



REVIEW

Recycling of Electronic Wastes to Produce Metallic Nanoparticles: A Review

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Innovations in technology are crucial to the survival of modern society. As a result, the output of electronic garbages (E-wastes), which contain recyclable and reusable components, has significantly increased. Electronic waste represents a significant environmental challenge which is rapidly intensifying on a global scale. Batteries and used printed circuit boards are examples of e-waste that can be recycled. The current scenario to recycle electronic waste severely needs the environmentally friendly and resource recovery methods. The study of alternate inputs for nanoparticle manufacturing as well as the application of green synthesis methodologies is driven by the area of materials science and engineering's growing interest in enhancing the sustainability of the processes involved in their manufacture. Recovered metals can be used for a variety of purposes and one of them is as a great substitute source for making nanoparticles at a low cost. Finding a less expensive substitute precursor is crucial since it enables the commercialization of numerous uses for metal nanoparticles. Every year, tonnes of technological goods are transported across oceans, which degrade into complex trash after use. More than 75% of e-wastes are unsure of their purpose or trying to find ways to be used, such as refurbishing, remanufacturing and parts reusability for repair. The generation of e-wastes from large household appliances represents the largest proportion of waste, followed by information and communications technology equipment and consumer electronics. The purpose and significance of recycling e-wastes for the recovery of nanomaterials, as well as prospective uses for producing renewable energy, are covered in this review.

Keywords: Electronic wastes, Recycling, Nanoparticles, Metallic oxide, Sustainability.

INTRODUCTION

E-waste refers to electrical devices, such as computers, laptops, household appliances, recreational equipment, and electronic products, once they have reached the end of their usable life. These items may comprise various elements or metals such as platinum, gold, silver, copper, iron, nickel, cadmium, zinc, cobalt, lithium, manganese, tin, aluminium, arsenic and others [1]. More than 60% of the composition consists of metals, approximately 30% is attributed to plastics and hazardous pollutants account for merely 2.80%. The country's usage of electrical and electronic devices has increased, including products like computers, mobile phones and televisions. Often, these dangerous materials are indiscriminately in residential gardens, waste disposal areas and along roadside drains [2]. The composition of e-waste is highly diverse, differing significantly across various product lines and categories. A significant number of the comp-

ounds found in e-waste remain unidentified as hazardous. A significant number of e-recyclers have been found to export hazardous materials such as leaded glass and mercury lights. To extract valuable metals such as gold, platinum and cadmium, the process involves burning circuits. Nonetheless, wire coats consist of PVC, a material that may release carbon particles or harmful smoke, potentially leading to skin and lung cancer [3]. In India, there are scrap markets where large quantities of e-waste are sorted for recycling, employing around 80,000 individuals in the recycling sector [4]. Following the incineration of the wires, the copper is extracted from them. The potential for adverse effects on both the environment and public health due to the release of harmful substances through emissions and effluents is considerable.

Preventing hazardous exposure during recycling processes and the leaking of elements such as heavy metals from landfills and incinerator ashes requires careful attention. The recycling

and disposal of e-waste can present considerable risks for workers and communities in developed countries [5]. The evolution of contemporary living, advancements in technology and the expansion of the global economy have led to a significant rise in electronic waste, which poses critical environmental and health challenges [6]. This review discusses the purpose and significance of e-waste recycling for the recovery of nanomaterials, along with potential applications for generating renewable energy. The findings and constraints of different investigations into e-waste management, along with suggestions for future research, are also discussed. The electronic waste produced following the use of different electronic devices can be classified as outlined in Table-1.

Recycling of electronic waste: The e-waste is composed of various constituents such as plastics, glass, chemicals and metals. Various elements of e-waste have been documented as being hazardous in nature. The primary approach to managing e-waste involves recycling and recovery processes aimed at minimizing the presence of hazardous compounds and components in various environmental segments [7]. Certain e-waste components act as secondary raw materials, facilitating the extraction of valuable items throughout the recycling or recovery process [8]. E-waste management focuses on recycling and recovering e-waste as these supports human health, ecology as well as economy. E-waste may be considered as resource, if it is recycled and extraction of valuable substances are performed. Dismantling is the first step in this process, which entails the extraction of parts that harbour hazardous substances [such as chlorofluorocarbons (CFCs), mercury switches and printed circuit boards (PCBs)], in addition to components that are easily reachable and consist of valuable materials. Dismantling encompasses a range of actions, including unscrewing, tearing, burning and shredding [1]. The second step involves the separation of plastic, ferrous metal and non-ferrous metal. A shredding procedure is commonly employed to achieve this separation. The third phase involves refurbishing and reusing e-waste, which holds the potential for application to any used electrical and electronic equipment that can be swiftly restored to its original function [9]. The fourth phase involves the recycling or recovery of valuable materials. Precious metals undergo separation, non-ferrous metals are subjected to smelting and ferrous metals are processed in the electrical furnaces [10]. The final stage encompasses the oversight and removal of waste and toxic materials, as mercury is often subjected to recycling processes or disposed of in underground landfill locations. The light fraction from the shredder is sometimes incinerated, while CFCs undergo thermal treatment. When appropriate technologies are utilized, the value of recovery from the elements

can be significantly enhanced. The PCB stands as a fundamental component within electronic equipment and several precious metals and toxic substances found in electronic waste are present in these printed circuit boards [11].

Three methods utilized for recycling PCB wastes include pretreatment, physical recycling and chemical recycling [12]. The physical recycling process is succeeded by the pretreatment stage, initiating with the disassembly of recyclable and harmful components through shredding or separation. The material is ultimately retrieved through a chemical recycling method that utilizes pyrolysis and gasification [13]. Various traditional and modern methods exist to extract valuable metallic and non-metallic components from electronic waste [14]. Fig. 1 illustrates the different sources of e-waste, along with their associated health effects and the metals they contain.

Synthesis of nanoparticles from E-waste: A wide range of applications have been identified for synthesized nanoparticles, with significant interest directed towards those derived from precious metals. This section explores the production techniques and applications of transition metals and metal oxides. The most common transition metals extracted are silver (Ag), gold (Au), palladium (Pd) and platinum (Pt).

Metallic oxide nanoparticles from E-waste: Ferrites are materials made of iron that are typically grey or black in colour and have a polycrystalline structure characterized by a multitude of small crystals. Ferrites are materials that exhibit a ceramic like structure and possess magnetic properties, which are essential in various types of electronic devices. Ferrite materials may incorporate with various additional transition metals [15]. Magnetic ferrite is highly valued across various industries due of its relatively low cost, mechanical stiffness, chemical stability, high electrical resistance and exceptional magnetic properties [16]. Over the last decade, the recycling and recovery of ferrite nanoparticles from e-waste has been a focus of study. Xi *et al.* [17] was among the first to recover Zn-Mn magnetic ferrite nanoparticles successfully from dry Zn-MnO₂ batteries using co-precipitation methods. The findings indicate that Zn-Mn magnetic ferrite nanoparticles can be effectively recycled at co-precipitation pHs of 7.0-7.5 and calcined at 1100-1150 °C. The zinc-manganese oxide battery wastes were utilized and the cathode material underwent leaching with HNO₃ (0.5 mol/L) and H₂O₂ (30% v/v) at 80 °C. This was followed by a reaction with FeCl₃ and the resulting coprecipitate was calcined at 450 °C, resulting in the preparation of manganese ferrite (MnFe₂O₄) [18].

Zinc oxide: ZnO has shown significant potential for application in addressing organic wastewater contamination [19]. Various recovery techniques for Zn-based materials have been

TABLE-1
DIFFERENT TYPES OF ELECTRONIC WASTE

Categories of E-waste	Examples
Automatic dispensers	Drink dispenser, money dispenser
Telecommunication equipments	Phones, laptops, scanners, Wi-Fi
Monitoring instruments	Sensors, smoke detectors, thermostats
Sports equipments	Video games, electronic cars & trains
Electronic tools	Drill machines, electric saw
House hold appliances	Microwave, washing machines & air conditioners

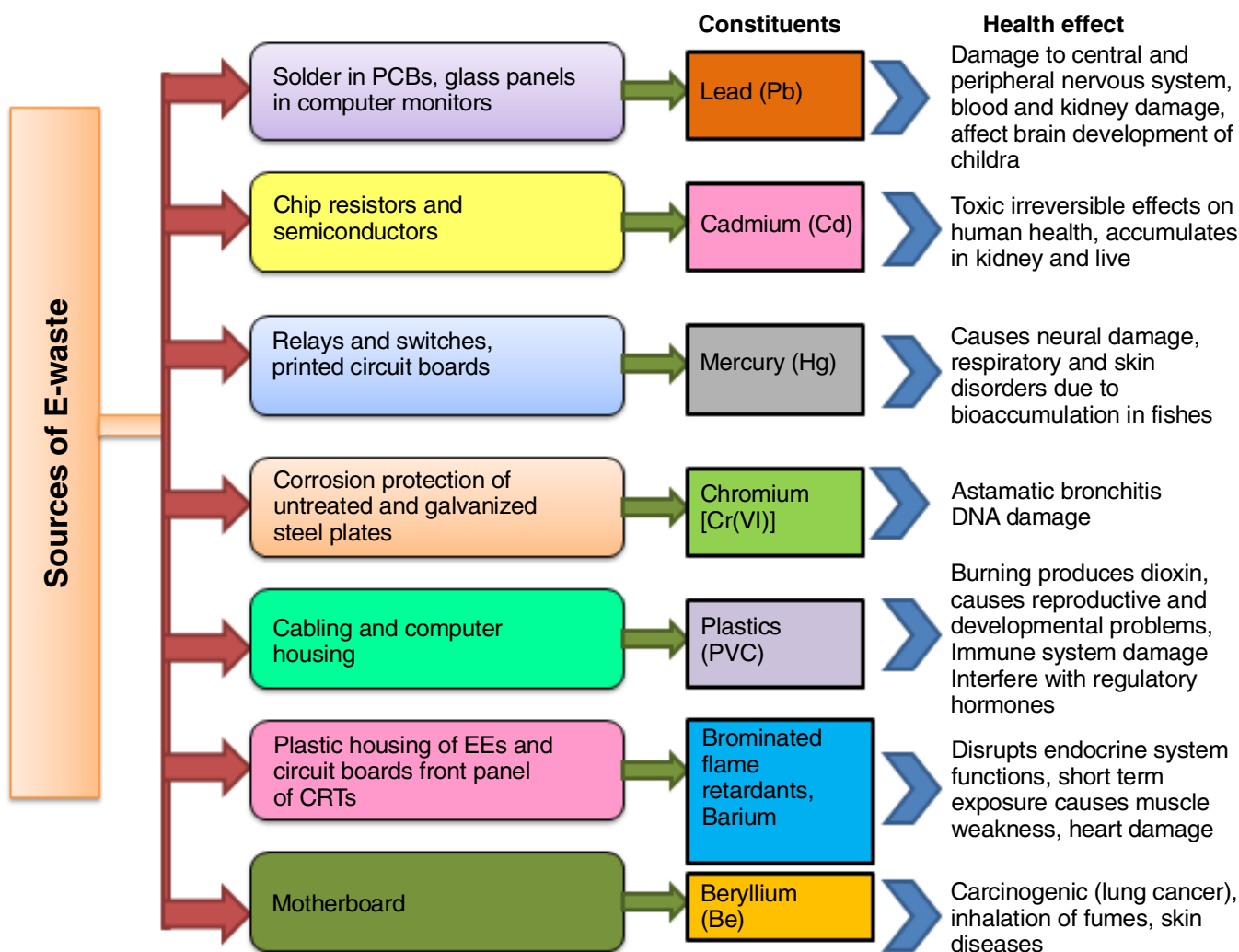


Fig. 1. Sources of e-waste and their health effects

suggested by experts globally. The techniques can primarily be classified into two main categories *viz.* hydrometallurgy and pyrometallurgy. The usage of zinc oxide for battery production in China increased from 373 Gg in 2003 to 535 Gg in 2005 [20]. Zinc underwent rapid oxidation, even with the use of supplementary materials such as charcoal or lead powder to sequester the oxygen. Nonetheless, zinc can be evaporated and subsequently recovered through zinc hull by employing blowing airflow at 723 K and a heating temperature of 1123 K, an air pressure of 3 kPa. The efficiency of zinc recovery is approximately 98.99% prior to its oxidation into nanotetrapod ZnO [21]. Utilizing air as an oxidizer and carrier gas in high-temperature evaporation-separation and oxygen control oxidation processes on spent Zn-Mn dry batteries led to the successful generation of nanoparticles [20]. Through the application of oxygen control and vacuum evaporation techniques, ZnO nanoparticles exhibiting diverse morphologies were synthesized from discarded Zn-Mn batteries [19]. The morphology of ZnO nanoparticles can be modified by adjusting several factors, including the flow rate of the nitrogen conveyor, the concentration of the oxygen oxidizer, the calcination temperature, the substrate used and the condensing distance [20].

Indium tin oxide (ITO): The world's present indium reserves are estimated to be between 12,000 and 13,000 tonnes, which is approximately one-sixth of the reserves for gold [22]. Recently, ternary or binary oxides of indium have garnered considerable technological and scientific interest due to their fascinating structural chemistry and functions [23]. Indium-based substances have been widely utilized in various processes due to their distinct electrical, physical and chemical properties, including semiconductor production, radioelectronics and spintronics [24]. As a result, considering the recent expansion in industry, it is regarded as an essential strategic asset. The development of ITO materials, comprising over 90% indium oxide and under 10% tin oxide, utilizes more than 80% of the indium extracted worldwide [25]. LCD panels and touch screens for smartphones are often constructed using indium and tin oxides [26]. Given its limited availability on this planet, indium is increasingly becoming more costly. The regulation of indium recovery from e-wastes is of immediate necessity [27]. The LCD board consists of two glass substrates coated with an indium tin oxide layer, two polarising films, a colour filter film and a liquid crystal band. Since indium tin oxide films contain a substantial amount of indium, LCD waste offers a possible

secondary source of indium [24]. Nevertheless, the presence of hazardous contaminants and components in the display, including mercury, polymers and liquid crystals, may be released during the LCD dismantling process, making the recovery of indium from LCD displays a challenging endeavor [28]. The aqueous hydrometallurgical method has garnered significant focus in studies aimed at recovering indium from discarded LCD screens. For example, Li *et al.* [27] documented the recovery of indium through a multi-step process from discarded LCD screens. This process involved the extraction of liquid crystals and LCD polarizing film, along with the recovery of indium from indium tin oxide glass through acid dissolution. The efficiency of recovering indium from discarded LCD panels can be greatly influenced by the dimensions of the indium titanium oxide particles processed through ball milling and the concentration of HCl in the solution [28]. An additional method for recovering indium from thin-film transistor LCD wastes is through solvent extraction. This process includes H₂SO₄ leaching, followed by extraction using (di(2-ethylhexyl)-phosphoric acid) (D2EHPA) and concludes with back extraction using HCl [21]. By dissolving the waste materials in H₂SO₄ solution, followed by two extraction processes using 30% D2EHPA for 5 min and acid solution concentration having 4M HCl, the recovery of indium from raw materials was found to be 97%. Indium recovery from wasted ITO waste exceeded 99% using a 30% HCl solution for 30 min at 80 °C followed by immersion in KOH solution for 10 min at 300 °C [29,30].

SnO₂ Nanoparticles: Nitric acid facilitated the synthesis of tin oxide (SnO₂) and silver nanoparticles (AgNPs) through the leaching process of PCBs. Initially, three distinct methods, for example, microwave heating, conventional heating and ultrasonic treatment, are employed to extract tin oxide from a nitric acid solution [31]. Next, the precursor undergoes heating in a furnace to produce tin oxide nanoparticles. To precipitate silver chloride, a solution of nitric acid is subsequently mixed with hydrochloric acid. Then, by employing glucose as a reducing agent, silver chloride is transformed into AgNPs in ammonia solution. The reduction reaction was conducted utilizing conventional warming, microwave scavenging and ultrasound therapy [32].

Transition metal nanoparticles

Silver nanoparticles: According to a 2018 survey, 533 tons of silver were utilized globally in the electronic industry [33]. The pins (metal foil contacts), PCBs, connectors and conductive material of electronic components contain the majority of silver, with microchips having the highest concentration. The mechanism to recover AgNPs from electronic waste is the sequence of both physical and chemical procedures. In first phase, the silver rich material is mechanically separated and after that hydrometallurgical procedure is followed to produce silver enriched solution. The recovery of silver by incineration is extremely challenging and costly owing to degradation of environment. The three primary techniques for the recovery of metals are pyrometallurgy, hydrometallurgy and biometallurgy [34]. The pyrometallurgy route involves smelting at high temperatures, but the main drawback of this route is formation of

halogenated flame retardants, dioxins and slag formation [35]. Various leaching agents are used to prepare leach liquor. Leaching, separation and purification through adsorption, solvent extraction, precipitation, ion-exchange, *etc.* are the main steps after pre-processing of waste PCBs [36]. Leaching agents include thiourea, cyanide, thiosulphate, sulfuric acid and nitric acid [37,38].

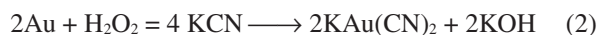
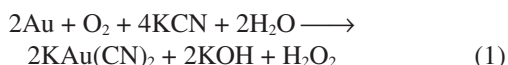
It has been observed that cyanide lixiviant is generally used in 90% of silver recovery procedures. Cyanide ions can exist in solutions in a variety of forms, including complexes, free cyanide (CN⁻), hydrogen cyanide and a few other common compounds, depending on the pH of the solution [39,40]. The utilization of non-cyanide leaching agents are examined due to toxic nature of cyanide ion [41]. The traditional and dangerous cyanide leaching of silver has been replaced with the thiourea leaching process [42]. Using thiourea lixiviant to leach silver from secondary and naturally occurring resources offers greater potential than cyanide lixivants. Thiourea breaks down readily in a basic solution and is unstable. As a result, acidic liquors should be used for the reactions. Li *et al.* [43] conducted experiments on the thiourea leaching of silver from waste PCBs using 24 g/L thiourea and 0.6% Fe³⁺ concentration at room temperature. They found that 90% of the silver was leached in just 2 h and the removal of silver in acidic thiourea solution is most effective when Fe³⁺ was used.

In a study investigated by Öncel *et al.* [44], 98.6% of silver was extracted from the solid waste in 24 min using thiourea leaching, which was conducted out in a lab setting using ultrasound power at 77 °C and a pulp density of 100 g/L. Advances in the study of non-cyanide leaching process with ammonium thiosulphate have been made in recent decades. Compared to cyanide leaching, thiosulphate leaching is less hazardous and comparatively inexpensive. Ficeriová *et al.* [45] used ammonium thiosulphate to extract silver from two different kinds of waste PCBs *viz.* pre-processed PCBs in the second instance and raw WPCBs with attached components. They found that the leaching efficiency results in the two scenarios differed by nearly 13%. After 48 h of leaching of preprocessed waste PCBs, 93% of the silver was extracted. The use of inorganic acids such as sulphuric acid and nitric acid was also used to produce silver nanoparticles through the leaching of PCBs. To obtain silver chloride, a solution of nitric acid is subsequently combined with hydrochloric acid [38]. The use of glucose as a reducing agent, silver chloride is transformed into AgNPs within an NH₃ solution. Moderate warming, microwave scavenging and ultrasound therapy were employed to conduct the reduction reaction [46]. In comparison to other reagents (such as cyanide and thiourea), ammonium thiosulphate produced the best leaching results [47]. Now, the hydrometallurgical recovery of silver from leach liquor is applied to purification and separation by techniques like cementation, solvent extraction and ion-exchange.

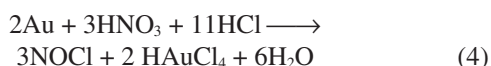
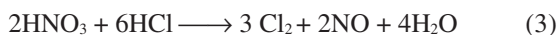
Gold nanoparticles: Gold is a valuable, fundamental and essential metal used in several technological devices. Due to its higher electrical and thermal conductivity and elevated melting point it is mainly found in printed circuit boards (PCBs), connector pins, switches, medical devices, servers, *etc.* In particular, the concentrations of gold in PCBs are nearly 100 times

greater than those in natural ore [48]. The factors that affect the leaching rates include reaction solid interface, initial concentrations, contact time and temperature [49]. After leaching, the gold needs to be separated and purified from the leaching liquors in order to be recovered with high efficiency and purity. Two major processes employed are liquid-liquid extraction and adsorption. Adsorption is a most recommended technique for separation of gold as it is simple and cost-effective. Ion-exchange resins and activated carbon have been commonly used to separate gold from e-waste leachates.

After pre-processing techniques *i.e.* separation of metallic from non-metallic parts than shedding, milling, gravity separation and electrostatic separation, the leaching of metals from PCBs is conducted [50-52]. Gold is conventionally leached using cyanide solution but due to both environmental safety and sustainability variety of alternatives are used such as thiocyanate, thiosulphate, thiourea, aqua regia and alkaline glycine solutions [53]. The cyanide leaching involves the dissolution of gold in dilute cyanide solution (usually KCN and NaCN) in the presence of oxygen [54]. The recovery of gold is found 98% at pH 10-10.5 [55]. The reaction mechanism followed is shown in eqns. 1 & 2:



Aqua regia (a mixture of HCl and HNO₃ in 3:1 ratio) dissolves gold by forming chloroauric acid (HAuCl₄) [56], where HNO₃ acts as a strong oxidizing agent to form Au³⁺ ions whereas HCl supplies excess of Cl⁻ ions for the formation of HAuCl₄ complex (eqns. 3 & 4). Gold remains unaffected by aqua regia, while other impurities are readily dissolved in this solution. The solution containing gold is filtered off and found to be upto 90% depending on the influence temperature, particle size and temperature [57]. The advantages of utilizing aqua regia include its rapid dissolution rate, ease of use, versatility, and minimal cost requirements [58,59]. However, due to its intense corrosive properties, chemical instability and high cost, it is not recommended for large-scale applications [60].



Thiosulphate leaching is an alternative method to cyanide leaching with efficiency of recovery from 80% to 100% [61]. Gold recovery can be increased under the influence thiosulphate, ammonia and copper sulphate. The ideal parameters for recovering 98% of the extracted gold are 0.12 M thiosulfate, 20 mM Cu, 0.2 M NH₃, 25 °C, 10 h of leaching time and 66 g/L pulp density [62]. The two main thiosulphate leaching agents are ammonium sulphate and sodium thiosulphate [63]. Both types are alkaline, non-corrosive, non-toxic and stable. This leaching process requires copper as oxidising agents and ammonia as co-leaching agent for the recovery of gold [60].

Halide leaching includes strong oxidizing agents such as chlorine, bromine and iodine for leaching of gold from waste PCBs [64]. The leaching kinetics is the inverse of the complex

stability ranking, which is iodine > bromine > chlorine [65]. In an aqueous solution, the gold iodide (AuI₂) complex is the most stable due to its lower redox potential than other halogens [66]. Since halide leaching has no negative effects on the environment, it is also utilized as a substitute for cyanide leaching, similar to thiosulphate leaching. Improved gold leaching upto 99.40% was achieved by employing halide as a media since it improved solubility, redox potential and leaching rates. This approach is cost-effective, recyclable, targeted, particular and considered an ideal leaching agent [60,67]. Thiourea is an organic complex agent based on sulfur that exhibits high selectivity and rapid reaction kinetics [68]. With this leaching technique, leaching rates can reach upto 99%. Similar to acidic leaching, the presence of Fe³⁺ ions that were forcing oxidation within the acidic media caused the leaching rates to increase until they decreased once more when the concentration of thiourea was increased [60,69].

Palladium nanoparticles: Palladium is a precious metal utilized in printed circuit boards (PCBs) and as an electrode material in multi-layer ceramic capacitors due to its durability and electrical conductivity [70]. It is used as an autocatalysts in chemical processes, PdNPs are used in dehalogenation and various environmental remediation processes. The price of palladium has recently surged significantly due to a constrained market, consistent supply and rising demand for its applications [71]. Over the past three years, the price of palladium has more than doubled and even surpassed that of gold in January 2019. Since then, the price of palladium has consistently reached about 45 k€/kg (1600 \$/oz). As the palladium market is expected to continue to decline, production from other secondary resources becomes essential to fulfill palladium needs [72]. It is obvious that recycling palladium from used PCBs deserves much more attention, considering that the production of electronic goods comprises between 8 to 9% of the world's palladium demand. Palladium levels in waste PCBs range from 10 to 100 mg/kg, according to the data, which is currently available [73]. After shredding the recovery of palladium is waste PCBs is done through hydrometallurgical process based on selective leaching with conc. HNO₃ and HCl at 25 °C than the solvent extraction is done with quaternary NH₄Cl in limonene than the precipitation with NaBH₄ gives 98.8 % recovery of Pd [74]. Another method to recover Pd from multi-layer ceramic capacitors is leaching with HCl and H₂O₂ followed by precipitation. Palladium is isolated as Pd(II) salt *i.e.* dichlorodiammine palladium(II) Pd(NH₃)₂Cl₂ with exceptionally high purity [75]. A summary of the different extraction methods employed for various types of electronic wastes is presented in Table-2.

Platinum nanoparticles: Platinum is another precious metal widely used to catalyze the chemical processes and for biosensing uses including cancer cell detection and drug delivery systems [94]. It has low chemical reactivity and high resistance to dissolution. It is also used in gas sensors and in fabrication of devices like organic light-emitting diodes as they have ability to interact with light [95]. In spite of so many applications the studies focussing on platinum nanoparticles are minimal when compared to the extensive research conducted on other precious metals such as palladium, silver and gold nanoparticles. As

TABLE-2
SUMMARY OF DIFFERENT EXTRACTION METHODS USED FOR VARIOUS TYPES OF ELECTRONIC WASTES

S. No.	Target material	Recyable waste	Recycling method	Recovery (%)	Ref.
1	Manganese zinc ferrites	Spent Zn-Mn batteries	Coprecipitation	–	[17]
2	Nano ZnO	Waste Zn-Mn battery	High temperature and oxygen control oxidation	–	[20]
3	Indium	Waste LCD panel	Dissolution	92.0	[27]
4	Indium	End-of-life LCD panels	Mechanical pre-treatment, leaching and cementation	96.2	[24]
5	In ₂ O ₃ , ZnO, SnS	Spent LCDs	Solvent extraction, precipitation and calcinations	>98.0	[76]
6	Indium	LCD panels	High energy ball milling	86.0	[28]
7	Indium	In ₂ O ₃ and LCD powder	Chloride volatilization process using PVC	98.7	[29]
8	SnO ₂	Printed circuit boards	Ultrasound and microwaves assistance	90.0	[31]
9	Au	Electronic waste (PCB)	Thiourea leaching	99.0	[60,69]
10	Au	Processors waste	Oxidation using ammonium persulphate	99.4	[67]
11	Pd	Waste PCBs	Leaching, SX and precipitation	99.0	[74]
12	Pd	MLCCs	Acid leaching (HCl/ H ₂ O ₂) and precipitation	90.0	[75,76]
13	Pt	Waste LIBs	SX, precipitation and calcinations	>98.5	[77]
14	Pt	Printed circuit boards	SX and precipitation	94.6	[78]
15	Ag	PCBs	Thiourea leaching	90.0	[43]
16	Ag	PCBs	Oxidation using ammonium thiosulphate	93.0	[45]
17	Co ferrites	Li ion batteries	Coprecipitation, sol-gel, hydrometallurgy	–	[79]
18	Polyaniline/graphite	Spent battery powder	–	–	[80]
19	Zn NPs	Zn-Mn batteries	Ultrasound-assisted acid	–	[81]
20	Lead iodide	Car batteries	Roasting (500-600 °C) then dissolution	–	[82]
21	Zn _x Mn _{1-x} O NPs	Zn-MnO ₂ batteries	Liquid extraction, hydrometallurgy	–	[83]
22	Zn-Mn	Mn-Zn ferrites	Hydrometallurgy	–	[84]
23	Ni-Mn-Zn	Zn-C batteries	Co-precipitation	–	[85]
24	Graphenenano composites	Zn-MnO ₂ acidic dry batteries	–	–	[86]
25	Nano-Pb	PCB	Hydrometallurgy-leaching, precipitation, liquid-liquid extraction	–	[87]
26	Purified C nanotubes	Supercapacitor	Extraction, filtration	–	[88]
27	TiO ₂	PCBs	–	–	[89]
28	Cu ₂ O NPs	PCBs	–	–	[90]
29	PbO	Lead acid batteries	Catalytic conversion, desulfurization, recrystallization	–	[91]
30	Zn, Cu	Automobile shredder	Ultrasound-assisted acid	–	[92]
31	Mn, Fe, Ni	Automobile shredder	Ultrasound-assisted acid	–	[93]

compared to pyrometallurgical method hydrometallurgical method is more exact, predictable and easily controlled [96]. The platinum rich fractions are sorted and selected for further processing. After sorting the leaching is done with the help of HCl. The leaching efficiency was above 90% with 4 M HCl, temperature 40 °C and 0.34 MPa pressure [78]. The use of cyanide or volatile organic compounds raises several environmental concerns so their use is avoided. Now the process used for separation is could be precipitation, adsorption and solvent extraction. Ionic liquids are gaining lot of attention due to certain intrinsic benefits over traditional organic solvents, these are also known as "green solvents" [97]. A range of metal ions have been examined using phosphonium ionic liquids sold under the brand name Cyphos. Cyphos IL 101 (tetradecyl (triethyl) chloride) and Cyphos IL 104 (triethyl (tetradecylphosphonium bis-2,4,4-trimethylpentyl) phosphinate) have been extensively studied for the extraction of various transition and rare earth metals, whereas research on Cyphos IL 102 has mostly concentrated on platinum group metals [77,98,99].

Future considerations: The summary of data provided indicates that the electronics sector is currently utilizing nanomaterials in numerous and diverse applications. The range of applications for diverse industrial, medical, electronic, electrical

and other commercial products is anticipated to grow through investigation and innovation, resulting in a rise in production [95]. Furthermore, it is crucial to consider stability and specialized recovery techniques in a more comprehensive manner. The importance of reusing materials that have been created or deteriorated after application cannot be overstated, particularly in light of the significant production costs associated with nanoparticles composed of high-purity metallic oxides. The large scale production of nanomaterials poses a heightened risk of environmental pollution and increases the potential for worker exposure. The final outcomes and effects of nanomaterials once released into the environment remain ambiguous and challenging to forecast. The investigation into the toxicity of various nanomaterials already raises alarm [100]. Currently, there are little information regarding the health and ecological risks associated with nanoparticles. In situations where the application of nanomaterials presents uncertain yet possibly harmful effects to the environment and human health, it is prudent to adopt the precautionary principle. Greenpeace is urging an instant ban on the release of all nanoproductions and nanomaterials in this regard. It is regarded important to undertake a cautious assessment of proposed nanoparticles in order to shift the "burden of evidence" [101]. The industry and regulators are responsible

for determining if a product satisfies health, safety and environmental standards before it is authorized for use and release under the precautionary principle [102]. It is still crucial to continue to develop the method for evaluating toxicity that anticipates potential effects on the human health and environment. Last but not least, using a green procedure may greatly increase the advantages of pilot projects, thus it should be considered.

Conclusion

Metal constitutes 40% of e-waste, followed by plastic polymers, oxides of various materials and other metals. The essential phases in recycling and recovering e-waste include collecting, washing, sorting, pre-treatment and treatment. At present, Europe is the region that collects the most of this garbage, followed by Asia, America, Oceania and Africa. Around 83% of global electronic garbage is undocumented and will be burned or dumped illegally, jeopardizing the environment and human health. To manage e-wastes, which will be a significant contributor to the circular economy, national and international organizations must work together and raise public awareness. The importance of recovering and regenerating high-value items, such as minerals, nanoparticles and other materials as well as recycling used materials is without debate. Due to cost-effectiveness restrictions, the literature in this work must still be discussed as it uses ineffective technology. Furthermore, even while recycling is advantageous for the environment, it is frequently impossible to establish economic sustainability for a sophisticated process without supporting the nation due to poor or non-existent earnings. New approaches, however, seem more promising, thus it is possible that they will make current trade models more profitable than trash. Traditional methods for transforming bulk resources into metallic oxide nanoparticles can slightly boost supply. Thus, the prospect that some of the most crucial components would establish a secondary supply chain is made possible by recycling such commodities from recycled costs. The present study indicated that most recycling technologies need extensive improvement to produce final commercial commodities.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. B. Hu and W. Hui, *J. Hazard. Mater.*, **343**, 220 (2018); <https://doi.org/10.1016/j.jhazmat.2017.09.034>
2. O. Capraz, O. Polat and A. Gungor, *Front. Environ. Sci. Eng.*, **11**, 5 (2017); <https://doi.org/10.1007/s11783-017-0992-9>
3. J. Li, M. Barwood and S. Rahimifard, *Robot. Comput. Integr. Manuf.*, **50**, 203 (2018); <https://doi.org/10.1016/j.rcim.2017.09.013>
4. S. Lakshmi, A. Raj and T. Jarin, *Asian J. Appl. Sci. d Technol.*, **1**, 33 (2017).
5. Eurostat EU, Waste Statistics-Electrical and Electronic Equipment, November 2017; http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_electrical_and_electronic_equipment; (Accessed on 3 January 2025).
6. A. Vijayvargiya and K. Sahu, *Int. J. Eng. Res. Technol.*, **4**, 32 (2016).
7. P.G. Nagajothi and T. Felixkala, *Int. J. Appl. Eng. Res.*, **10**, 133 (2015).
8. J. Ruan, Y. Guo and Q. Qiao, *Proced. Environ. Sci.*, **16**, 545 (2012); <https://doi.org/10.1016/j.proenv.2012.10.075>
9. J.V. Yken, N.J. Boxall, K.Y. Cheng, A.N. Nikoloski, N.R. Moheimani and A.H. Kaksonen, *Metals*, **11**, 1313 (2021); <https://doi.org/10.3390/met11081313>
10. R.A. Patil and S. Ramakrishna, *Environ. Sci. Pollut. Res.*, **27**, 14412 (2020); <https://doi.org/10.1007/s11356-020-07992-1>
11. M.N.O. Sadiku, S.M. Musa and S.R. Nelatury, *J. Sci. Eng. Res.*, **3**, 128 (2016).
12. S. Kumari, R. Panda, R. Prasad, R.D. Alorro and M.K. Jha, *Sustainability*, **16**, 418 (2024); <https://doi.org/10.3390/su16010418>
13. M. Kachniarz, J. Salach, R. Szweczyk and A. Bienkowski, in eds.: In: R. Szweczyk, C. Zielinski and M. Kaliczynska, Temperature Influence on the Magnetic Characteristics of Mn-Zn Ferrite Materials, In: Progress in Automation, Robotics and Measuring Techniques. Advances in Intelligent Systems and Computing, vol 352. Springer, Cham. (2015).
14. N.M. DiFilippo and M.K. Jouaneh, *IEEE Trans. Autom. Sci. Eng.*, **15**, 887 (2017); <https://doi.org/10.1109/TASE.2017.2679720>
15. C. Cao, A. Xia, S. Liu and L. Tong, *J. Mater. Sci.: Mater. Electron.*, **24**, 4901 (2013); <https://doi.org/10.1007/s10854-013-1495-5>
16. T.S. Karpova, V.G. Vasil'ev, E.V. Vladimirova and A.P. Nosov, *Inorg. Mater. Appl. Res.*, **3**, 107 (2012); <https://doi.org/10.1134/S2075113312020086>
17. G. Xi, Y. Li and Y.M. Liu, *Mater. Lett.*, **58**, 1164 (2004); <https://doi.org/10.1016/j.matlet.2003.08.029>
18. F. Tudorache and I. Petrila, *J. Electron. Mater.*, **43**, 3522 (2014); <https://doi.org/10.1007/s11664-014-3190-6>
19. J.-P. Zhou, W.-L. Fu, K.-Q. Qiu and Q.-Y. Chen, *J. Funct. Mater. Dev.*, **13**, 195 (2007).
20. L. Zhan, O. Li and Z. Xu, *J. Clean. Prod.*, **251**, 119691 (2020); <https://doi.org/10.1016/j.jclepro.2019.119691>
21. M.F. Bekheet, M.R. Schwarz, P. Kroll and A. Gurlo, *J. Solid State Chem.*, **229**, 278 (2015); <https://doi.org/10.1016/j.jssc.2015.06.007>
22. T. Boundy, M. Boyton and P. Taylor, *J. Clean. Prod.*, **154**, 436 (2017); <https://doi.org/10.1016/j.jclepro.2017.04.038>
23. L. Schlicker, M.F. Bekheet, A. Gili, A. Doran, A. Gurlo, K. Ploner, T. Schachinger and S. Penner, *J. Solid State Chem.*, **266**, 93 (2018); <https://doi.org/10.1016/j.jssc.2018.07.010>
24. V. Lahtela, S. Virolainen, A. Uwaoma, M. Kallioinen, T. Kärki and T. Sainio, *J. Clean. Prod.*, **230**, 580 (2019); <https://doi.org/10.1016/j.jclepro.2019.05.163>
25. K. Inoue, M. Nishiura, H. Kawakita, K. Owatari and H. Harada, *Chem. Eng. J.*, **34**, 282 (2008); <https://doi.org/10.1252/kakoronbunshu.34.282>
26. K. Zhang, Y. Wu, W. Wang, B. Li, Y. Zhang and T. Zuo, *Resour. Conserv. Recycl.*, **104**, 276 (2015); <https://doi.org/10.1016/j.resconrec.2015.07.015>
27. J. Li, S. Gao, H. Duan and L. Liu, *Waste Manage.*, **29**, 2033 (2009); <https://doi.org/10.1016/j.wasman.2008.12.013>
28. C.-H. Lee, M.-K. Jeong, M.F. Kilicaslan, J.-H. Lee, H.-S. Hong and S.-J. Hong, *Waste Manage.*, **33**, 730 (2013); <https://doi.org/10.1016/j.wasman.2012.10.002>
29. K.-S. Park, W. Sato, G. Grause, T. Kameda and T. Yoshioka, *Thermochim. Acta*, **493**, 105 (2009); <https://doi.org/10.1016/j.tca.2009.03.003>
30. S.J. Hsieh, C.C. Chen and W.C. Say, *Mater. Sci. Eng. B*, **158**, 82 (2009); <https://doi.org/10.1016/j.mseb.2009.01.019>
31. P. Cerchier, M. Dabalà and K. Brunelli, *JOM*, **69**, 1583 (2017); <https://doi.org/10.1007/s11837-017-2464-x>

32. P. Nowakowski, *J. Clean. Prod.*, **172**, 2695 (2018); <https://doi.org/10.1016/j.jclepro.2017.11.142>
33. C. Alexander, B. Alway, S. Litosh, J. Wiebe, W. Yao, D. Saha and S. Goenka, World Silver Survey 2019. The Silver Institute: Washinton, DC, USA (2019).
34. J. Yu, E. Williams and M. Ju, Review and Prospects of Recycling Methods for Waste Printed Circuit Boards, In: 2009 IEEE International Symposium on Sustainable Systems and Technology, IEEE, pp. 1-5 (2009); <https://doi.org/10.1109/ISSST.2009.5156727>
35. U. Jadhav and H. Hocheng, *Scient. Rep.*, **5**, 14574 (2015); <https://doi.org/10.1038/srep14574>
36. E.-Y. Kim, M.S. Kim, J.C. Lee and B.D. Pandey, *J. Hazard. Mater.*, **198**, 206 (2018); <https://doi.org/10.1016/j.jhazmat.2011.10.034>
37. S. Syed, *Waste Manage.*, **50**, 234 (2016); <https://doi.org/10.1016/j.wasman.2016.02.006>
38. M. Guilger-Casagrande and R.D. Lima, *Front. Bioeng. Biotechnol.*, **7**, 287 (2019); <https://doi.org/10.3389/fbioe.2019.00287>
39. B. Debnath, R. Chowdhury and S.K. Ghosh, *Front. Environ. Sci. Eng.*, **12**, 2 (2018); <https://doi.org/10.1007/s11783-018-1044-9>
40. Y. Lu and Z. Xu, *Resour. Conserv. Recycl.*, **113**, 28 (2016); <https://doi.org/10.1016/j.resconrec.2016.05.007>
41. R. Montero, A. Guevara and E. dela Torre, *J. Earth Sci. Eng.*, **2**, 590 (2019); <https://doi.org/10.17265/2159-581X/2012.10.004>
42. P. Balá, J. Ficeriová, V. Šepelák and R. Kammel, *Hydrometallurgy*, **43**, 367 (1996); [https://doi.org/10.1016/0304-386X\(96\)00015-1](https://doi.org/10.1016/0304-386X(96)00015-1)
43. J.Y. Li, X.-L. Xu and W.-Q. Liu, *Waste Manage.*, **32**, 1209 (2012); <https://doi.org/10.1016/j.wasman.2012.01.026>
44. M.S. Öncel, M. Ince and M. Bayramoglu, *Ultrason. Sonochem.*, **12**, 237 (2005); <https://doi.org/10.1016/j.ultsonch.2003.10.007>
45. J. Ficeriová, P. Balá and E. Gock, *Acta Montan. Slov.*, **16**, 128 (2011).
46. J.R.V. do Nascimento, K. Wohnrath and J.R. Garcia, *Orbital: Electron. J. Chem.*, **13**, 153 (2021); <https://doi.org/10.17807/orbital.v13i2.1455>
47. P.M.H. Petter, H.M. Veit and A.M. Bernardes, *Waste Manage.*, **34**, 475 (2014); <https://doi.org/10.1016/j.wasman.2013.10.032>
48. A. Rigoldi, E.F. Trogu, G.C. Marcheselli, F. Artizzu, M. Colledani, N. Picone, P. Deplano and A. Serpe, *ACS Sustain. Chem. Eng.*, **7**, 1308 (2019); <https://doi.org/10.1021/acssuschemeng.8b04983>
49. L. Zhang, X.-Y. Guo, Q.-H. Tian, D. Li, S.-P. Zhong and H. Qin, *Miner. Eng.*, **178**, 107403 (2022); <https://doi.org/10.1016/j.mineng.2022.107403>
50. J. Wu, J. Li and Z.-M. Xu, *J. Hazard. Mater.*, **154**, 161 (2008); <https://doi.org/10.1016/j.jhazmat.2007.10.018>
51. H.R. Verma, K.K. Singh and T.R. Mankhand, *J. Clean. Prod.*, **142**, 1721 (2017); <https://doi.org/10.1016/j.jclepro.2016.11.118>
52. S.B. Wath, M.N. Katariya, S.K. Singh, G.S. Kanade and A.N. Vaidya, *Chem. Eng. J.*, **280**, 391 (2015); <https://doi.org/10.1016/j.cej.2015.06.007>
53. E.A. Oraby, H. Li and J.J. Eksteen, *Waste Biomass Valor.*, **11**, 3897 (2020); <https://doi.org/10.1007/s12649-019-00780-0>
54. J. Han, S. Dai, J. Deng, S. Que and Y. Zhou, *Separations*, **11**, 228 (2024); <https://doi.org/10.3390/separations11080228>
55. R. Dorin and R. Woods, *J. Appl. Electrochem.*, **21**, 419 (1991); <https://doi.org/10.1007/BF01024578>
56. P.P. Sheng and T.H. Etsell, *Waste Manage. Res.*, **25**, 380 (2007); <https://doi.org/10.1177/0734242X0707694>
57. P. Cyganowski, K. Garbera, A. Lesniewicz, J. Wolska, P. Pohl and D. Jermakowicz-Bartkowiak, *J. Saudi Chem. Soc.*, **21**, 741 (2017); <https://doi.org/10.1016/j.jscs.2017.03.007>
58. J. Wang, Y. Lu and Z. Xu, *ACS Sustain. Chem. Eng.*, **7**, 7260 (2019); <https://doi.org/10.1021/acssuschemeng.9b00283>
59. M. Gökelma, A. Birich, S. Stopic and B. Friedrich, *J. Mater. Sci. Chem. Eng.*, **4**, 8 (2016); <https://doi.org/10.4236/msce.2016.48002>
60. A. Ashiq, J. Kulkarni and M. Vithanage, in eds.: M.N.V. Prasad and M. Vithanage, Hydrometallurgical Recovery of Metals from E-waste, In: Electronic Waste Management and Treatment Technology, Butterworth-Heinemann, Chap. 10, pp. 225-246 (2019); <https://doi.org/10.1016/B978-0-12-816190-6.00010-8>
61. B. Xu, W. Kong, Q. Li, Y. Yang, T. Jiang and X. Liu, *Metals*, **7**, 222 (2017); <https://doi.org/10.3390/met7060222>
62. V.H. Ha, J.-C. Lee, J. Jeong, H.T. Hai and M.K. Jha, *J. Hazard. Mater.*, **178**, 1115 (2010); <https://doi.org/10.1016/j.jhazmat.2010.01.099>
63. X. Liu, Tao Jiang, B. Xu, Y. Zhang, Q. Li, Y. Yang and Y. He, *Miner. Eng.*, **151**, 106336 (2020); <https://doi.org/10.1016/j.mineng.2020.106336>
64. Z.W. Liu, X.Y. Guo, Q.H. Tian and L. Zhang, *J. Hazard. Mater.*, **440**, 129778 (2022); <https://doi.org/10.1016/j.jhazmat.2022.129778>
65. Q. Meng, X. Yan and G. Li, *J. Clean. Prod.*, **323**, 129115 (2021); <https://doi.org/10.1016/j.jclepro.2021.129115>
66. Y.J. Zhang, R. Huang, X.F. Zhu, L.Z. Wang and C.X. Wu, *Chin. Sci. Bull.*, **57**, 238 (2012); <https://doi.org/10.1007/s11434-011-4747-x>
67. A. Alzate, M.E. López and C. Serna, *Waste Manage.*, **57**, 113 (2016); <https://doi.org/10.1016/j.wasman.2016.01.043>
68. X.Y. Guo, L. Zhang, Q.H. Tian and H. Qin, *Hydrometallurgy*, **194**, 105330 (2020); <https://doi.org/10.1016/j.hydromet.2020.105330>
69. R. Torres and G.T. Lapidus, *J. Hazard. Mater.*, **57**, 131 (2016); <https://doi.org/10.1016/j.wasman.2016.03.010>
70. A. Isildar, E.R. Rene, E.D. van Hullebusch and P.N. Lens, *Resour. Conserv. Recycl.*, **135**, 296 (2018); <https://doi.org/10.1016/j.resconrec.2017.07.031>
71. A. Cowley, Johnson Matthey Pgm Market Report, February 2019.
72. H.I. Sverdrup and K.V. Ragnarsdottir, *Resour. Conserv. Recycl.*, **114**, 130 (2016); <https://doi.org/10.1016/j.resconrec.2016.07.011>
73. E.Y. Yazici and H. Deveci, *Hydrometallurgy*, **139**, 30 (2013); <https://doi.org/10.1016/j.hydromet.2013.06.018>
74. D. Fontana, M. Pietrantonio, S. Pucciarmati, G.N. Torelli, C. Bonomi and F. Masi, *J. Mater. Cycles Waste Manag.*, **20**, 1199 (2018); <https://doi.org/10.1007/s10163-017-0684-3>
75. G. Prabaharan, S.P. Barik and B. Kumar, *Waste Manage.*, **52**, 302 (2016); <https://doi.org/10.1016/j.wasman.2016.04.010>
76. S. Dhiman and B. Gupta, *Sep. Purif. Technol.*, **237**, 116407 (2020); <https://doi.org/10.1016/j.seppur.2019.116407>
77. S. Dhiman and B. Gupta, *J. Clean. Prod.*, **225**, 820 (2019); <https://doi.org/10.1016/j.jclepro.2019.04.004>
78. G. Martinez-Ballesteros, J.L. Valenzuela-García, A. Gómez-Alvarez, M.A. Encinas-Romero, F.A. Mejía-Zamudio, A.J. Rosas-Durazo and R. Valenzuela-Frisby, *Recycling*, **6**, 67 (2021); <https://doi.org/10.3390/recycling6040067>
79. A. Deep, K. Kumar, P. Kumar, P. Kumar, A.L. Sharma, B. Gupta and L.M. Bharadwaj, *Environ. Sci. Technol.*, **45**, 10551 (2011); <https://doi.org/10.1021/es201744t>
80. X. Duan, J. Deng, X. Wang, J. Guo and P. Liu, *J. Hazard. Mater.*, **312**, 319 (2016); <https://doi.org/10.1016/j.jhazmat.2016.03.009>
81. X. Xiang, F. Xia, L. Zhan and B. Xie, *Sep. Purif. Technol.*, **142**, 227 (2015); <https://doi.org/10.1016/j.seppur.2015.01.014>
82. A.M. Belcher, P.-Y. Chen, P.T. Hammond-Cunningham and J. Qi, Recycling Car Batteries for Perovskite Solar Cells, US Patent US9590278B2 (2015).
83. J. Qu, Y. Feng, Q. Zhang, Q. Cong, C. Luo and X. Yuan, *J. Alloy Compd.*, **622**, 703 (2015); <https://doi.org/10.1016/j.jallcom.2014.10.166>
84. A. Deep, A.L. Sharma, G.C. Mohanta, P. Kumar and K.-H. Kim, *Waste Manage.*, **51**, 190 (2016); <https://doi.org/10.1016/j.wasman.2016.01.033>

85. M.A. Gabal, E.A. Al-Harthy, Y.M. Al Angari, M. Abdel Salam and A.M. Asiri, *J. Magn. Magn. Mater.*, **407**, 175 (2016); <https://doi.org/10.1016/j.jmmm.2016.01.061>
86. J. Deng, X. Wang, X. Duan and P. Liu, *ACS Sustain. Chem. Eng.*, **3**, 1330 (2015); <https://doi.org/10.1021/acssuschemeng.5b00305>
87. L. Zhan, X. Xiang, B. Xie and J. Sun, *Chem. Eng. J.*, **303**, 261 (2016); <https://doi.org/10.1016/j.cej.2016.06.002>
88. E.C. Vermisoglou, M. Giannouri, N. Todorova, T. Giannakopoulou, C. Lekakou and C. Trapalis, *Waste Manage. Res.*, **34**, 337 (2016); <https://doi.org/10.1177/0734242X15625373>
89. J.A. Bennett, K. Wilson and A.F. Lee, *J. Mater. Chem. A*, **4**, 3617 (2016); <https://doi.org/10.1039/C5TA09613H>
90. P. Gautam, A.K. De, I. Sinha, C.K. Behera and K.K. Singh, *Environ. Res.*, **229**, 115951 (2023); <https://doi.org/10.1016/j.envres.2023.115951>
91. K. Shah, K. Gupta and B. Sengupta, *J. Environ. Chem. Eng.*, **6**, 2874 (2018); <https://doi.org/10.1016/j.jece.2018.04.044>
92. J. Pan, X. Zhang, Y. Sun, S. Song, W. Li and P. Wan, *Ind. Eng. Chem. Res.*, **55**, 2059 (2016); <https://doi.org/10.1021/acs.iecr.5b04221>
93. R.R. Søndergaard, Y.-S. Zimmermann, N. Espinosa, M. Lenz and F. Krebs, *Energy Environ. Sci.*, **9**, 857 (2016); <https://doi.org/10.1039/C6EE00021E>
94. J.A. Bennett, G.A. Attard, K. Deplanche, M. Casadesus, S.E. Huxter, L.E. Macaskie and J. Wood, *ACS Catal.*, **2**, 504 (2012); <https://doi.org/10.1021/cs200572z>
95. E. Ahmed, S. Kalathil, L. Shi, O. Alharbi and P. Wang, *J. Saudi Chem. Soc.*, **22**, 919 (2018); <https://doi.org/10.1016/j.jscs.2018.02.002>
96. D. Andrews, A. Raychaudhuri and C. Frias, *J. Power Sources*, **88**, 124 (2000); [https://doi.org/10.1016/S0378-7753\(99\)00520-0](https://doi.org/10.1016/S0378-7753(99)00520-0)
97. J.F. Liu, G.B. Jiang and J.A. Jönsson, *TrAC Trends Anal. Chem.*, **24**, 20 (2005); <https://doi.org/10.1016/j.trac.2004.09.005>
98. N. Papaiconomou, L. Svecova, C. Bonnaud, L. Cathelin, U. Billard and E. Chainet, *Dalton Trans.*, **44**, 20131 (2015); <https://doi.org/10.1039/C5DT03791C>
99. L. Svecova, N. Papaiconomou and I. Billard, *Dalton Trans.*, **45**, 15162 (2016); <https://doi.org/10.1039/C6DT02384C>
100. J.A. Elegbede, A. Lateef, M.A. Azeez, T.B. Asafa, T.A. Yekeen, I.C. Oladipo and E.B. Gueguim-Kana, *IET Nanobiotechnol.*, **12**, 857 (2018); <https://doi.org/10.1049/iet-nbt.2017.0299>
101. J.G. Rouse, J. Yang, A.R. Barron and N.A. Monteiro-Riviere, *Toxicol. in Vitro*, **20**, 1313 (2016); <https://doi.org/10.1016/j.tiv.2006.04.004>
102. M. Allsopp, A. Walters and D. Santillo, Nanotechnologies and Nanomaterials in Electrical and Electronic Goods: A Review of Uses and Health Concerns, Greenpeace Research Laboratories Technical Note 09/2007 (2007).