observed the application of miniaturized devices in metal extraction resulting in high mass transfer coefficient for shorter contact time. The most important details are how various microflow extraction concepts are implemented in various microfluidic device designs. Use of different extractant like organic solutions, ionic liquids, and combination of them is utilized for efficient recovery of metals (Tsaoulidis et al. 2013; Yang et al. 2013; Yamamoto et al. 2015; Yin et al. 2015; Kriel et al. 2015; Li and Angeli 2016; Zhang et al. 2017b; Jeong et al. 2019; Xie et al. 2019; Angeli et al. 2019).

In most cases, the microfluidic extraction is compared by batch extraction by carrying out the batch operation in parallel (discussed in Table 6). In contrast to microchip extraction, batch process provides lower $k_L a$ values and requires more contact time making it less efficient than microflow extraction.

The graph plotted in Fig. 14 (Zhang et al. 2015, 2017b) with reference to Table 5 gives the comparison of extraction of metals in microflow and batch operation in two different studies. Zhang et al. (2017b) used microscale coiled flow inverter (CFI) for extraction of Co from Ni sulfate solution with Cyanex 272 and then compared it with the conventional batch extraction in parallel. It was observed that faster extraction times, higher extraction ability for Co, lower extraction for Ni, and then better selectivity between Co and Ni at industrial-matching concentrations as compared to batch extraction. When compared to a 450-s batch, the near-optimal 60-s residence time in microflow is much narrower which is approximately 6 times lesser than batch (Zhang et al. 2017b). In microflow, the contact time has very little impact on the extractability. In a 15-s microflow, 96.7% of Co and 6.3% of Ni are extracted. However, in the case of batch, as shown in Fig. 14b, the contact time greatly impacts the extraction rate of Co, while the co-extraction of Ni instead steadily increases with the lengthening of residence time. According to the findings, batch Co extraction kinetics are much slower than microflow kinetics. For neodymium extraction in a Y type microchannel using P507 extractant, the extraction equilibrium was obtained in the batch process in at least 60 s, according to Fig. 14b, while the contact time of 1.5 s implies that the highest extraction rate could

be achieved for a short residence time among both phases in the microfluidic device.

The microfluidic extraction is compared by batch extraction in Table 6. The batch operations are carried out in parallel in the mentioned studies to see the effect of contact time on batch and microflow extraction. As we can clearly deduct from Table 6 and Fig. 14, extraction in batch extraction is highly dependent on contact time thus requiring longer periods to achieve same extraction efficiencies as microflow extraction.

Effect of pH on extraction rate

Figure 15 shows the effect of acidity on the extraction of metals using microdevices. The graph is plotted by using the data taken from plots described in earlier studies by various researchers (initial point of each study is different due to difference in property of metal ion extracted, solvent used, and the interaction conditions of both organic and aqueous phases). From the plot of Fig. 15, we can clearly deduce that as the acidity of the feed solution is decreased, the extraction rate is increasing since the concentration of H^+ ions continuously decreased as pH rose; metal ions are progressively favored to form complexes with extractant used. As the pH (range is mentioned in Table 5) is increased, further metal cations reach saturation in the solution thereby decreasing the extraction rate (Kagawa et al. 2009; Vural Gürsel et al. 2015; Zhang et al. 2017b; Abbasi et al. 2018).

Mondal and Kumar (Mondal and Majumder 2018) studied the effect of pH on extraction rate in packed and unpacked channel. Extraction rate decreases with increasing pH from 5.92 to 7.86 due to the formation of $Cu(OH)_2$ in the presence of OH^- ion separating the Cu^{2+} as the precipitate, decreasing the solubility of the copper ion in the aqueous phase. It increases with increasing pH from 7.86 to 9.26 and again decreases from pH 9.26 to 10.20. The basicity of the aqueous phase rises with increasing pH, promoting the forward reaction, and the metal ion develops a tendency to move towards the organic phase, leading to a rise in extraction percentage within pH 7.86 to 9.26. The Cu^{2+} ion has an isoelectric point of 9.5; thus, at pH greater than 9.50, the extractant molecule is more likely to extract a statistically neutral molecule, resulting in a decrease in %E (Mondal and Majumder 2018). Eosin Y could partially dissociate in an aqueous phase above pH 5.0, and it was fully dissolved in a solution above pH 6.4. When $Ag(I)$ and eosin Y were present in an aqueous phase with a pH of 6.0 as shown in Fig. 15, the largest amount of the formed ion pair was found. The achieved extraction rate was 95% (Nagai et al. 2009). It is apparent that a boost in H^+ concentration restricts the reversible reaction equilibrium from tending in the right way because the extraction efficiencies

Table 6 Comparison between the extraction performance of batch and microreactors

References	Metal of interest	Extractant used	Design specification, reaction conditions, and flow properties				Feed conc.	Extractant conc.	Stirring/shaking time (min)	Phase separation time (s)	$k_L a$ (s^{-1})	Comparison with microfluidic extraction
			Vol. of reactor (mL)	Vol. of organic feed (mL)	Vol. of aqueous feed (mL)	Stirring speed (rpm)						
Abbasi et al. (2018)	Gadolinium	MDEPHA	25	5	5	350	10–50 mg/L	1–3% v/v	5	300	0.0087	Compared to microchip extraction, batch process gives lower $k_L a$ values and requires more time
Jeong et al. (2019)	REE (neodymium)	P507	---	---	---	200–500	90 mg/L	1% v/v	300	900	---	Extraction is found to be mass transfer limited, increases as the agitation speed increases
Xie et al. (2019)	Zn(II)	D2EHPA	50	15	15	---	0.50 mg/L	5–30% v/v	1.56 and 480	600	---	The extraction ratios in the slug flow microreactor at 94.2 s are remarkably similar to those obtained in the batch extraction at 8 h
Zhang et al. (2017b)	Co and Ni	Cyanex 272	---	20	20	---	2.578 (Cu) g/L and 66.34 (Ni) g/L	5–25% v/v	480	1800	0.053–0.013 for Co and 0.024–0.012	Maximum $\beta_{Co/Ni}=426$ is achieved in $\tau=600$ s (almost 10 times compared to microflow)

Table 6 (continued)

References	Metal of interest	Extractant used	Design specification, reaction conditions, and flow properties				Feed conc.	Extractant conc.	Stirring/shaking time (min)	Phase separation time (s)	k_La (s ^{−1})	Comparison with microfluidic extraction
			Vol. of reactor (mL)	Vol. of organic feed (mL)	Vol. of aqueous feed (mL)	Stirring speed (rpm)						
Zhang et al. (2015)	Neodymium	P507	---	---	---	---	0.001 mol/L	---	---	60	---	Batch extraction requires 4 times more contact time than microextraction to reach equilibrium

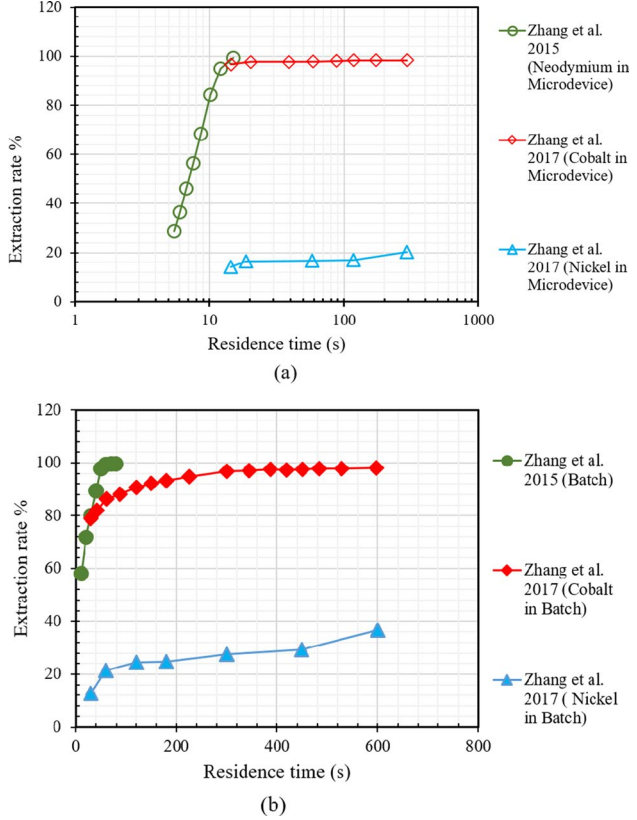


Fig. 14 Comparison of extraction rate in **a** microflow and **b** batch extraction

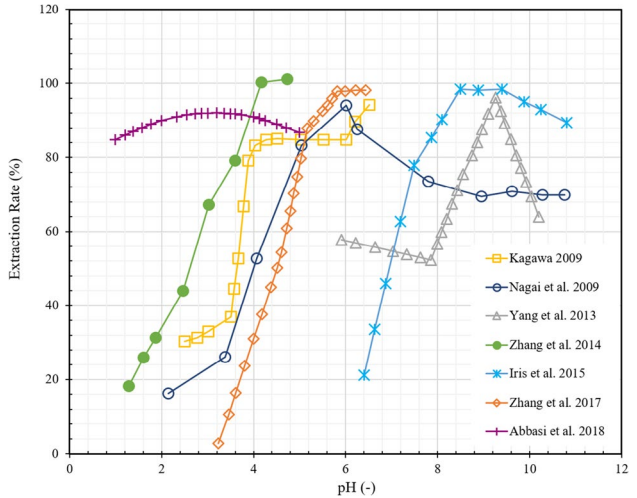
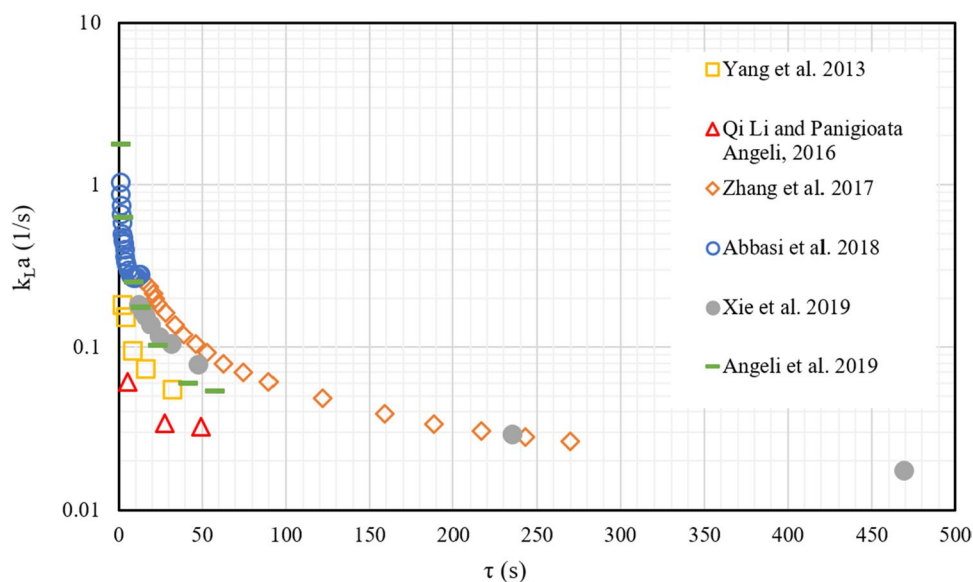


Fig. 15 Effect of pH on extraction rate of various microdevices

declined as the pH of the aqueous phase dropped significantly. Additionally, the distribution of Cu^{2+} in the two phases is adversely affected by an increment in the aqueous phase's H^+ concentration (Yang et al. 2013).

Fig. 16 Effect of residence time on overall volumetric mass transfer coefficients



Effect of contact time on mass transfer coefficient

For the analysis of mass transfer coefficient in microdevices, the experimental data extracted from plots presented in various studies are plotted in Fig. 16 in terms of residence time vs volumetric mass transfer coefficient. Figure 16 describes the effect of contact time on mass transfer coefficient. As we can observe from the plot that with longer residence times, the mass transfer coefficient in the microchannel dropped significantly (Abbasi et al. 2018; Xie et al. 2019). This is due to the inverse correlation between residence time and the total superficial flow rate of the two immiscible liquid–liquid phases in the microchannel, since the two immiscible fluids increased interface interaction (Yang et al. 2013).

Also, the two main factors influencing the k_La are $1/\tau$ and outlet metal ion concentration in aqueous phase. Since the extraction rate depends meagrely on residence time, thus outlet aqueous phase concentration is almost unconstrained of contact time, making k_La approximately equal to inverse of residence time (Xie et al. 2019). The increased surface area and significantly greater extraction of gadolinium during shorter residence time in the microchannel are the factors of the higher volumetric mass transfer coefficient in the microdevices as shown in Fig. 16 (Abbasi et al. 2018). The k_La values comprise of the mass transfer at the entry point and in the entire microchannel, but it is more at entry points where contact time is very short. This can also be considered as the influencing factors for decrease in k_La values for longer contact times (Li and Angeli 2016; Angeli et al. 2019). As a result, a cutting-edge technology has been proposed to improve the recovery, reusability, and recycling of e-waste through the use of micro-greener solvent extraction. It is

possible to combine the solvent and the e-waste slurry at the microscale to create a two-phase flow (slug, plug, dispersed, etc.) that can flow through a microdevice to improve extraction before the metal-rich and metal-deficient streams are separated using micro-separators.

However, over the course of this work, certain limitations were discovered that need addressing for large-scale applications of e-waste metal recovery via micro-solvent extraction. Inadequate biodegradability, high production costs, high viscosity, and high toxicity are just some of the problems associated with using conventional solvents for extractions. The increased amount of solvent required and the resulting waste could be harmful to the environment. It is necessary to thoroughly investigate various types of extractants, such as ionic liquids; organic solvents; primary, secondary, and tertiary amines; and their substitutes, since different types of extractants were mentioned in the literature but not in great detail regarding their role in the extraction of metal ions. The study of the influence of changes in physiochemical characteristics, viscosities, densities, solubilities, thermal stability, and saponification requirements may be advantageous for greater metal recovery with a minimal amount of extractant. Because e-waste has a complex composition, the extraction effectiveness of microdevices will be hampered at higher temperatures due to interference by non-metallic polymeric compounds present in e-waste.

Conclusion

Metal recovery from waste sources is necessary due to the increased rates of metal depletion and e-waste generation. The currently employed conventional techniques are

effective but require improvements in order to recover metals from e-waste commercially in a continuous manner using zero discharge technology. In order to recover metals and other minerals, it is crucial to investigate economic, environmentally friendly, and sustainable processes. Therefore, based on the analysis provided in this work, the following conclusion may be inferred:

- i. Sustainable recycling of the e-waste using conventional methods is a challenging task due to the complex composition of the e-waste, which contains metals, organics, polymer layers, glass, and non-metals. Thus, novel hybrid processes must be developed to recover metals from the e-waste.
- ii. It is demonstrated by few studies that in large-scale metal separation processes, intensified miniaturized extraction devices can improve metal extraction efficiency (20–25%) and offer new industrial viability. Thus, e-waste metal extraction could be investigated using microfluidic devices. Continuous metal extraction using microdevices improves extraction rates, mass transfer coefficients (increased to approximately 30 times), and contact times (within a few seconds), so switching from batch to continuous mode may boost metal recovery.
- iii. Hazardous reagents/extractants hamper industrial solvent extraction due to their higher consumption, corrosive and toxic nature, and higher cost. Greener solvents, biodegradable agents like glycine, chelating reagents, ionic liquids, and deep eutectic solvents may be a promising alternative for industrializing metal recovery technologies. To avoid by-product recovery or to obtain high purity metal, solvents must be customized to extract specific metals at a time.
- iv. Microdevices in metal extraction allow numbering up instead of scale-up for throughput, thus reduces hazardous chemical accidents at large scale and requires less installation space.
- v. The combination of microfluidic technology and greener solvents for process intensification of e-waste metal recovery is expected to garner more attention from researchers in the coming years.
- vi. Noting that there are not many computational studies in the literature, this work proposes a computational analysis of metal extraction from e-waste as a way to broaden the scope of future investigation.

Finally, it is concluded that the proposed technology for extracting metal from WEEE using microflow extraction and green solvents may prove useful in sustainable e-waste recovery and environment waste management.

Nomenclature *EEE*: electrical and electronic equipment; *WEEE*: waste electrical and electronic equipment; *PI*: process intensification; *PCBs*: printed circuit boards; *CPCBs*: computer printed circuit boards; *REE*: rare earth elements; *PGMs*: platinum group metals; *SIM*: subscriber identification module; *WMMs*: waste memory modules; *PV*: photovoltaic; *PC*: *Pseudomonas chlororaphis*; *CFI*: coiled flow inverter; D_c : coil/curvature diameter; P : tube pitch; d_t : tube diameter; E : extraction rate; *MDEPHA*: di-2-ethylhexyl phosphoric acid and mono-2-ethylhexyl phosphoric acid; *AD-100*: 2-hydroxy-5-nonylbenzaldehyde oxime; *P507*: 2-ethylhexyl phosphoric acid-2-ethylhexyl ester; Re_M : Reynolds number of the two immiscible liquids; *TBP*: tri-*n*-butyl phosphate; *D2EHPA*: di-(2-ethylhexyl) phosphoric acid; J : mass transfer rate; *CPMO*: *N*-octyl(phenyl)-*N,N*-diisobutyl carbamoylmethyl phosphine oxide; $[C_4mim][NTf_2]$: 1-butyl-3-methylimidazolium bis{(trifluoromethyl)sulfonyl} amide; $[C_{10}mim][NTf_2]$: 1-decyl-3-methylimidazolium bis{(trifluoromethyl)sulfonyl} amide; $[P_{66614}][NTf_2]$: trihexyltetradecylphosphonium bis{(trifluoromethyl)sulfonyl} amide; τ : residence time; Θ : unmixedness coefficient; k_{La} : volumetric liquid mass transfer coefficient; β : separation factor

Author contribution Both the authors have equally contributed in this review article. Dr. Jogender Singh had the idea for the article. Ms. Aaliya Javed performed the literature search and data analysis. The manuscript is written by both the authors in parts and finally revised critically by Dr. Jogender Singh.

Funding This research is a product of the Project titled “Continuous and Sustainable Extraction of Critical Metals from E-Waste”, funded by the Seed Money/Research Grant as per the letter number Dean (R&C)/Seed Money/2020-21/1483, dated 08.12.2020.

Data availability Not applicable (since, it is a review article).

Declarations

Ethics approval The authors declare that there are no potential conflicts of interest (financial or non-financial) and the research does not involve human participants and animals.

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interest The authors declare no competing interests.

References

- Abbasi A, Rahbar-Kelishami A, Ghasemi MJ (2018) Development of a microfluidic-chip system based on parallel flow for intensified Gd(III) extraction from nitrate media using cationic extractant. *J Rare Earths* 36:1198–1204. <https://doi.org/10.1016/j.jre.2018.03.024>
- Akcil A, Erust C, Gahan CS et al (2015) Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants – a review. *Waste Manag* 45:258–271. <https://doi.org/10.1016/j.wasman.2015.01.017>
- Angeli P, Tsaoulidis D, Hashi Weheliye W (2019) Studies on mass transfer of europium(III) in micro-channels using a micro laser induced fluorescence technique. *Chem Eng J* 372:1154–1163. <https://doi.org/10.1016/j.cej.2019.04.084>

- Ardente F, Latunussa CEL, Blengini GA (2019) Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. *Waste Manag* 91:156–167. <https://doi.org/10.1016/j.wasman.2019.04.059>
- Asrami MR, Tran NN, Nigam KDP, Hessel V (2021) Solvent extraction of metals: role of ionic liquids and microfluidics. *Sep Purif Technol* 262: 1–15
- Assmann N, Ladosz A, Rudolf von Rohr P (2013) Continuous micro liquid-liquid extraction. *Chem Eng Technol* 36:921–936. <https://doi.org/10.1002/ceat.201200557>
- Bas AD, Deveci H, Yazici EY (2013) Bioleaching of copper from low grade scrap TV circuit boards using mesophilic bacteria. *Hydrometallurgy* 138:65–70. <https://doi.org/10.1016/j.hydromet.2013.06.015>
- Benz K, Jäckel K-P, Regenauer K-J et al (2001) Utilization of micro-mixers for extraction processes. *Chem Eng Technol* 24:11–17. [https://doi.org/10.1002/1521-4125\(200101\)24](https://doi.org/10.1002/1521-4125(200101)24)
- Bhutta MKS, Omar A, Yang X (2011) Electronic waste: a growing concern in today's environment. *Econ Res Int* 2011:1–8. <https://doi.org/10.1155/2011/474230>
- 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 Manag* 34:2581–2586. <https://doi.org/10.1016/j.wasman.2014.08.028>
- Ceballos DM, Dong Z (2016) The formal electronic recycling industry: challenges and opportunities in occupational and environmental health research. *Environ Int* 95:157–166. <https://doi.org/10.1016/j.envint.2016.07.010>
- Chauhan G, Jadhao PR, Pant KK, Nigam KDP (2018) Novel technologies and conventional processes for recovery of metals from waste electrical and electronic equipment: challenges & opportunities – a review. *J Environ Chem Eng* 6:1288–1304. <https://doi.org/10.1016/j.jece.2018.01.032>
- Cheikh M, Magnin JP, Gondrexon N et al (2010) Zinc and lead leaching from contaminated industrial waste sludges using coupled processes. *Environ Technol* 31:1577–1585. <https://doi.org/10.1080/09593331003801548>
- Choi S, Lee A, Choi G et al (2022) Free cortisol mediates associations of maternal urinary heavy metals with neonatal anthropometric measures: a cross-sectional study. *Toxics* 10:167. <https://doi.org/10.3390/toxics10040167>
- Chowdhury S, Rahman KS, Chowdhury T, Nuthammachot N, Techato K, Akhtaruzzaman Md, Tiong SK, Sopian K, Amin N (2020) An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strat Rev* 27:100431. <https://doi.org/10.1016/j.esr.2019.100431>
- Cui J, Zhang L (2008) Metallurgical recovery of metals from electronic waste: a review. *J Hazard Mater* 158:228–256. <https://doi.org/10.1016/j.jhazmat.2008.02.001>
- Debnath B, Chowdhury R, Ghosh SK (2018) Sustainability of metal recovery from E-waste. *Front Environ Sci Eng* 12:2. <https://doi.org/10.1007/s11783-018-1044-9>
- Dias P, Javimczik S, Benevit M et al (2016) Recycling WEEE: extraction and concentration of silver from waste crystalline silicon photovoltaic modules. *Waste Manag* 57:220–225. <https://doi.org/10.1016/j.wasman.2016.03.016>
- Ding Y, Zhang S, Liu B et al (2019) Recovery of precious metals from electronic waste and spent catalysts: a review. *Resour Conserv Recycl* 141:284–298. <https://doi.org/10.1016/j.resconrec.2018.10.041>
- Erickson D, Li D (2004) Integrated microfluidic devices. *Anal Chim Acta* 507:11–26. <https://doi.org/10.1016/j.aca.2003.09.019>
- Filiz M (2007) Extraction of Mn(II) from aqueous hydrochloric acid solutions into Alamine 336–m-xylene system. *Hydrometallurgy* 87:58–62. <https://doi.org/10.1016/j.hydromet.2007.02.001>
- Forti V, Baldé CP, Kuehr R, Bel G (2020) The global E-waste monitor:2020
- Frazzoli C, Orisakwe OE, Dragone R, Mantovani A (2010) Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. *Environ Impact Assess Rev* 30:388–399. <https://doi.org/10.1016/j.eiar.2009.12.004>
- Gaakeer WA, de Croon MHJM, van der Schaaf J, Schouten JC (2012) Liquid-liquid slug flow separation in a slit shaped micro device. *Chem Eng J* 207–208:440–444. <https://doi.org/10.1016/j.cej.2012.06.148>
- Gande VV, Vats S, Bhatt N, Pushpavanam S (2021) Sequential recovery of metals from waste printed circuit boards using a zero-discharge hydrometallurgical process. *Clean Eng Technol* 4:100143. <https://doi.org/10.1016/j.clet.2021.100143>
- Haase S, Tolvanen P, Russo V (2022) Process intensification in chemical reaction engineering. *Processes* 10:99. <https://doi.org/10.3390/pr10010099>
- Heacock M, Kelly CB, Asante KA et al (2016) E-Waste and harm to vulnerable populations: a growing global problem. *Environ Health Perspect* 124:550–555. <https://doi.org/10.1289/ehp.1509699>
- Hong Y, Thirion D, Subramanian S et al (2020) Precious metal recovery from electronic waste by a porous porphyrin polymer. *Proc Natl Acad Sci* 117:16174–16180. <https://doi.org/10.1073/pnas.2000606117>
- Huang J, Chen M, Chen H et al (2014) Leaching behavior of copper from waste printed circuit boards with brønsted acidic ionic liquid. *Waste Manag* 34:483–488. <https://doi.org/10.1016/j.wasman.2013.10.027>
- Huh YS, Jeong CM, Chang HN et al (2010) Rapid separation of bacteriorhodopsin using a laminar-flow extraction system in a microfluidic device. *Biomicrofluidics* 4: 1–10. <https://doi.org/10.1063/1.3298608>
- Hunt AJ, Farmer TJ, Clark JH (2013) Chapter 1. In: Elemental sustainability and the importance of scarce element recovery, pp 1–28
- Jadhao P, Chauhan G, Pant KK, Nigam KDP (2016) Greener approach for the extraction of copper metal from electronic waste. *Waste Manag* 57:102–112. <https://doi.org/10.1016/j.wasman.2015.11.023>
- Jadhao PR, Ahmad E, Pant KK, Nigam KDP (2022) Advancements in the field of electronic waste recycling: critical assessment of chemical route for generation of energy and valuable products coupled with metal recovery. *Sep Purif Technol* 289:120773. <https://doi.org/10.1016/j.seppur.2022.120773>
- Jadhao PR, Pandey A, Pant KK, Nigam KDP (2021) Efficient recovery of Cu and Ni from WPCB via alkali leaching approach. *J Environ Manage* 296:113154. <https://doi.org/10.1016/j.jenvm.2021.113154>
- Jafari O, Rahimi M, Kakavandi FH (2016) Liquid-liquid extraction in twisted micromixers. *Chem Eng Process: Process Intensif* 101:33–40. <https://doi.org/10.1016/j.cep.2015.12.013>
- Jeong H-H, Chen Z, Yadavali S et al (2019) Large-scale production of compound bubbles using parallelized microfluidics for efficient extraction of metal ions. *Lab Chip* 19:665–673. <https://doi.org/10.1039/C8LC01267A>
- Jha R, Rao MD, Meshram A, Verma HR, Singh KK (2020) Potential of polymer inclusion membrane process for selective recovery of metal values from waste printed circuit boards: a review. *J Clean Prod* 265:121621. <https://doi.org/10.1016/j.jclepro.2020.121621>
- Kagawa T, Ohno M, Seki T, Chikama K (2009) Online determination of copper in aluminum alloy by microchip solvent extraction using isotope dilution ICP-MS method. *Talanta* 79:1001–1005. <https://doi.org/10.1016/j.talanta.2009.02.017>
- Kashid MN, Renken A, Kiwi-Minsker L (2011) Influence of flow regime on mass transfer in different types of microchannels. *Ind Eng Chem Res* 50:6906–6914. <https://doi.org/10.1021/ie102200j>

- Kováts P, Velten C, Mansour M et al (2020) Mixing characterization in different helically coiled configurations by laser-induced fluorescence. *Exp Fluids* 61:1–17. <https://doi.org/10.1007/s00348-020-03035-0>
- Kriel FH, Holzner G, Grant RA et al (2015) Microfluidic solvent extraction, stripping, and phase disengagement for high-value platinum chloride solutions. *Chem Eng Sci* 138:827–833. <https://doi.org/10.1016/j.ces.2015.08.055>
- Kumari A, Jha MK, Lee J, Singh RP (2016) Clean process for recovery of metals and recycling of acid from the leach liquor of PCBs. *J Clean Prod* 112:4826–4834. <https://doi.org/10.1016/j.jclepro.2015.08.018>
- Kurt SK, Vural Gürsel I, Hessel V, Nigam KDP, Kockmann N (2016) Liquid–liquid extraction system with microstructured coiled flow inverter and other capillary setups for single-stage extraction applications. *Chem Eng J* 284:764–777. <https://doi.org/10.1016/j.cej.2015.08.099>
- Lee H, Molstad E, Mishra B (2018) Recovery of gold and silver from secondary sources of electronic waste processing by thio-urea leaching. *JOM* 70:1616–1621. <https://doi.org/10.1007/s11837-018-2965-2>
- Li H, Eksteen J, Oraby E (2018) Hydrometallurgical recovery of metals from waste printed circuit boards (WPCBs): Current status and perspectives – a review. *Resour Conserv Recycl* 139:122–139. <https://doi.org/10.1016/j.resconrec.2018.08.007>
- Li K, Xu Z (2015) Application of supercritical water to decompose brominated epoxy resin and environmental friendly recovery of metals from waste memory module. *Environ Sci Technol* 49:1761–1767. <https://doi.org/10.1021/es504644b>
- Li Q, Angeli P (2016) Intensified Eu(III) extraction using ionic liquids in small channels. *Chem Eng Sci* 143:276–286. <https://doi.org/10.1016/j.ces.2016.01.004>
- Liu L, Yao L, Dong M, Liu T, Lai W, Yin X, Zhou S, Lv L, Li L, Wang J, Jiang X, Parveen B, Chen J, Sun X (2021) Maternal urinary cadmium concentrations in early pregnancy in relation to prenatal and postpartum size of offspring. *J Trace Elem Med Bio* 68. <https://doi.org/10.1016/j.jtemb.2021.126823>
- Maus V, Giljum S, Gutschhofer J, da Silva DM, Probst M, Gass SLB, Luckeneder S, Lieber M, McCallum I (2020) A global-scale data set of mining areas. *Scientific Data* 7:1–13. <https://doi.org/10.1038/s41597-020-00624-w>
- Mondal S, Majumder SK (2018) Studies on the copper extraction in a channel-based packed extraction device. *Miner Eng* 126:194–206. <https://doi.org/10.1016/j.mineng.2018.05.013>
- Mridha M, Nigam KDP (2008) Coiled flow inverter as an inline mixer. *Chem Eng Sci* 63:1724–1732. <https://doi.org/10.1016/j.ces.2007.10.028>
- Nagai H, Miwa N, Segawa M et al (2009) Quantification of Ag(I) and kinetic analysis using ion-pair extraction across a liquid/liquid interface in a laminar flow by fluorescence microscopy. *J Appl Phys* 105:102015. <https://doi.org/10.1063/1.3116092>
- Nakamura H, Suzuki S, Tezuka T et al (2015) Sooting limits and PAH formation of n-hexadecane and 2,2,4,4,6,8,8-heptamethylnonane in a micro flow reactor with a controlled temperature profile. *Proc Combust Inst* 35:3397–3404. <https://doi.org/10.1016/j.proci.2014.05.148>
- Noel-Brune M, Goldizen FC, Neira M et al (2013) Health effects of exposure to e-waste. *Lancet Glob Health* 1:e70. [https://doi.org/10.1016/S2214-109X\(13\)70020-2](https://doi.org/10.1016/S2214-109X(13)70020-2)
- Ola PD, Matsumoto M (2019) Use of deep eutectic solvent as extractant for separation of Fe (III) and Mn (II) from aqueous solution. *Sep Sci Technol* 54:759–765. <https://doi.org/10.1080/01496395.2018.1517796>
- Oraby EA, Eksteen JJ (2014) The selective leaching of copper from a gold–copper concentrate in glycine solutions. *Hydrometallurgy* 150:14–19. <https://doi.org/10.1016/j.hydromet.2014.09.005>
- Oraby EA, Eksteen JJ (2015) The leaching of gold, silver and their alloys in alkaline glycine–peroxide solutions and their adsorption on carbon. *Hydrometallurgy* 152:199–203. <https://doi.org/10.1016/j.hydromet.2014.12.015>
- Panda R, Pant KK, Bhaskar T (2021) Efficient extraction of metals from thermally treated waste printed circuit boards using solid state chlorination: statistical modeling and optimization. *J Clean Prod* 313. <https://doi.org/10.1016/j.jclepro.2021.127950>
- Perkins DN, Brune Drisse M-N, Nxele T, Sly PD (2014) E-waste: a global hazard. *Ann Glob Health* 80:286. <https://doi.org/10.1016/j.aogh.2014.10.001>
- Petter PMH, Veit HM, Bernardes AM (2014) Evaluation of gold and silver leaching from printed circuit board of cellphones. *Waste Manag* 34:475–482. <https://doi.org/10.1016/j.wasman.2013.10.032>
- Ramirez-Tijerina R, Rivera-Solorio C, Singh J, Nigam K (2018) Numerical study of heat transfer enhancement for laminar nanofluids flow. *Appl Sci* 8:2661. <https://doi.org/10.3390/app8122661>
- Rao MD, Singh KK, Morrison CA, Love JB (2021) Recycling copper and gold from e-waste by a two-stage leaching and solvent extraction process. *Sep Purif Technol* 263:118400. <https://doi.org/10.1016/j.seppur.2021.118400>
- Ruan J, Zhu X, Qian Y, Hu J (2014) A new strain for recovering precious metals from waste printed circuit boards. *Waste Manag* 34:901–907. <https://doi.org/10.1016/j.wasman.2014.02.014>
- Sahni A, Kumar A, Kumar S (2016) Chemo-biohydrometallurgy—a hybrid technology to recover metals from obsolete mobile SIM cards. *Environ Nanotechnol Monit Manag* 6:130–133. <https://doi.org/10.1016/j.enmm.2016.09.003>
- Santana HS, Silva JL, Aghel B, Ortega-Casanova J (2020) Review on microfluidic device applications for fluids separation and water treatment processes. *SN Appl Sci* 2:395. <https://doi.org/10.1007/s42452-020-2176-7>
- Sánchez-Ortiz W, Aldana-González J, Le Manh T, Romero-Romo M, Mejía-Caballero I, Ramírez-Silva MT, Arce-Estrada EM, Mugica-Álvarez V, Palomar-Pardavé M (2021) A deep eutectic solvent as leaching agent and electrolytic bath for silver recovery from spent silver oxide batteries. *J Electrochem Soc* 168(1):016508. <https://doi.org/10.1149/1945-7111/abdb01>
- Sheffield P, Rowe M, Agu D et al (2014) Health impact assessments for environmental restoration: the case of Caño Martín Peña. *Ann Glob Health* 80:296. <https://doi.org/10.1016/j.aogh.2014.07.001>
- Singh H, Chauhan G, Jain AK, Sharma SK (2017) Adsorptive potential of agricultural wastes for removal of dyes from aqueous solutions. *J Environ Chem Eng* 5(1):122–135. <https://doi.org/10.1016/j.jece.2016.11.030>
- Singh J, Choudhary N, Nigam KDP (2014a) The thermal and transport characteristics of nanofluids in a novel three-dimensional device. *Can J Chem Eng* 92:2185–2201. <https://doi.org/10.1002/cjce.12045>
- Singh J, Kockmann N, Nigam KDP (2014b) Novel three-dimensional microfluidic device for process intensification. *Chem Eng Process: Process Intensif* 86:78–89. <https://doi.org/10.1016/j.cep.2014.10.013>
- Singh J, Montesinos-Castellanos A, KDP N (2019a) Process intensification for compact and micro heat exchangers through innovative technologies: a review. *Ind Eng Chem Res* 58:13819–13847. <https://doi.org/10.1021/acs.iecr.9b02082>
- Singh J, Montesinos-Castellanos A, Nigam KDP (2019b) Thermal and hydrodynamic performance of a novel passive mixer ‘waving coiled flow inverter’. *Chem Eng Process: Process Intensif* 141:107536. <https://doi.org/10.1016/j.cep.2019.107536>
- Singh J, Nigam KDP (2016) Pilot plant study for effective heat transfer area of coiled flow inverter. *Chem Eng Process: Process Intensif* 102:219–228. <https://doi.org/10.1016/j.cep.2016.02.001>
- Singh J, Srivastava V, Nigam KDP (2016) Novel membrane module for permeate flux augmentation and process intensification. *Ind*

- Eng Chem Res 55:3861–3870. <https://doi.org/10.1021/acs.iecr.5b04865>
- Singh J, Sharma L, Chaouki J (2020) Process Intensification for Micro-flow Extraction: Batch to Continuous Process. Sustainable Metal Extraction from Waste Streams 207–230. <https://doi.org/10.1002/9783527826704.ch9>
- Singh J, Verma V, Nigam KDP (2013) Flow Characteristics of power-law fluids in coiled flow inverter. Ind Eng Chem Res 52:207–221. <https://doi.org/10.1021/ie300516w>
- Tran MK, Rodrigues MTF, Kato K, Babu G, Ajayan PM (2019) Deep eutectic solvents for cathode recycling of Li-ion batteries. Nat Energy 4(4):339–345. <https://doi.org/10.1038/s41560-019-0368-4>
- Tang Y, Xie H, Zhang B et al (2019) Recovery and regeneration of LiCoO₂-based spent lithium-ion batteries by a carbothermic reduction vacuum pyrolysis approach: controlling the recovery of CoO or Co. Waste Manag 97:140–148. <https://doi.org/10.1016/j.wasman.2019.08.004>
- Tsaoulidis D, Dore V, Angeli P et al (2013) Extraction of dioxouranium(VI) in small channels using ionic liquids. Chem Eng Res Des 91:681–687. <https://doi.org/10.1016/j.cherd.2013.01.008>
- Valdés Vergara MA, Lijanová I v., Likhanova N v., et al (2015) Recycling and recovery of ammonium-based ionic liquids after extraction of metal cations from aqueous solutions. Sep Purif Technol 155:110–117. <https://doi.org/10.1016/j.seppur.2015.05.031>
- van Yken J, Boxall NJ, Cheng KY et al (2021) E-waste recycling and resource recovery: a review on technologies, barriers and enablers with a focus on oceania. Metals (Basel) 11:1313. <https://doi.org/10.3390/met11081313>
- Vural Gürsel I, Aldiansyah F, Wang Q et al (2015) Continuous metal scavenging and coupling to one-pot copper-catalyzed azide-alkyne cycloaddition click reaction in flow. Chem Eng J 270:468–475. <https://doi.org/10.1016/j.cej.2015.02.035>
- Vural Gürsel I, Kurt SK, Aalders J et al (2016) Utilization of milli-scale coiled flow inverter in combination with phase separator for continuous flow liquid–liquid extraction processes. Chem Eng J 283:855–868. <https://doi.org/10.1016/j.cej.2015.08.028>
- Wang H, Mustaffar A, Phan AN et al (2017) A review of process intensification applied to solids handling. Chem Eng Process: Process Intensif 118:78–107. <https://doi.org/10.1016/j.cep.2017.04.007>
- Wang Q, He AM, Gao B et al (2011) Increased levels of lead in the blood and frequencies of lymphocytic micronucleated binucleated cells among workers from an electronic-waste recycling site. J. Environ. Sci. Health. Part A 46:669–676. <https://doi.org/10.1080/10934529.2011.563176>
- Wang X, Miller G, Ding G et al (2012) Health risk assessment of lead for children in tinfoil manufacturing and e-waste recycling areas of Zhejiang Province, China. Sci Total Environ 426:106–112. <https://doi.org/10.1016/j.scitotenv.2012.04.002>
- Woitalka A, Kuhn S, Jensen KF (2014) Scalability of mass transfer in liquid-liquid flow. Chem Eng Sci 116:1–8. <https://doi.org/10.1016/j.ces.2014.04.036>
- Wu K, Xu X, Peng L et al (2012) Association between maternal exposure to perfluorooctanoic acid (PFOA) from electronic waste recycling and neonatal health outcomes. Environ Int 48:1–8. <https://doi.org/10.1016/j.envint.2012.06.018>
- Xie W, Zhang L, Yang J et al (2019) Separation of Zn(II) from Zn-Ni-Co sulphate solution by di-(2-ethylhexyl)phosphoric acid (D2EHPA) using a slug flow microreactor. Chem Eng Process: Process Intensif 143:107562. <https://doi.org/10.1016/j.cep.2019.107562>
- Xu L, Ge J, Huo X et al (2016) Differential proteomic expression of human placenta and fetal development following e-waste lead and cadmium exposure in utero. Sci Total Environ 550:1163–1170. <https://doi.org/10.1016/j.scitotenv.2015.11.084>
- Xu L, Huo X, Liu Y et al (2020) Hearing loss risk and DNA methylation signatures in preschool children following lead and cadmium exposure from an electronic waste recycling area. Chemosphere 246:125829. <https://doi.org/10.1016/j.chemosphere.2020.125829>
- Xu L, Huo X, Zhang Y et al (2015a) Polybrominated diphenyl ethers in human placenta associated with neonatal physiological development at a typical e-waste recycling area in China. Environ Pollut 196:414–422. <https://doi.org/10.1016/j.envpol.2014.11.002>
- Xu P, Lou X, Ding G et al (2014) Association of PCB, PBDE and PCDD/F body burdens with hormone levels for children in an e-waste dismantling area of Zhejiang Province, China. Sci Total Environ 499:55–61. <https://doi.org/10.1016/j.scitotenv.2014.08.057>
- Xu X, Liu J, Huang C et al (2015b) Association of polycyclic aromatic hydrocarbons (PAHs) and lead co-exposure with child physical growth and development in an e-waste recycling town. Chemosphere 139:295–302. <https://doi.org/10.1016/j.chemosphere.2015.05.080>
- Xu X, Zeng X, Boezen HM, Huo X (2015c) E-waste environmental contamination and harm to public health in China. Front Med 9:220–228
- Yamamoto M, Taguchi S, Sato S, Surugaya N (2015) Evaluation of plutonium(IV) extraction rate between nitric acid and tri-*n*-butylphosphate solution using a glass chip microchannel. J Sep Sci 38:1807–1812. <https://doi.org/10.1002/jssc.201401315>
- Yamane LH, Tavares de Moraes V, Espinosa DCR, Tenório JAS (2011) Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. Waste Management 31(12):2553–2558. <https://doi.org/10.1016/j.wasman.2011.07.006>
- Yang L, Zhao Y, Su Y, Chen G (2013) An experimental study of copper extraction characteristics in a T-junction microchannel. Chem Eng Technol 36:985–992. <https://doi.org/10.1002/ceat.201200464>
- Yang WD, Sun Q, Ni HG (2021) Cost-benefit analysis of metal recovery from e-waste: implications for international policy. Waste Manage 123:42–47. <https://doi.org/10.1016/j.wasman.2021.01.023>
- Yang Y, Lai M, Zhong Q et al (2019) Study on intensification behavior of bismuth ions on gold cyanide leaching. Metals (Basel) 9:362. <https://doi.org/10.3390/met9030362>
- Yin S, Zhang L, Peng J et al (2015) Microfluidic solvent extraction of La(III) with 2-ethylhexyl phosphoric acid-2-ethylhexyl ester (P507) by a microreactor. Chem Eng Process: Process Intensif 91:1–6. <https://doi.org/10.1016/j.cep.2015.03.003>
- Zeng X, Xu X, Boezen HM et al (2017) Decreased lung function with mediation of blood parameters linked to e-waste lead and cadmium exposure in preschool children. Environ Pollut 230:838–848. <https://doi.org/10.1016/j.envpol.2017.07.014>
- Zeng X, Xu X, Qin Q et al (2019) Heavy metal exposure has adverse effects on the growth and development of preschool children. Environ Geochem Health 41:309–321. <https://doi.org/10.1007/s10653-018-0114-z>
- Zeng Z, Huo X, Zhang Y et al (2018) Lead exposure is associated with risk of impaired coagulation in preschool children from an e-waste recycling area. Environ Sci Pollut Res 25:20670–20679. <https://doi.org/10.1007/s11356-018-2206-9>
- Zhang B, Huo X, Xu L et al (2017a) Elevated lead levels from e-waste exposure are linked to decreased olfactory memory in children. Environ Pollut 231:1112–1121. <https://doi.org/10.1016/j.envpol.2017.07.015>
- Zhang L, Hessel V, Peng J et al (2017b) Co and Ni extraction and separation in segmented micro-flow using a coiled flow inverter. Chem Eng J 307:1–8. <https://doi.org/10.1016/j.cej.2016.08.062>
- Zhang L, Xie F, Li S et al (2015) Solvent extraction of Nd(III) in a Y type microchannel with 2-ethylhexyl phosphoric acid-2-ethylhexyl ester. Green Process Synth 4:3–10. <https://doi.org/10.1515/gps-2014-0095>

- Zhang Q, de Oliveira VK, Royer S, Jérôme F (2012) Deep eutectic solvents: syntheses, properties and applications. *Chem Soc Rev* 41:7108. <https://doi.org/10.1039/c2cs35178a>
- Zhang Y, Huo X, Cao J et al (2016) Elevated lead levels and adverse effects on natural killer cells in children from an electronic waste recycling area. *Environ Pollut* 213:143–150. <https://doi.org/10.1016/j.envpol.2016.02.004>
- Zhang Y, Xu X, Sun D et al (2017c) Alteration of the number and percentage of innate immune cells in preschool children from an e-waste recycling area. *Ecotoxicol Environ Saf* 145:615–622. <https://doi.org/10.1016/j.ecoenv.2017.07.059>
- Zhang Y, Zhao Z, Sun J et al (2013) A new mutation in the human cytomegalovirus UL97 gene may confer ganciclovir resistance in Chinese kidney transplant recipients. *Arch Virol* 158:247–250. <https://doi.org/10.1007/s00705-012-1479-4>
- Zhao B-Y, Xu P, Yang F-X et al (2015) Biocompatible deep eutectic solvents based on choline chloride: characterization and application to the extraction of rutin from *Sophora japonica*. *ACS Sustain Chem Eng* 3:2746–2755. <https://doi.org/10.1021/acssuschemeng.5b00619>
- Zhao R, Li X, Mao C et al (2019) [HDMF]Cl-based DES as highly efficient extractants and catalysts for oxidative desulfurization of model oil. *RSC Adv* 9:14400–14406. <https://doi.org/10.1039/C8RA10554E>
- Zheng G, Xu X, Li B et al (2013) Association between lung function in school children and exposure to three transition metals from an e-waste recycling area. *J Expo Sci Environ Epidemiol* 23:67–72. <https://doi.org/10.1038/jes.2012.84>
- Zi J, Soh EN, Supriyanto E (2017) An investigation of mixing in micro coiled flow inverter in varying tube diameter with fixed Reynolds number. *WSEAS Trans Fluid Mech* 12:83–90

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.