Journal of Material Cycles and Waste Management
https://doi.org/10.1007/s10163-024-01917-7

REVIEW

Discarded e-waste/printed circuit boards: a review of their recent methods of disassembly, sorting and environmental implications

Emmanuel A. Oke[1] · Herman Potgieter[1,2]

Received: 31 October 2023 / Accepted: 19 February 2024

Abstract

The improper disposal of discarded electronic and electrical equipment raises environmental and health concerns, spanning air pollution to water and soil contamination, underscoring the imperative for responsible management practises. This review explores the complex composition of discarded printed circuit boards (DPCBs), crucial components in electronic devices. Comprising substrates, electronic elements and solder, DPCBs showcase a heterogeneous structure with metal (30.0–50.0%) and non-metal (50.0–70.0%) fractions. Notably abundant in precious metals such as Au, Ag, and Pd, DPCBs offer a compelling avenue for recycling initiatives. The inclusion of heavy metals and flame retardants adds complexity, necessitating environmentally sound disposal methods. Ongoing research on smart disassembly, utilising 3D image recognition technology, underscores the importance of accurate identification and positioning of electronic components (ECs). The targeted approach of smart disassembly, centred on valuable components, highlights its significance, albeit with challenges in equipment costs and capacity limitations. In mechanical disassembly, techniques such as grinding and heat application are employed to extract ECs, with innovations addressing gas emissions and damage induced by overheating. Chemical disassembly methods, encompassing epoxy resin delamination and tin removal, present promising recovery options, whilst the integration of chemical and electrochemical processes shows potential. Efficient sorting, encompassing both manual and automated methods, is imperative post-disassembly, with smart sorting technologies augmenting accuracy in the identification and categorisation of ECs. In addition, explorations into NH_3/NH_4^+ solutions for selective metal recovery underscore challenges and stress the necessity for meticulous process optimisation in environmentally sustainable PCB recycling. Challenges and future perspectives have also been expounded.

Keywords Printed circuit boards · Metals · E-waste disassembly · E-waste sorting · Environmental effects of metals

Introduction

The continuous progression of modern lifestyles, technological advancements and global economic growth has resulted in a growing issue of electronic waste (e-waste), which poses significant concerns for the environment and public health [1, 2]. The e-waste industry is a significant sector that is expanding at an annual rate of approximately 2 million tonnes (Mt), with the potential to reach 74.7 Mt by the year 2030 [3]. The global volume of e-waste has seen a sharp increase, reaching 53.6 million tonnes in 2019, marking a 21% rise since 2015 [4]. Alarmingly, a substantial 83.0% of the total e-waste produced in 2019 remained undocumented, raising concerns that it might be openly burned or disposed of illegally, posing serious threats to human well-being and the environment [5]. In contrast, only 17% of the e-waste generated in 2019 was collected and properly recycled.

When examining e-waste generation on a continental scale, Asia led the way in 2019, accounting for 46.4% of the global total, followed by America at 24.4%, Europe at 22.4%, Africa at 5.4% and Oceania at 1.3% [6]. It is worth noting that although Asia produced the most e-waste amongst continents, it had a lower per capita waste generation at 5.6 kg per person, mainly due to its large population of 4.40 billion. In contrast, Europe (16.2 kg/inh), Oceania (16.1 kg/inh) and

✉ Emmanuel A. Oke
emmanuel.oke@wits.ac.za; okeemmanuela@gmail.com

1 School of Chemical and Metallurgical Engineering, University of the Witwatersrand Johannesburg, Private Bag X3 PO Wits 2050, Johannesburg, South Africa

2 School of Science and the Environment, Manchester Metropolitan University, Chester Street, Manchester M1 5GD, UK

the Americas (13.3 kg/inh) had higher per capita e-waste generation. Africa stood as the lowest e-waste generator, with just 2.5 kg per person [6]. Therefore, the adoption of effective waste management methods and the secure disposal of e-waste has emerged as a worldwide imperative to reduce the health risks to people and the environmental damage associated with the practise of landfilling [7, 8].

Metals, encompassing varying metal elements and alloys, metalloids and rare earth elements, collectively referred to as 'metals,' are in exceptionally high demand, playing an indispensable role in the development of modern cities and technological products [9]. Meeting the continuously growing demand for metals has become a challenging task due to the declining quality of ore sources [10, 11]. Certain metals such as rare earth elements, Li, Co, Cu, Sn Zn, Al and Fe amongst others are categorised as critical metals owing to their supply vulnerabilities and substantial economic significance [12, 13]. In the past decade, materials containing metals at the end of their useful life, often referred to as metal-bearing wastes, have gained widespread recognition as secondary resources for critical raw materials. This acknowledgement stems from the fact that the metal content in such wastes is comparable to that found in natural ores [9, 14, 15]. For instance, e-waste can contain Cu levels up to 26.0 times higher and Au content up to 50.0 times higher compared to ores and concentrates [16]. Most of the available base, precious and hazardous metals in e-waste are landfilled in the printed circuit boards (PCBs). The recycling of discarded PCBs (DPCBs) can indeed prove to be profitable serving as a means of conserving valuable resources and acquiring potentially hazardous yet valuable elements [17]. For instance, materials recovered from e-waste amounted to approximately $57 billion in 2019 [18]. Before material recovery from e-waste can be done effectively, an understanding of the disassembly and sorting of electronic components (ECs) is essential.

This review stands out in the literature by not only examining the detailed composition of DPCBs and the recovery of precious metals but also by addressing contemporary knowledge gaps. Existing review papers extensively cover mechanical, hydrometallurgical, pyrometallurgical and biometallurgical processes for metal recovery from DPCBs. However, recent literature on material composition, modern e-waste disassembly, sorting methodologies and metal recovery via ammoniacal solutions is limited [19–21]. Review papers on these processes have been published extensively [22–25]. Our review comprehensively aims to fill this void, concentrating on the latest advancements in e-waste disassembly and sorting techniques, particularly exploring the recovery of metals through ammoniacal solutions (NH_3/NH_4^+). By investigating these crucial aspects, we provide an invaluable resource for researchers and environmentalists, offering essential insights into resource recovery from DPCBs and other electronic waste components. This holistic approach distinguishes our review, positioning it as an up-to-date and informative guide in the field of electronic waste management.

PCBs and their categories

PCBs constitute a notable portion of e-waste, comprising discarded items, such as televisions, MP3 players, computers, laptops and appliances [26, 27]. They contribute around 3.0–5.0% of the total mass of e-waste [28]. PCBs play a central role in EEE by enabling both mechanical and electrical connections. These connections are established using conductive pathways, tracks, or signal traces that are etched onto a non-conductive substrate. This substrate involves layering Cu sheets to facilitate the functioning of various components [29]. The recycling of DPCBs has posed a challenge due to their intricate and convoluted structures alongside their compositions. Hence, it is vital to assess and comprehend the structural and compositional aspects of PCBs before embarking on the recycling process.

The distinct designs of PCBs in different EEE items make the recycling of DPCBs a highly intricate process. Outlining the types and arrangements of PCBs is vital for creating recycling methods that are both cost-effective and environmentally conscious. PCBs can be sorted based on their physical attributes, chemical compositions and intended applications. The fundamental composition of PCBs is the Cu-clad laminate, which comprises organic substrates, such as polyimide, epoxy resin with glass fibre reinforcement, and polytetrafluoroethylene [30–32]. This laminate incorporates various metallic elements, including valuable metals, to achieve internal electrical connectivity within the board [33]. Categorised by their structure, arrangement, and board configuration, PCBs can be classified into the following categories, based on the number of layers and board forms:

(i) Single sided: They are usually applied to televisions and household appliances. In addition, they feature a conducting layer on just one side of the laminate and these designs are straightforward to produce.
(ii) Double sided: These employ conducting layers on both sides of the laminate to establish connectivity and are utilised in instrumentation, computers, and light-emitting diode lighting, amongst others.
(iii) Multi-layer: They consist of three layers of printed wiring, interconnected by metallised holes that link the various layers. This kind of PCB design is found in medical equipment and satellite systems.
(iv) Rigid: Through the use of a rigid substrate, the board is effectively safeguarded against twisting. They have

similar applications to single, double, and multi-layer PCBs earlier highlighted.

(v) Flex: They are easily bendable, foldable, and coilable. They also have the same application as single, double, and multi-layer PCBs. Furthermore, these kinds of PCBs can be used to meet specific demands, such as achieving intricate shapes.

(vi) Flex-rigid PCBs: These categories of PCBs are ideal for creating streamlined designs, which in turn reduces both the overall board size and its weight [34–36].

Most electronic devices adopt a multi-layer structure due to the advantages of reduced PCB sizes and increased chip density. Figure 1a provides the geometry of major types of

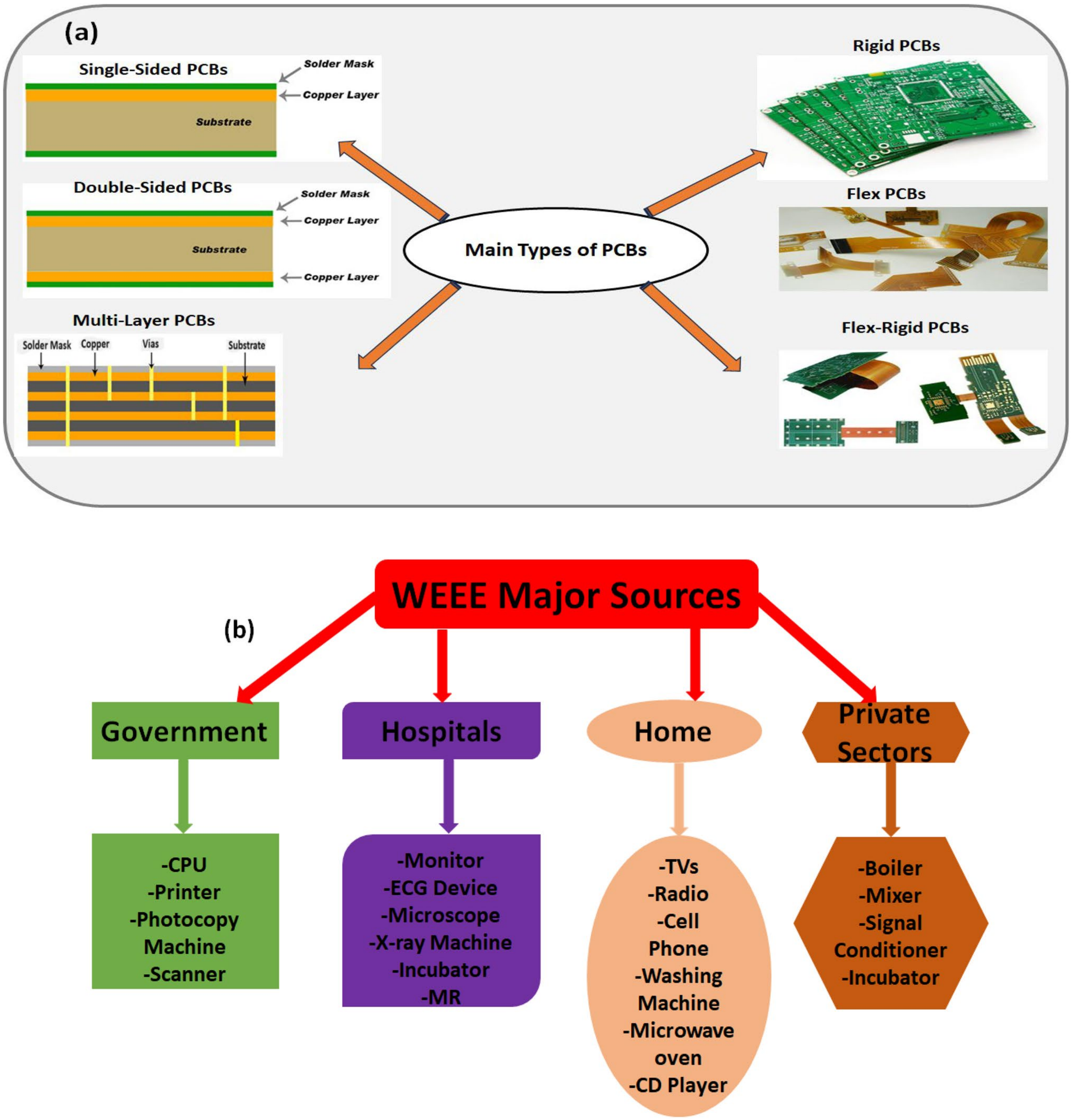

Fig. 1 **a** Geometric structure of six main types of PCBs, adapted from [37]; **b** four major sources of DPCBs

PCB [37]. These PCBs consist of six substrate fibreglass layers, two insulating fibreglass layers, conductive tracks, and solder masks. Notably, there are distinctions between PCBs in various electronic products. For instance, desktop computers incorporate two copper foil layers, whilst video devices feature only one. These variations in metal content result in diverse economic benefits at the end of the life cycle of PCBs [34, 38, 39].

Based on the content related to Ag, DPCBs can be categorised into three grades: (a) low (< 100.0 g/t), (b) medium (100.0–400.0 g/t) and (c) high (> 400.0 g/t) grades [29]. The recycling focuses primarily centres on high- and medium-grade DPCBs due to their substantial Au, Ag and Pd content, which constitute about 90.0% of their inherent value. A more detailed classification approach was introduced by Oguchi et al. by considering different metal contents and annual quantities to label DPCBs as high, medium or low grade [40]. For instance, metals such as Al and Cu from items such as refrigerators, washing machines and air conditioners fall under the high-grade category. Conversely, items such as personal computers, mobile phones and video games are considered high grade due to their Au and Ag content. The wider spectrum of DEEE originates from various sources, including household appliances, medical equipment in hospitals, office machines in government and private sector offices [35]. This is highlighted in Fig. 1b, and it aims to provide a clear means of sorting these materials.

Material constituents of DPCBs

PCBs play an essential role as fundamental components in a diverse range of electronic and electrical devices, as previously mentioned. These boards are primarily composed of substrates, ECs and solder. The substrate, a critical element, is predominantly fabricated by bonding polymer (resin), glass fibre cloth and metal Cu foil together [41]. A combination of multiple metals (constituting approximately 30.0–50.0% by weight of DPCBs) and non-metals (comprising around 50.0–70.0% by weight of DPCBs) is integrated within the structure of the PCBs [32]. This is needed to establish effective connections amongst the distinct components within electronic devices. Within the domain of e-waste, the metallic makeup of PCBs displays variability influenced by factors such as the specific categorisation of discarded materials, the origin of the materials and the manufacturing timeframe of the PCBs. DPCBs inherently harbour significant quantities of precious metals, rendering them an exceptionally enticing segment within the electronic waste domain, and consequently establishing them as a particularly alluring stream for recycling initiatives [23, 33].

Typically, PCBs are composed of 30.0–35.0% by weight of metals, 24.0–30.0% by weight of resins and 32.0–35.0% by weight of refractories [23, 42]. Around 69 distinct metals can be found in e-waste, with most of these metals being extractable from PCBs, waste from subscriber identification modules, and discarded memory modules [43]. On average, the metallic components present in DPCB primarily comprise the following ranges: 11.0–28.0 wt% Cu, 8.0–36.0 wt% Fe, 3.0–20.0 wt% Al, 2.0–5.0 wt% Pb, 1.0–4.0 wt% Ni, 200.0–2800.0 ppm Ag, 150.0–2000.0 ppm Au, and 30.0–350.0 ppm Pd, based on the type of electronic device involved [34, 44, 45]. Metal contents in DPCBs are much higher than those in ore, indicating its economic potential for the recovery of precious metals such as Au, Ag and Pd, and base metals, such as Cu, Fe, Al, etc. [46]. DPCBs encompasses also hazardous heavy metals, notably Pb, As, Hg, Cd, Se and Cr. Amongst these, certain heavy metals such as Cd, Pb and Hg exhibit non-biodegradable properties, resulting in their tendency to readily bioaccumulate within biological entities [47]. The composition of various metals and other substances in DPCB as reported in the literature by various authors is presented in Table 1. Fluctuations in metal concentration and type are determined by their specific applications; for instance, devices such as cell phones demand superior connectivity, leading to higher levels of precious metals within them. The heterogeneous nature of DPCBs and the method of detection also contribute significantly to the variation in the results obtained by different authors. Cu is predominantly found in its elemental state within the wiring and connections and because it is very soft, and it is usually laminated/alloyed with Ni in the contacts [48, 49].

Precious metals and platinum group metals (PGMs) find regular application in components that necessitate elevated conductivity, such as central processing units (CPU), random access memory and specific contact points [32, 63]. Nevertheless, the quantities of precious metals found in DPCB have somehow diminished in recent times due to resource scarcity and advancements in technology [23]. Pb, Zn and Sn are employed in the creation of solder, whilst Ag and Au are added for specific electrical connections and sensitive membrane switches [64, 65]. In addition, the primary presence of Au is within memory chips, as discussed previously by some researchers [66]. Furthermore, Ta capacitors usually contain a significant amount of the scare metal Ta, constituting about 30.0–40.0 wt% of the component [67]. It is worth noting that approximately 34.0% of the worldwide Ta production was utilised in Ta capacitors in 2016. This situation underscores the significance of discarded Ta capacitors as a noteworthy reservoir of Ta. Recovering tantalum from these waste tantalum capacitors becomes a crucial avenue to address the depletion of tantalum resources [68, 69]. In multi-layer ceramic capacitors, there is a distinct concentration of Pd as noted by researchers [70]. In the context of DPCBs, the majority of Al, along with some Fe, originate from capacitors [64, 71]. Cu is the foremost economically crucial base metal for extraction across all types

Table 1 Composition of different kinds of DPCBs

Nature of DPCB	Composition (wt%)											References
	Cu	Al	Zn	Fe	Sn	Ni	Pb	Ag	Au	Pd	Ca	
Desktop computers	14.47	1.03	0.10	0.11	0.97	0.03	0.07	0.01	–	–	4.49	[50]
Desktop computers	17.84	9.55	0.23	0.20	1.19	0.06	1.00	0.01	–	–	–	[51]
Desktop computers	52.36	1.01	11.48	3.38	10.31	0.15	5.01	1.24×10^{-2}	4.4×10^{-3}	6.5×10^{-4}	–	[52]
Personal computers	19.34	–	0.11	6.89	2.16	0.26	1.01	–	–	–	–	[53]
Central processing units	30.51	9.44	0.27	9.44	1.80	3.61	0.83	0.13	–	–	–	[45]
Digital video disc	17.80	10.10	1.99	5.51	2.57	0.36	3.33	–	–	–	0.88	[54]
Vacuum cleaner	7.08	3.26	5.54	4.40	2.75	0.26	3.71	–	–	–	0.65	[54]
Mobile phones	27.83	3.70	0.75	1.30	1.50	2.00	0.29	0.13	0.06	0.01	1.80	[55]
Mobile phones	34.38	3.00	0.05	0.39	0.02	0.61	0.42	1.50×10^{-2}	–	–	–	[56]
Mobile phones	28.66	0.38	0.15	0.39	1.50	0.80	0.39	8.18×10^{-2}	1.76×10^{-2}	6.8×10^{-3}	–	[57]
Mobile phones	47.90	–	–	0.50	2.00	0.80	–	0.13	0.10	0.01	–	[58]
Mobile Phones	32.62	1.52	1.70	1.46	2.37	2.93	1.55	0.47	0.14	0.04	–	[59]
Mobile phones	33.50	1.41	1.92	2.32	3.16	2.50	1.20	0.36	0.14	0.03	–	[60]
Printers	32.50	3.73	0.64	1.42	0.96	0.34	0.00	0.31	4.0×10^{-3}	–	1.13	[61]
Television	10.00	10.00	–	28.00		0.30	1.00	2.80×10^{-2}	2.0×10^{-3}	1.0×10^{-3}	–	[62]
Televisions	14.44	4.14	2.06	5.00	3.61	0.24	2.18	4.30×10^{-2}	–	–	–	[45]
Copy machine	21.29	5.06	0.93	4.81	2.51	0.35	1.29	0.13	–	–	–	[45]
Fax machine	21.03	6.14	1.26	6.57	3.04	0.57	1.77	0.14	–	–	–	[45]

of PCBs. The economic value ranking (recovery significance) of e-waste follows this order: CPUs >, computers PCBs with wire ≥ fax PCBs ≥ mobile phones PCBs ≥ copy machines PCBs > televisions PCBs > computers PCBs without wire [45].

The non-metallic portion of PCBs constitutes around 65.0–70.0% and is normally discarded in landfills [72]. Research findings indicate that the non-metal fraction is composed of specific elements, with glass fibres accounting for approximately 65.0% of its weight, followed by epoxy resins making up about 32.0% by weight and a few impurities of about 3.0% Cu and less than 0.1% solder [73]. These materials are integrated into the PCBs to confer both robust thermal stability to the boards and effective insulating attributes at elevated temperatures [74]. The plastic component of DPCBs contains minimal levels of halogens, which serve as flame retardants to curb combustion. This includes brominated flame retardants (BFRs) that contain polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA) [75, 76]. Elements such as Si, C, Cl, B, Br, S, P, F and I which are non-metals have also been found in DPCBs, as reported by some authors [77–79]. In addition, there are residual metals present in this fraction [80, 81].

Methods for disassembly of discarded electronic components

The initial and pivotal stage in attaining the recycling of ECs involves the ecologically and economically sound disassembly of ECs on DPCBs. Utilising an array of desoldering techniques aimed at detaching the ECs from the DPCBs, the primary objectives encompass the following:

(i) To facilitate the efficient recycling of materials such as Cu, Al, Zn, Fe, Sn, Al, Au, Ag, Pd, phenolic resin and others from DPCBs, mitigating the subsequent intricate procedures linked with diverse ECs.
(ii) The extraction of non-destructive ECs, such as obsolete chips, can subsequently be repurposed for the maintenance of products or in cases where demanding performance criteria are not applicable.
(iii) Identification and categorisation of non-reusable ECs for the extraction of valuable precious metals.
(iv) Implementation of environmentally benign treatments for ECs containing hazardous or toxic components [33, 82].

Presently, various disassembly methods, encompassing manual, smart, mechanical and chemical approaches, are employed to separate ECs from DPCBs. Manual unsoldering of ECs is prevalent within some domestic workshops, primarily aiming to recycle high-value ECs. In general, electric soldering iron and manual tin absorbers are commonly utilised for the direct removal of components. In addition, electric tin absorbers are employed for the extraction of directly inserted components, whilst hot air guns are utilised for the removal of surface-mount devices [33]. However, manual EC dismantling exhibits low disassembly efficiency. Moreover, certain risks, such as electrolytic capacitor explosions and the release of poisonous gases, could pose serious harm to the operator's well-being [83]. Manual dismantling fails to meet the prerequisites of safe production and presents difficulties in achieving large-scale application [33, 83]. In contrast, alternative disassembling processes have been comprehensively documented and put into practise within the industry. Consequently, this section predominantly introduces the principles and specific implementation procedures of smart, mechanical and chemical disassembly. The respective advantages and disadvantages of each approach are also analysed following each section.

Smart disassembly

Presently, there is an increasing focus on the utilisation of artificial intelligence in the smart disassembling of ECs. The pioneering development of smart dismantling equipment was carried out by Feldmann's group [84]. Before initiating the automated disassembling process, the ECs that are suitable for reuse and contain toxic substances require manual disassembly. Following this, for components necessitating specific disassembly methods, their positional information is obtained using 3D image recognition technology based on the vision of the machine. These components are then automatically disassembled using mechanised devices. Subsequently, for the left-over components, infrared radiation is usually employed to raise the temperature of the DPCBs. As the solder reaches its melting point, all the remaining components are detached. Finally, a visual identification system is deployed to perform automatic categorisation of these components through visual recognition. Subsequently, Kopacek et al. introduced a design blueprint for an intelligent and adaptable disassembly cell [85, 86]. They then advanced this concept by creating a semi-automated disassembly setup that encompasses a vision system, a laser desoldering system, a robot-assisted removal station, an infrared heating removal station, and a storage area for de-soldered components. They emphasised that the machine vision system's precision in identifying ECs within the setup should not fall below a 95.0% threshold. Nonetheless, their studies did not refer to the disassembly rate.

Marconi et al. introduced an innovative robotic system designed for the smart disassembly of ECs with an exceptional damage-free rate of 100.0% [87]. This system utilises wave soldering as the initial step to remove solder from DPCBs. Subsequently, a suction gripper mounted on a mobile robot arm is employed to pick up the dislodged ECs. One notable feature of this robotic system is that each component is equipped with sensors and controllers, allowing for precise regulation of the disassembly process at any given moment. Based on test results, it takes approximately 2 min and 17 s to process a DPCB, and the ECs that are disassembled can be directly reused on a new PCB without requiring additional processing steps. Recently, researchers have developed and put into operation a disassembly system focussed on capacitors, both electrolytic cylindrical capacitors and solid dielectric capacitors, positioned on DPCB [88]. This setup encompasses a versatile six-axis industrial robot, specialised sensors and custom tools. Employing this tool, the success rate achieved by the authors after the end of the separation process reached 75.0%.

In summary, ongoing investigations into smart disassembly underscore the pivotal role of 3D image recognition technology, underpinned by machine vision, in the identification and precise positioning of ECs on DPCBs. Given the diverse array of DPCBs and ECs, coupled with varying dimensions within the same component class, image recognition technology constitutes a primary and essential phase [89]. Achieving effective image recognition necessitates the acquisition of comprehensive information regarding the constituents of various ECs and PCBs—a task that entails substantial data processing. Moreover, the hallmark of smart disassembly lies in its targeted approach. Particularly, the retrieval of valuable ECs appears more suitable, considering the high costs associated with smart assembly systems, which are designed to handle one circuit board at a time [90, 91]. The strengths of smart disassembly lie in its automation and the precise extraction of specific ECs. On the flip side, its weaknesses encompass the considerable costs of equipment and its restricted capacity.

Mechanical disassembly

Disassembly of ECs at a mechanical level includes mechanical desoldering, achieved through mechanical grinding, as well as desoldering through the application of heat. The popular methods for heat-based desoldering encompass hot air heating, infrared heating and liquid heating amongst others [82]. Once the solder reaches a melting point exceeding 250.0 °C, an external force becomes necessary to disengage ECs from the main board. Typical techniques for separation involve ultrasonic vibration, mechanical scraping, pulse injection and so on [92]. In addition, the inherent forces within the ECs, such as gravity, electromagnetic force and centrifugal force, can also be harnessed to facilitate their detachment from the substrate [33, 93]. With this mechanical disassembly method, the solder can melt and be extracted at around 260.0 °C. Nevertheless, there is an unavoidable emission of harmful gases from the organic constituents of the DPCBs, including flame-retardant substances [94].

To prevent gas emissions and prevent local overheating-induced damage to ECs, Wang et al. designed a disassembly system paired with a gas purification system, depicted in Fig. 2a–e [62]. According to the authors, this device boasts three distinct characteristics. The first feature is the heating process which involves the electric heating tube working in tandem with the circulation of hot air, providing the necessary heat for the disassembly of components. This heating technique ensures uniformity in the temperature distribution, conserves energy and reduces the harm to ECs. The elevated platform which supplies the required vibrational force for the component disassembly procedure is the second great feature of this device. Last but not least is the off-gas purification mechanism which is integrated into the setup. With disassembly parameters set at 265.0 ± 5.0 °C for temperature, 10.0 rpm for rotation speed and 8 min for incubation time, the solder is effectively and completely extracted. Furthermore, this fabricated system produces no emissions of pollutants.

Chemical disassembly

Chemical disassembling has emerged as a promising approach to efficiently recover valuable components and metals from DPCBs. This part of the article delves into three key categories of chemical disassembly methods, DPCBs delamination, and tin removal technology whilst highlighting the integration of chemical and electrochemical processes for enhanced recycling.

DPCBs delamination: dissolving epoxy resin

The DPCBs delamination process focuses on dissolving the epoxy resin that encapsulates the ECs. Organic solvents

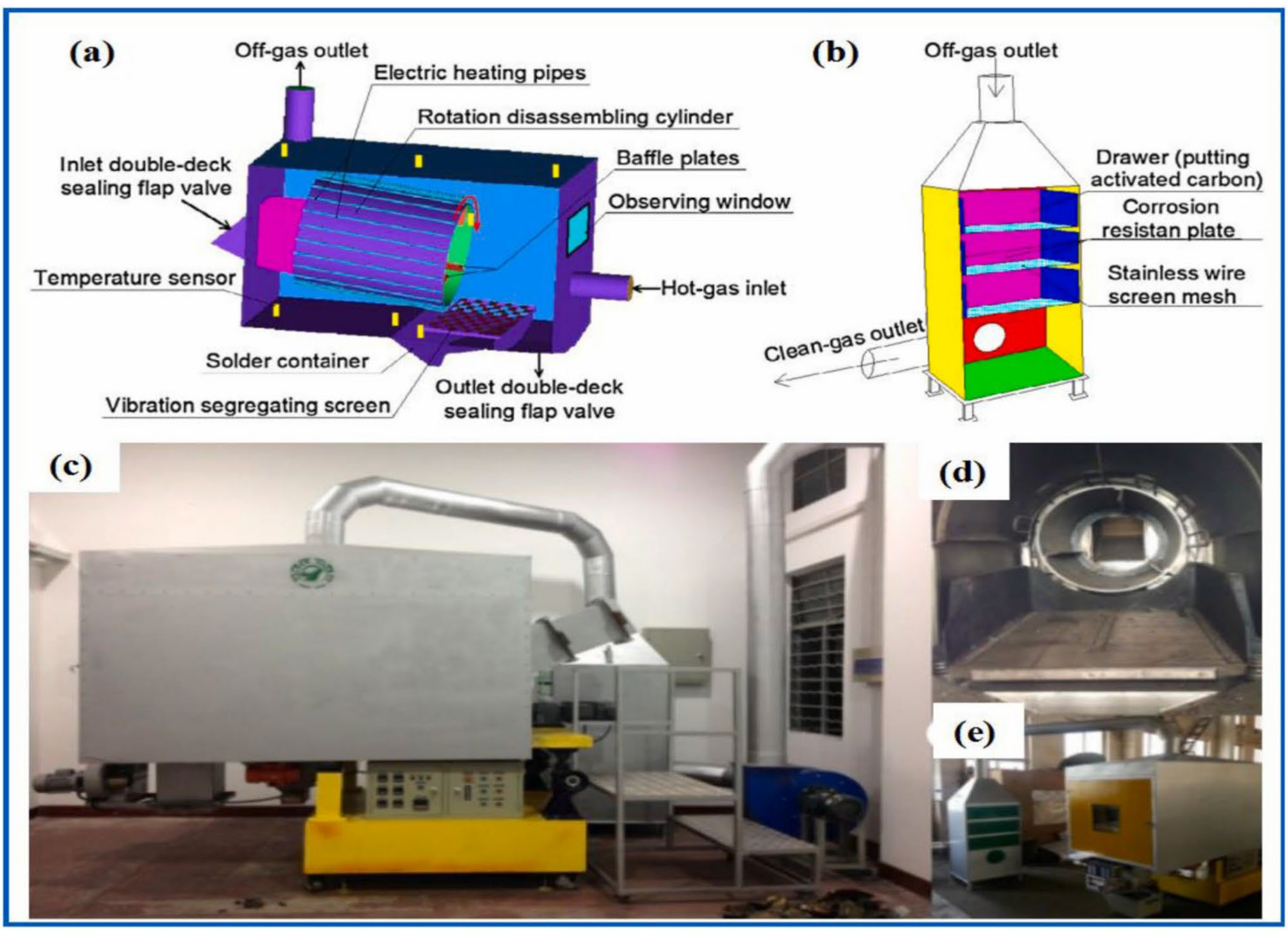

Fig. 2 Structures of **a** electronic components (ECs) automatically disassembling machine and **b** off-gas purification device; photographs of **c** ECs disassembling system, **d** internal structure and **e** feed inlet. Copyright 2023, with permission from Elsevier [62]

such as dimethyl sulfoxide, *N*, *N*-dimethylpyrrolidone, dimethylacetamide, dimethylformamide cyclohexanone, γ-butyrolactone, tetrahydrofurfuryl alcohol and dimethyl malonate are employed for this purpose [39, 95, 96]. To expedite the dissolution process, techniques such as ultrasonic treatment, at low temperature (50.0 °C), and reducing the size of DPCBs have been employed [34]. However, challenges arise due to the potential harm these solvents can pose to the environment and human health.

Chemical tin removal: recovering solder

Another critical aspect of DPCBs is the solder, usually composed of a Sn alloy. Chemical tin removal technology involves transforming the solder into an ionic state through the use of strong acids/bases, including, but not limited to, HCl, HNO_3, aqua regia, NaOH, and powerful oxidation solutions [33, 64, 97, 98]. A notable challenge in this process is the potential dissolution of other metals along with the solder. To address this, an innovative approach has been developed recently, such as utilising HBF_4 with H_2O_2 to achieve selective desoldering whilst preserving metals, such as Cu, Sn, etc. [99–101]. The introduction of the oxidant facilitated the effortless removal of ECs from the board whilst preserving their desirable external characteristics. For instance, the research group of Guan employed a combination of methanesulfonic acid (MSA) solution and H_2O_2 to effectively dissolve the solder present in DPCBs [100]. By utilising a solution consisting of 3.5 mol/L MSA with 0.5 mol/L H_2O_2, they achieved an impressive leaching rate of nearly 100.0% for Sn–Pb, whilst the total dissolution rate of Cu remained below 5.0%. This high efficiency was achieved within a reaction time of 45 min. Most recently, Soni et al. employed grey relational analysis and the Taguchi technique to identify the optimal conditions for solder treatment [102]. They found that the best results were attained by employing a solution containing 2.5 mol/L HBF_4, 0.40 mol/L H_2O_2 and 3.0% HNO_3. After a 40-min reaction period, the solder was completely dissolved, and the ECs could be easily detached. Importantly, this process did not adversely affect the colour, symbols or characters on the surface of the PCB.

Combining chemical and electrochemical processes

One compelling advancement in chemical disassembling is the integration of chemical and electrochemical processes, offering a comprehensive solution for both recovering ECs and reclaiming metals from DPCBs. Fogarasi et al. successfully implemented a leaching system constituted by 0.3 mol/L $FeCl_3$ in 0.5 mol/L HCl that not only disassembles ECs from DPCBs but also facilitates the electrowinning of Cu from Cu-rich leaching solutions [103]. This approach yielded high-purity Cu deposits (Cu > 99.9%) with high current efficiency and low energy consumption. Cocchiara et al. proposed a similar strategy involving H_2SO_4–$CuSO_4$–NaCl solutions, resulting in undamaged ECs and high-purity Cu with minor impurities [104]. Whilst chemical disassembling offers numerous advantages, including simplicity, cost-effectiveness, and versatility in handling various DPCBs, challenges persist. Proper disposal of waste liquids, the potential damage caused by strong inorganic acids to ECs, and the development of environmentally friendly and economically viable desoldering chemicals are areas that require attention. Moreover, enhancing the regeneration and recycling of reagents is essential to reduce costs and environmental impact.

Sorting of electronic components

To facilitate the reuse of ECs after the disassembly process, it is essential to classify them based on their function and nature. Hence, it is imperative to develop environmentally friendly component sorters for ECs, including DPCBs and others. E-waste treatment involves a combination of manual and automated sorting procedures, with manual methods predominantly employed in developing nations, whilst developed countries utilise automated systems [105]. In recent times, advanced technologies such as smart sorting equipment, contour vision sensors, and robotics have also been adopted for e-waste sorting. For instance, Katti et al. developed a machine vision system that can effectively sort and automatically separate ECs according to their functions [106]. The system successfully distinguishes between ECs such as integrated circuits, capacitors, relays, and rectifiers. Its cost-effectiveness is attributed to the use of a simple webcam and a basic microcontroller for identification and sorting. Recently, Naito et al. also proposed a PCB recycling system based on deep learning techniques, which performed well in the identification and categorisation of recycled components [107]. In this system, a mechanical gripper equipped with sensors utilises convolutional neural networks to process images, enabling the identification of different types of ECs and their subsequent separation. One drawback of this system is its insufficient recognition accuracy and speed, coupled with a low success rate when clamping with the robot. Notably, a recent study by Lu et al. introduced an automated sorting system specifically designed for ECs separated from DPCBs [108]. This system utilised smart sorting equipment driven by an emerging image detection algorithm, all within an inert nitrogen environment. It is essential to stress that sorting constitutes the initial and indispensable stage in metal extraction processes for e-waste treatment.

Recovery of metals from DPCBs mediated by ammonia/ammonium solutions

In the pursuit of efficiently recovering metals from DPCBs, researchers have explored various methods, with a particular emphasis on selectivity due to the presence of multiple metals and complex chemical compositions. One approach involves the use of solutions containing NH_3/NH_4^+ mixtures. NH_3 is relatively inexpensive and readily available, making it an attractive choice for leaching processes compared to other reagents. In addition, it can be selective in dissolving specific minerals or metals, which can be advantageous when extracting valuable elements from ores or waste materials [109].

In a study conducted by Liu and Kao, ammonia-based solutions were found to be effective, especially when the pH was maintained at 10.0, and a low S/L ratio was employed, resulting in the highest Cu extraction from PCB sludge rich in Cu and Pb [110]. PCB sludge typically refers to the residue or waste generated during the treatment or processing of PCBs. It may contain various substances, including metals, chemicals and other contaminants, depending on the methods used in PCB recycling or disposal processes. Oishi et al.'s investigation centred on the recovery of Cu from waste PCBs using ammonium sulphate and chlorine solutions and found that ammonium sulphate exhibited greater selectivity compared to the chloride system [111]. Furthermore, research by Yang et al. utilised an ammonia-based system with ammonium sulphate solutions, achieving a notable 96.7% Cu recovery under specific conditions [112]. This emphasised the significance of ammonia concentration, liquid-to-solid ratio and temperature control. Moreover, a remarkable 98.0% Cu recovery was accomplished using an ammonium citrate solution with ammonia, highlighting the importance of ammonia content, S/L ratio, stirring rate and controlled temperature [113]. Nevertheless, the ammoniacal leaching system's selectivity for Cu also results in the dissolution of Zn and Ni from PCB components, forming stable ammine complexes [109]. However, when electrowinning is employed for Cu extraction, impurities and organic compounds from PCB dissolution pose challenges, resulting in reduced Cu purity and increased current voltage and energy consumption [114–116]. These challenges emphasise the need for meticulous process optimisation in PCB recycling to achieve efficient and environmentally sustainable recovery. In addition, despite the benefits of utilising an ammoniacal leaching system, which includes cost-effectiveness and high selectivity, it is important to acknowledge the potential hazards associated with the decomposition and volatility of NH_3 during the leaching process, as it can pose risks to both human health and the environment.

Environmental and health effects of some toxic substances present in DPCBs

DEEE comprises a multitude of vital constituents, encompassing PBCs and assorted noxious compounds as previously described. Inadequate disposal and repurposing of DEEE can engender the liberation of various injurious substances, thereby exerting deleterious effects on atmospheric, aquatic and terrestrial domains, as well as human well-being [117, 118]. Electronic waste harbours dangerous substances and deleterious additives, which, if dispersed via unsuitable handling and disposal methodologies, can present a substantial peril to the quality of the atmosphere [119]. Furthermore, the reclamation activities related to e-waste encompass conveyance, disassembly of materials, incineration, and, notably, the metallurgical extraction of constituents such as Au and Cu from DEEE. These operations are predominantly practised in economies with modest means, often within informal frameworks, giving rise to air pollution primarily due to the incineration and metallurgical processing of e-waste, thereby discharging aerial contaminants into the atmosphere [120]. The disassembly of e-waste also serves as a source of volatile organic compounds [121]. Prior investigations have unveiled that a diverse array of hazardous airborne pollutants can be discharged during the incineration of e-waste, giving rise to polyhalogenated aromatic hydrocarbons, dioxins, polycyclic aromatic hydrocarbons, furans and substantial quantities of particulate matter.

Numerous DEEE gadgets contain hazardous metals that possess the capacity to contaminate water sources if subjected to improper disposal practises. Hg represents a significant constituent within e-waste, manifesting in all three states, and has the potential to contaminate water bodies, particularly when existing in its liquid phase, and can persist for extensive periods [122]. Outcomes of a preceding investigation elucidated that unregulated recycling of e-waste exerted adverse effects on aquatic life, seafood, rice and crops, accumulating heavy metals, as well as affecting livestock with enduring airborne pollutants [123]. Furthermore, e-waste is predominantly discarded and exported from developed nations to developing nations in Asia, Africa, the Middle East, etc. Reports have demonstrated that roughly 12.5% of such waste undergoes rudimentary recycling methods, leading to the release of toxic substances into the ecosystem [119]. Beyond persistent organic pollutants, a multitude of heavy metals pervade the groundwater and rivers of developing countries and render their water unsuitable for consumption and culinary use [124]. Furthermore, DPCBs cannot only contaminate water but also produce significant volumes of wastewater during the process of gathering Cu particles [125].

The impact of e-waste also extends to soil and its biological constituents. The accumulation of electronic waste in elevated terrains and disposal sites, notably in nations including various African countries (Egypt, Nigeria, South Africa, Ghana etc.), and Asian countries (India, China, and Pakistan) have had repercussions on the microbial population existing within contaminated locations. Modifications in the microbial community hold the potential to considerably influence soil's ecological functions. To illustrate, e-waste encompasses heavy metals such as Hg, Pb, Cd, Ni, As, Cr, and persistent organic pollutants, engendering the diminution of the conventional microbial biota within the soil [126]. An instance pertains to a study conducted in a southeastern Chinese region engaged in e-waste dismantlement, which revealed profound Cd and Cu contamination of the soil due to unregulated e-waste dismantling activities [127]. The act of open incineration serves as another notable source for discharging harmful substances and heavy metals into soil environments [128]. Multiple nations have reported the deleterious consequences on soil ecosystems due to the disposal and recycling procedures integral to e-waste management. Recycling actions, encompassing the liquefaction of plastics, the incineration of circuitry, the recuperation of Cu from wires, and the retrieval of Au using acidic agents, can potentially culminate in significant metallic pollution [129]. Such practises may also give rise to surface soil contamination due to the presence of heavy metals within the DPCBs [130].

There are three primary routes through which individuals can come into contact with the hazardous substances present in e-waste: consumption via contaminated food, inhalation of pollutants and ingestion of soil/dust combined with potential direct skin exposure [131]. Toxic heavy metals and organic contaminants leaching from DPCBs into water, air or landfills trigger the formation of micronuclei and chromosomal anomalies, leading to genetic instability in individuals exposed to these pollutants. These effects have been well-documented in previous studies [132, 133]. Once these hazardous substances enter the human body, they distribute themselves within various tissues and organs, undergoing intricate metabolic processes that can impact a range of physiological functions. Specifically, Pb has been associated with reproductive issues, cognitive instability, cytotoxicity, ischaemia, trauma and damage to human DNA [134–136]. Moreover, preschool children residing in e-waste regions have been observed to be vulnerable to lead exposure, suffering especially from periodontitis and various other oral ailments [137]. In addition, exposure to high concentrations of Cu could result in headaches, dizziness and irritation of the eyes, nose, and mouth [47, 138]. Furthermore, Sn exposure has been linked to disorders of the central nervous system and visual impairments [139]. Ni exposure may lead to lung dysfunction, asthma, skin allergies, and carcinogenic effects [140, 141]. Exposure has been found to cause respiratory problems and could lead to a high risk of developing tumours of the lung, skin, liver, bladder, colon and kidney [142]. Moreover, the health effects associated with Hg encompass a range of outcomes, spanning from nuanced neurological changes affecting coordination and motor functions to more severe impacts, including convulsions, impaired mobility, and, in extreme cases, even mortality [143, 144].

BFRs stand as significant deleterious compounds within non-metallic powders of DPCBs. Driven by the imperative for fire resistance, these agents frequently serve as additives in resin adhesives [74]. Consequently, the resin becomes affixed to fibreglass surfaces, rendering the polymer less susceptible to combustion [145]. BFRs, or their resultant decomposition products, exhibit facile release during the disassembly, fragmentation and heating of DPCBs, thereby posing potential hazards [146, 147]. BFRs are known to emit carcinogenic and teratogenic phenolic gases during combustion, thereby significantly impacting various systems, including the liver [148]. Due to their resistance to degradation, these flame retardants can infiltrate water, soil and air, perpetuating long-term environmental contamination [149]. Notably, TBBPA, a commonly studied BFR, has been established to accumulate within the brain through transfer over the blood–brain barrier, causing neurotoxic effects, abnormal behaviours, and reduced red blood cell concentrations [150]. More information obtained from the literature on the adverse effects of harmful substances in DPCBs on humans is illustrated in Fig. 3 [47, 151, 152].

Future perspectives

Looking ahead, there are several promising areas for future exploration and development:

(i) Advanced sorting technologies: Continued research into more efficient, cost-effective and environmentally friendly sorting technologies is crucial. Innovations such as artificial intelligence and robotics hold the potential to revolutionise the sorting process.
(ii) Environmental impact mitigation: As interest in resource recovery grows, research should focus on minimising the environmental footprint of disassembly and metal recovery techniques. This includes efforts to reduce energy consumption, emissions and waste.
(iii) Policy and regulation: The development of clear, standardised and globally harmonised regulations and policies for e-waste management will be vital. Governments and international bodies must play a pivotal role in encouraging responsible disposal and recycling practises. A thoughtful approach to policy and regulation

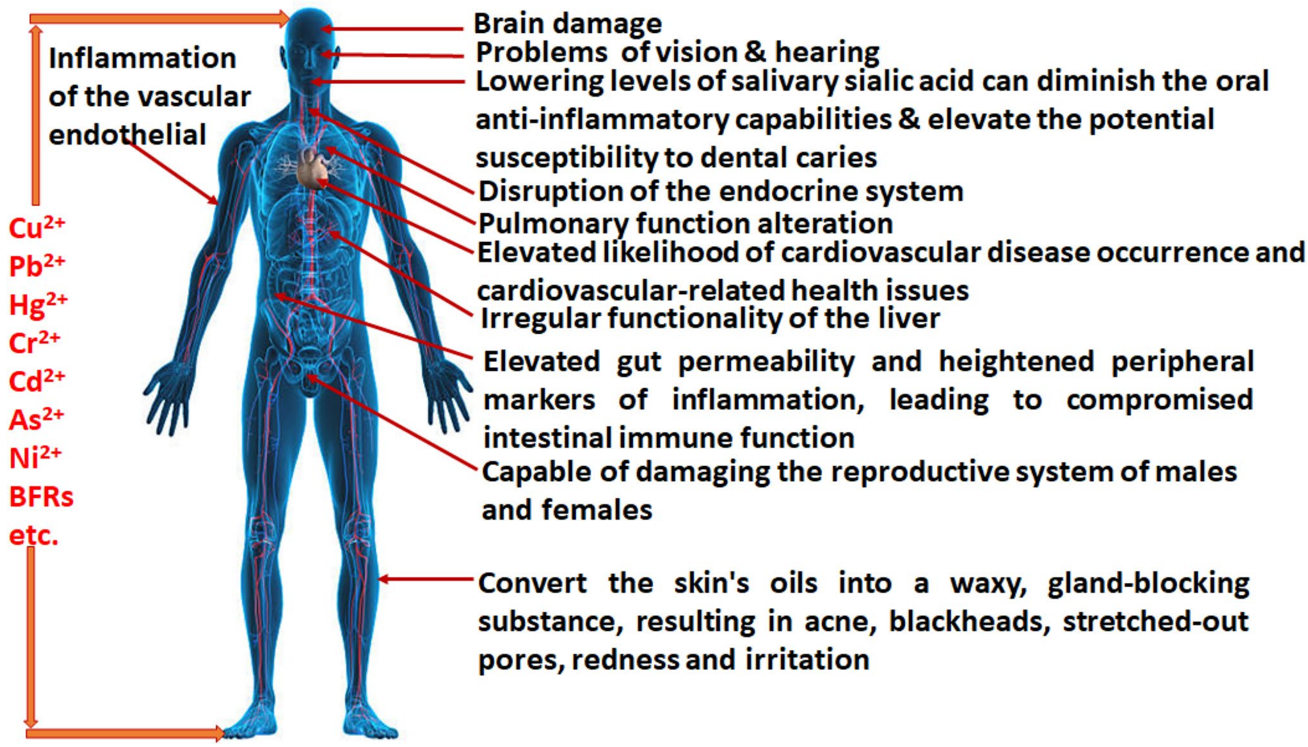

Fig. 3 Additional adverse effects of toxic metals/compounds from DPCBs on humans [47, 151, 152]

formulation should involve a deep understanding of the e-waste management, engagement with stakeholders, scientific insights, a global perspective, sustainability considerations, adaptability to change, robust enforcement mechanisms, and efforts to raise public awareness.

(iv) Circular economy models: Embracing a circular economy approach, where products are designed for recycling and reuse, can further enhance the sustainability of e-waste management.

(v) Solvent regeneration: As we look towards the future, the need for solvent regeneration becomes a pivotal aspect of sustainable metal recovery. It not only contributes to resource conservation, cost-effectiveness and environmental protection but also supports the development of more sustainable and efficient methods for extracting valuable metals from DPCBs. Future research and innovation in solvent regeneration hold the key to advancing the sustainability of metal recovery practises.

In the coming years, we anticipate a continued shift towards a more sustainable and responsible approach to e-waste management. With the advancements highlighted in this review and the dedication of researchers and environmentalists, the vision of e-waste as a valuable resource rather than a burden is on the horizon. The future holds immense potential for turning discarded PCBs and e-waste into sustainable sources of base and precious metals whilst safeguarding our environment.

Concluding remarks

Our review of DPCBs has unveiled a hidden world of possibilities within e-waste. By categorising PCBs and dissecting their material constituents, we have laid the foundation for a better understanding of this topic. We have also explored various disassembly methods, from manual to smart, mechanical and chemical techniques, highlighting their potential in resource recovery. The discussion on sorting methodologies underscores the importance of efficient separation processes. We have also illuminated on environmental and health effects of toxic substances present in DPCBs, emphasising the urgency of addressing these challenges. Furthermore, this review briefly discussed metal recovery mediated by ammonia/ammonium which could offer solutions for a sustainable future. As we look forward, future perspectives in this field hold great promise. Advanced sorting technologies, environmental impact mitigation, comprehensive policy frameworks, public awareness campaigns, circular economy models, and collaborative research efforts are set to shape the future of electronic waste management. By embracing these possibilities, we can transform the perception of discarded PCBs from waste to resource and, in doing so, pave the way for a more sustainable and responsible approach to e-waste management. Whilst the NH_3/NH_4^+ metal leaching process offers advantages such as cost-effectiveness and strong selectivity, it is crucial to recognise that the breakdown and volatility of ammonia in the leaching process can present dangers to both human well-being and the environment. Nevertheless, the future is bright for resource recovery and environmental preservation in the e-waste domain.

Furthermore, the findings of this review carry significant implications for various stakeholders within the field of electronic waste management. For policymakers and regulators, the comprehensive exploration of contemporary gaps in knowledge and the integration of smart disassembly and sorting technologies underscore the urgency of clear, standardised and globally harmonised regulations for e-waste management. Establishing such regulations becomes imperative for encouraging responsible disposal practises and ensuring the efficient recovery of valuable resources. Industry players and manufacturers can glean valuable insights from the review's emphasis on embracing a circular economy model. The recognition of the potential of DPCBs as rich sources of precious and base metals signals an opportunity for designing products with recycling and reuse in mind. This shift towards a circular economy not only aligns with sustainability goals but also enhances the viability of resource recovery practises. Researchers and environmentalists stand to benefit significantly from the detailed analysis of smart disassembly, chemical recovery methods and emerging technologies, such as NH_3/NH_4^+ solutions. The identification of knowledge gaps and the proposal of future perspectives provide a roadmap for further research initiatives. The inclusion of environmental implications also directs attention towards the development of environmentally friendly processes, addressing concerns related to emissions, energy consumption and waste in e-waste recycling. Finally, for practitioners involved in the practical aspects of e-waste disassembly, the review serves as a valuable guide. Insights into mechanical, chemical and electrochemical disassembly methods, coupled with advanced sorting technologies, offer practical considerations for the extraction and recovery of metals from DPCBs. The emphasis on meticulous process optimisation in environmentally sustainable PCB recycling reinforces the importance of balancing efficiency with environmental responsibility.

Acknowledgements Emmanuel A. Oke acknowledges the Research Office of the University of the Witwatersrand for the Centennial Postdoctoral Fellowship granted to him between 2023 and 2025.

Funding Open access funding provided by University of the Witwatersrand.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Matsakas L, Gao Q, Jansson S et al (2017) Green conversion of municipal solid wastes into fuels and chemicals. Electron J Biotechnol 26:69–83. https://doi.org/10.1016/j.ejbt.2017.01.004
2. Trihadiningrum Y, Anandita FD, Nadira A (2023) Electronic waste management in schools: a case of Surabaya City, Indonesia. J Mater Cycles Waste Manag 25:597–611. https://doi.org/10.1007/s10163-022-01540-4
3. Nithya R, Sivasankari C, Thirunavukkarasu A (2021) Electronic waste generation, regulation and metal recovery: a review. Environ Chem Lett 19:1347–1368. https://doi.org/10.1007/s10311-020-01111-9
4. Tiseo I (2023) Global e-waste—statistics & facts. In: Statista. https://www.statista.com/topics/3409/electronic-waste-worldwide/#topicOverview. Accessed 18 Oct 2023
5. Baldé CP, Forti V, Gray V, Kuehr R, Stegmann P (2017) The global E-waste monitor – 2017. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna
6. Forti V, Balde CP, Kuehr R, Bel G (2020) The global e-waste monitor 2020: quantities, flows, and the circular economy potential. Bonn, Geneva and Rotterdam
7. Shahabuddin M, Uddin MN, Chowdhury JI et al (2023) A review of the recent development, challenges, and opportunities of electronic waste (e-waste). Int J Environ Sci Technol 20:4513–4520. https://doi.org/10.1007/s13762-022-04274-w
8. Song Q, Li J (2015) A review on human health consequences of metals exposure to e-waste in China. Environ Pollut 196:450–461. https://doi.org/10.1016/j.envpol.2014.11.004
9. Lee H, Coulon F, Beriro DJ, Wagland ST (2022) Recovering metal(loids) and rare earth elements from closed landfill sites without excavation: Leachate recirculation opportunities and challenges. Chemosphere 292:133418. https://doi.org/10.1016/j.chemosphere.2021.133418
10. IEA (2021) The role of critical minerals in clean energy transitions. OECD
11. Potysz A, van Hullebusch ED, Kierczak J (2018) Perspectives regarding the use of metallurgical slags as secondary metal resources—a review of bioleaching approaches. J Environ Manage 219:138–152. https://doi.org/10.1016/j.jenvman.2018.04.083

12. Muddanna MH, Baral SS (2021) Bioleaching of rare earth elements from spent fluid catalytic cracking catalyst using *Acidothiobacillus ferrooxidans*. J Environ Chem Eng 9:104848. https://doi.org/10.1016/j.jece.2020.104848
13. Tezyapar Kara I, Kremser K, Wagland ST, Coulon F (2023) Bioleaching metal-bearing wastes and by-products for resource recovery: a review. Environ Chem Lett 21:3329–3350. https://doi.org/10.1007/s10311-023-01611-4
14. Shahbaz A (2022) A systematic review on leaching of rare earth metals from primary and secondary sources. Miner Eng 184:107632. https://doi.org/10.1016/j.mineng.2022.107632
15. Sarker SK, Haque N, Bhuiyan M et al (2022) Recovery of strategically important critical minerals from mine tailings. J Environ Chem Eng 10:107622. https://doi.org/10.1016/j.jece.2022.107622
16. 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 Manage 45:258–271. https://doi.org/10.1016/j.wasman.2015.01.017
17. Hino T, Agawa R, Moriya Y et al (2009) Techniques to separate metal from waste printed circuit boards from discarded personal computers. J Mater Cycles Waste Manag 11:42–54. https://doi.org/10.1007/s10163-008-0218-0
18. Jadhao PR, Mishra S, Singh A et al (2023) A sustainable route for the recovery of metals from waste printed circuit boards using methanesulfonic acid. J Environ Manage 335:117581. https://doi.org/10.1016/j.jenvman.2023.117581
19. Murali A, Sarswat PK, Benedict J et al (2022) Determination of metallic and polymeric contents in electronic waste materials and evaluation of their hydrometallurgical recovery potential. Int J Environ Sci Technol 19:2295–2308. https://doi.org/10.1007/s13762-021-03285-3
20. Narayanasamy M, Dhanasekaran D, Vinothini G, Thajuddin N (2018) Extraction and recovery of precious metals from electronic waste printed circuit boards by bioleaching acidophilic fungi. Int J Environ Sci Technol 15:119–132. https://doi.org/10.1007/s13762-017-1372-5
21. Anwer S, Panghal A, Majid I, Mallick S (2022) Urban mining: recovery of metals from printed circuit boards. Int J Environ Sci Technol 19:9731–9740. https://doi.org/10.1007/s13762-021-03662-y
22. Panda R, Jadhao PR, Pant KK et al (2020) Eco-friendly recovery of metals from waste mobile printed circuit boards using low temperature roasting. J Hazard Mater 395:122642. https://doi.org/10.1016/j.jhazmat.2020.122642
23. Zhu Y, Li B, Wei Y et al (2023) Recycling potential of waste printed circuit boards using pyrolysis: status quo and perspectives. Process Saf Environ Prot 173:437–451. https://doi.org/10.1016/j.psep.2023.03.018
24. Arya S, Kumar S (2020) Bioleaching: urban mining option to curb the menace of E-waste challenge. Bioengineered 11:640–660. https://doi.org/10.1080/21655979.2020.1775988
25. Ji X, Yang M, Wan A et al (2022) Bioleaching of typical electronic waste—printed circuit boards (WPCBs): a short review. Int J Environ Res Public Health 19:7508. https://doi.org/10.3390/ijerph19127508
26. Oke EA, Osibanjo O, Raheem SA et al (2021) Metals concentration levels in printed circuit boards of discarded cathode ray tube television: trends over the years. Int J Environ Anal Chem 103(18):6613–6624. https://doi.org/10.1080/03067319.2021.1958802
27. Awasthi AK, Zlamparet GI, Zeng X, Li J (2017) Evaluating waste printed circuit boards recycling: opportunities and challenges, a mini review. Waste Manag Res 35:346–356. https://doi.org/10.1177/0734242X16682607
28. Priya A, Hait S (2017) Comparative assessment of metallurgical recovery of metals from electronic waste with special emphasis on bioleaching. Environ Sci Pollut Res 24:6989–7008. https://doi.org/10.1007/s11356-016-8313-6
29. Hao J, Wang Y, Wu Y, Guo F (2020) Metal recovery from waste printed circuit boards: a review for current status and perspectives. Resour Conserv Recycl 157:104787. https://doi.org/10.1016/j.resconrec.2020.104787
30. Alwaidh A, Sharp M, French P (2014) Laser processing of rigid and flexible PCBs. Opt Lasers Eng 58:109–113. https://doi.org/10.1016/j.optlaseng.2014.02.006
31. Pietrelli L, Ferro S, Vocciante M (2019) Eco-friendly and cost-effective strategies for metals recovery from printed circuit boards. Renew Sustain Energy Rev 112:317–323. https://doi.org/10.1016/j.rser.2019.05.055
32. Faraji F, Golmohammadzadeh R, Pickles CA (2022) Potential and current practices of recycling waste printed circuit boards: a review of the recent progress in pyrometallurgy. J Environ Manage 316:115242. https://doi.org/10.1016/j.jenvman.2022.115242
33. Niu B, Shanshan E, Xu Z, Guo J (2023) How to efficient and high-value recycling of electronic components mounted on waste printed circuit boards: recent progress, challenge, and future perspectives. J Clean Prod 415:137815. https://doi.org/10.1016/j.jclepro.2023.137815
34. Yousef S, Tatariants M, Tichonovas M et al (2018) Recycling of bare waste printed circuit boards as received using an organic solvent technique at a low temperature. J Clean Prod 187:780–788. https://doi.org/10.1016/j.jclepro.2018.03.227
35. Kaya M (2016) Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manage 57:64–90. https://doi.org/10.1016/j.wasman.2016.08.004
36. Xu Y, Liu J (2015) Recent developments and perspective of the spent waste printed circuit boards. Waste Manag Res 33:392–400. https://doi.org/10.1177/0734242X15576024
37. World Electronics (2021) Types of printed circuit boards. World Electronics. https://worldsway.com/types-of-pcb-boards/. Accessed 31 Jan 2024
38. Mu MT, Cheng YJ (2018) Low-sidelobe-level short leaky-wave antenna based on single-layer PCB-based substrate-integrated image guide. IEEE Antennas Wirel Propag Lett 17:1519–1523. https://doi.org/10.1109/LAWP.2018.2851778
39. Verma HR, Singh KK, Mankhand TR (2017) Delamination mechanism study of large size waste printed circuit boards by using dimethylacetamide. Waste Manage 65:139–146. https://doi.org/10.1016/j.wasman.2017.04.013
40. Oguchi M, Murakami S, Sakanakura H et al (2011) A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Manage 31:2150–2160. https://doi.org/10.1016/j.wasman.2011.05.009
41. Ilyas S, Srivastava RR, Kim H (2021) Gold recovery from secondary waste of PCBs by electro-Cl_2 leaching in brine solution and solvo-chemical separation with tri-butyl phosphate. J Clean Prod 295:126389. https://doi.org/10.1016/j.jclepro.2021.126389
42. Kumar A, Holuszko ME, Janke T (2018) Characterization of the non-metal fraction of the processed waste printed circuit boards. Waste Manage 75:94–102. https://doi.org/10.1016/J.WASMAN.2018.02.010
43. Javed A, Singh J (2023) Process intensification for sustainable extraction of metals from e-waste: challenges and opportunities. Environ Sci Pollut Res 31(7):1–34. https://doi.org/10.1007/s11356-023-26433-3
44. Arya S, Kumar S (2020) E-waste in India at a glance: current trends, regulations, challenges and management strategies. J Clean Prod 271:122707. https://doi.org/10.1016/j.jclepro.2020.122707

45. Arshadi M, Yaghmaei S, Mousavi SM (2018) Content evaluation of different waste PCBs to enhance basic metals recycling. Resour Conserv Recycl 139:298–306. https://doi.org/10.1016/J.RESCONREC.2018.08.013
46. Lu Y, Xu Z (2016) Precious metals recovery from waste printed circuit boards: a review for current status and perspective. Resour Conserv Recycl 113:28–39. https://doi.org/10.1016/j.resconrec.2016.05.007
47. Brindhadevi K, Barceló D, Lan Chi NT, Rene ER (2023) E-waste management, treatment options and the impact of heavy metal extraction from e-waste on human health: scenario in Vietnam and other countries. Environ Res 217:114926. https://doi.org/10.1016/j.envres.2022.114926
48. Pascal Y, Abdedaim A, Labrousse D et al (2017) Using laminated metal foam as the top-side contact of a PCB-embedded power die. IEEE Electron Device Lett 38:1453–1456. https://doi.org/10.1109/LED.2017.2748223
49. Mesquita RA, Silva RAF, Majuste D (2018) Chemical mapping and analysis of electronic components from waste PCB with focus on metal recovery. Process Saf Environ Prot 120:107–117. https://doi.org/10.1016/j.psep.2018.09.002
50. Chen L, He J, Zhu L et al (2023) Efficient recovery of valuable metals from waste printed circuit boards via ultrasound-enhanced flotation. Process Saf Environ Prot 169:869–878. https://doi.org/10.1016/j.psep.2022.11.046
51. Yao Y, Zhou K, He J et al (2021) Efficient recovery of valuable metals in the disposal of waste printed circuit boards via reverse flotation. J Clean Prod 284:124805. https://doi.org/10.1016/j.jclepro.2020.124805
52. Meng L, Wang Z, Zhong Y et al (2017) Supergravity separation for recovering metals from waste printed circuit boards. Chem Eng J 326:540–550. https://doi.org/10.1016/j.cej.2017.04.143
53. Dutta D, Panda R, Kumari A et al (2018) Sustainable recycling process for metals recovery from used printed circuit boards (PCBs). Sustain Mater Technol 17:e00066. https://doi.org/10.1016/j.susmat.2018.e00066
54. Kumar V, Lee J, Jeong J et al (2015) Recycling of printed circuit boards (PCBs) to generate enriched rare metal concentrate. J Ind Eng Chem 21:805–813. https://doi.org/10.1016/j.jiec.2014.04.016
55. Gómez M, Grimes S, Qian Y et al (2023) Critical and strategic metals in mobile phones: a detailed characterisation of multigenerational waste mobile phones and the economic drivers for recovery of metal value. J Clean Prod 419:138099. https://doi.org/10.1016/J.JCLEPRO.2023.138099
56. Liang Q, Wang J, Chen S et al (2023) Electrolyte circulation: metal recovery from waste printed circuit boards of mobile phones by alkaline slurry electrolysis. J Clean Prod 409:137223. https://doi.org/10.1016/j.jclepro.2023.137223
57. Jadhao PR, Panda R, Pant KK, Nigam KDP (2023) Integrated approach for metallic fraction recovery and generation of valuable products from electronic waste. Ind Eng Chem Res. https://doi.org/10.1021/acs.iecr.3c00246
58. Park HS, Kim YJ (2019) A novel process of extracting precious metals from waste printed circuit boards: utilization of gold concentrate as a fluxing material. J Hazard Mater 365:659–664. https://doi.org/10.1016/j.jhazmat.2018.11.051
59. Kucuker MA, Kuchta K (2018) Biomining—biotechnological systems for the extraction and recovery of metals from secondary sources. Global NEST J 20:737–742. https://doi.org/10.30955/gnj.002692
60. Sahan M, Kucuker MA, Demirel B et al (2019) Determination of metal content of waste mobile phones and estimation of their recovery potential in Turkey. Int J Environ Res Public Health 16(5):887. https://doi.org/10.3390/ijerph16050887
61. Silvas FPC, Jiménez Correa MM, Caldas MPK et al (2015) Printed circuit board recycling: physical processing and copper extraction by selective leaching. Waste Manage 46:503–510. https://doi.org/10.1016/j.wasman.2015.08.030
62. Wang J, Guo J, Xu Z (2016) An environmentally friendly technology of disassembling electronic components from waste printed circuit boards. Waste Manage 53:218–224. https://doi.org/10.1016/j.wasman.2016.03.036
63. Wang J, Faraji F, Ramsay J, Ghahreman A (2021) A review of biocyanidation as a sustainable route for gold recovery from primary and secondary low-grade resources. J Clean Prod 296:126457. https://doi.org/10.1016/J.JCLEPRO.2021.126457
64. Pinho S, Ferreira M, Almeida MF (2018) A wet dismantling process for the recycling of computer printed circuit boards. Resour Conserv Recycl 132:71–76. https://doi.org/10.1016/j.resconrec.2018.01.022
65. Rigoldi A, Trogu EF, Marcheselli GC et al (2019) Advances in recovering noble metals from waste printed circuit boards (WPCBs). ACS Sustain Chem Eng 7:1308–1317. https://doi.org/10.1021/acssuschemeng.8b04983
66. Lu Y, Xu Z (2017) Recycling non-leaching gold from gold-plated memory cards: parameters optimization, experimental verification, and mechanism analysis. J Clean Prod 162:1518–1526. https://doi.org/10.1016/j.jclepro.2017.06.094
67. Niu B, Chen Z, Xu Z (2017) Method for recycling tantalum from waste tantalum capacitors by chloride metallurgy. ACS Sustain Chem Eng 5:1376–1381. https://doi.org/10.1021/acssuschemeng.6b01839
68. Agrawal M, Singh R, Ranitović M et al (2021) Global market trends of tantalum and recycling methods from waste tantalum capacitors: a review. Sustain Mater Technol 29:e00323. https://doi.org/10.1016/j.susmat.2021.e00323
69. Niu B, Chen Z, Xu Z (2017) An integrated and environmental-friendly technology for recovering valuable materials from waste tantalum capacitors. J Clean Prod 166:512–518. https://doi.org/10.1016/j.jclepro.2017.08.043
70. Fontana D, Pietrantonio M, Pucciarmati S et al (2018) Palladium recovery from monolithic ceramic capacitors by leaching, solvent extraction and reduction. J Mater Cycles Waste Manag 20:1199–1206. https://doi.org/10.1007/s10163-017-0684-3
71. Ravi Shankar A, Praveen K, Polaki SR et al (2020) Failure of printed circuit boards during storage and service: leaked capacitors and white residue. J Mater Eng Perform 29:6402–6411. https://doi.org/10.1007/s11665-020-05148-3
72. Hadi P, Ning C, Ouyang W et al (2015) Toward environmentally-benign utilization of nonmetallic fraction of waste printed circuit boards as modifier and precursor. Waste Manage 35:236–246. https://doi.org/10.1016/J.WASMAN.2014.09.020
73. Yokoyama S, Iji M (1997) Recycling of printed wiring boards with mounted electronic parts. In: IEEE International Symposium on Electronics & the Environment
74. Qiu R, Lin M, Qin B et al (2021) Environmental-friendly recovery of non-metallic resources from waste printed circuit boards: a review. J Clean Prod 279:123738. https://doi.org/10.1016/j.jclepro.2020.123738
75. Kwonpongsagoon S, Jareemit S, Kanchanapiya P (2017) Environmental impacts of recycled nonmetallic fraction from waste printed circuit board. Int J Geomater 12:8–14. https://doi.org/10.21660/2017.33.2584
76. Grigorescu RM, Ghioca P, Iancu L et al (2023) Electric and electronic equipment waste: reuse in elastomeric composites. J Polym Res 30:43. https://doi.org/10.1007/s10965-022-03432-5
77. 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

78. 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
79. Liu J, Zhan L, Xu Z (2023) Debromination with bromine recovery from pyrolysis of waste printed circuit boards offers economic and environmental benefits. Environ Sci Technol 57(9):3496–3504
80. Kumar A, Holuszko ME, Janke T (2022) Assessing the applicability of gravity separation for recycling of non-metal fraction from waste printed circuit boards. Adv Sustain Syst 6:2000231. https://doi.org/10.1002/adsu.202000231
81. Duan H, Hu J, Yuan W et al (2016) Characterizing the environmental implications of the recycling of non-metallic fractions from waste printed circuit boards. J Clean Prod 137:546–554. https://doi.org/10.1016/j.jclepro.2016.07.131
82. Maurice AA, Dinh KN, Charpentier NM et al (2021) Dismantling of printed circuit boards enabling electronic components sorting and their subsequent treatment open improved elemental sustainability opportunities. Sustainability 13:10357. https://doi.org/10.3390/su131810357
83. Wu C, Awasthi AK, Qin W et al (2022) Recycling value materials from waste PCBs focus on electronic components: technologies, obstruction and prospects. J Environ Chem Eng 10:108516. https://doi.org/10.1016/j.jece.2022.108516
84. Feldmann K, Scheller H (1994) Proceedings : 1994 IEEE International Symposium on Electronics and the Environment, ISEE-1994 : May 2–4, 1994, San Francisco, California. IEEE
85. Kopacek P, Kopacek B (2006) Intelligent, flexible disassembly. Int J Adv Manuf Technol 30:554–560. https://doi.org/10.1007/s00170-005-0042-9
86. Kopacek B (2016) Intelligent disassembly of components from printed circuit boards to enable re-use and more efficient recovery of critical metals. IFAC-PapersOnLine 49:190–195. https://doi.org/10.1016/j.ifacol.2016.11.100
87. Marconi M, Palmieri G, Callegari M, Germani M (2019) Feasibility study and design of an automatic system for electronic components disassembly. J Manuf Sci Eng 141(2):021011. https://doi.org/10.1115/1.4042006
88. Cazan S, Chirita D, Stamate C et al (2020) Dismantling strategy for capacitors placed on printed circuits boards: challenges and preliminary results. IOP Conf Ser Mater Sci Eng 997:012071. https://doi.org/10.1088/1757-899X/997/1/012071
89. Hayashi N, Koyanaka S, Oki T (2022) Verification of algorithm for automatic detection of electronic devices mounted on waste printed circuit boards. J Air Waste Manage Assoc 72:420–433. https://doi.org/10.1080/10962247.2022.2044408
90. Ramon H, Peeters JR, Sterkens W et al (2020) Techno-economic potential of recycling tantalum containing capacitors by automated selective dismantling. Procedia CIRP 90:421–425. https://doi.org/10.1016/j.procir.2020.01.110
91. He C, Jin Z, Gu R, Qu H (2020) Automatic disassembly and recovery device for mobile phone circuit board CPU based on machine vision. J Phys Conf Ser 1684:012137. https://doi.org/10.1088/1742-6596/1684/1/012137
92. Lee J, Kim Y, Lee J (2012) Disassembly and physical separation of electric/electronic components layered in printed circuit boards (PCB). J Hazard Mater 241–242:387–394. https://doi.org/10.1016/j.jhazmat.2012.09.053
93. Rubin RS, de Castro MAS, Brandão D (2019) Disassembly of waste printed circuit boards using air heating and centrifugal force. Rev Eletrônica Gest Educ Tecnol Ambient 23:28. https://doi.org/10.5902/2236117036837
94. Guo J, Ji A, Wang J et al (2019) Emission characteristics and exposure assessment of particulate matter and polybrominated diphenyl ethers (PBDEs) from waste printed circuit boards de-soldering. Sci Total Environ 662:530–536. https://doi.org/10.1016/j.scitotenv.2019.01.176
95. Verma HR, Singh KK, Mankhand TR (2017) Comparative study of printed circuit board recycling by cracking of internal layers using organic solvents-dimethylformamide and dimethylacetamide. J Clean Prod 142:1721–1727. https://doi.org/10.1016/j.jclepro.2016.11.118
96. Monteiro B, Martelo LM, Sousa PMS et al (2021) Microwave-assisted organic swelling promotes fast and efficient delamination of waste printed circuit boards. Waste Manage 126:231–238. https://doi.org/10.1016/j.wasman.2021.03.012
97. Jung M, Yoo K, Alorro RD (2017) Dismantling of electric and electronic components from waste printed circuit boards by hydrochloric acid leaching with stannic ions. Mater Trans 58:1076–1080. https://doi.org/10.2320/matertrans.M2017096
98. Guo XY, Liu ZK, Huang GY (2019) Recovery of solder from waste printed circuit boards in $(CH_3)_3COOH$-NaOH system. Zhongguo Youse Jinshu Xuebao/Chin J Nonferrous Metals 29:146–152. https://doi.org/10.19476/j.ysxb.1004.0609.2019.01.17
99. Zhang X, Guan J, Guo Y et al (2015) Selective desoldering separation of tin-lead alloy for dismantling of electronic components from printed circuit boards. ACS Sustain Chem Eng 3(8):1696–1700. https://doi.org/10.1021/acssuschemeng.5b00136
100. Zhang X, Guan J, Guo Y et al (2017) Effective dismantling of waste printed circuit board assembly with methanesulfonic acid containing hydrogen peroxide. Environ Prog Sustain Energy 36(3):873–878. https://doi.org/10.1002/ep.12527
101. Ping Z, Liu X, Tao Q et al (2019) Mechanism of dissolving tin solders from waste printed circuit board assemblies by cyclic fluoboric acid composite system. Environ Eng Sci 36:903–911. https://doi.org/10.1089/ees.2018.0308
102. Soni A, Patel RM, Kumar K, Pareek K (2022) Optimization for maximum extraction of solder from waste PCBs through grey relational analysis and Taguchi technique. Miner Eng 175:107294. https://doi.org/10.1016/j.mineng.2021.107294
103. Fogarasi S, Imre-Lucaci Á, Imre-Lucaci F (2021) Dismantling of waste printed circuit boards with the simultaneous recovery of copper: experimental study and process modeling. Materials 14:5186. https://doi.org/10.3390/ma14185186
104. Cocchiara C, Dorneanu S-A, Inguanta R et al (2019) Dismantling and electrochemical copper recovery from waste printed circuit boards in H_2SO_4–$CuSO_4$–NaCl solutions. J Clean Prod 230:170–179. https://doi.org/10.1016/j.jclepro.2019.05.112
105. Chakraborty SC, Zaman MdWU, Hoque M et al (2022) Metals extraction processes from electronic waste: constraints and opportunities. Environ Sci Pollut Res 29:32651–32669. https://doi.org/10.1007/s11356-022-19322-8
106. Katti S, Kulkarni N, Shaligram A (2021) Automated sorting of used electronic components. In: AIP conference proceedings. p 050004
107. Naito K, Shirai A, Kaneko S, Capi G (2021) Recycling of printed circuit boards by robot manipulator: a deep learning approach. In: 2021 IEEE International Symposium on Robotic and Sensors Environments (ROSE). IEEE, pp 1–5
108. Lu Y, Yang B, Gao Y, Xu Z (2022) An automatic sorting system for electronic components detached from waste printed circuit boards. Waste Manage 137:1–8. https://doi.org/10.1016/j.wasman.2021.10.016
109. Pinho SC, Ferraz CA, Almeida MF (2023) Copper recovery from printed circuit boards using ammonia-ammonium sulphate

system: a sustainable approach. Waste Biomass Valorization 14:1683–1691. https://doi.org/10.1007/s12649-022-01953-0

110. Liu JC, Kao T-H (2003) Extraction of Cu and Pb from printed circuit board sludge using ammonia solutions. Water Sci Technol 47:167–172. https://doi.org/10.2166/wst.2003.0044
111. Oishi T, Koyama K, Alam S et al (2007) Recovery of high purity copper cathode from printed circuit boards using ammoniacal sulfate or chloride solutions. Hydrometallurgy 89:82–88. https://doi.org/10.1016/j.hydromet.2007.05.010
112. Yang JG, Wu YT, Li J (2012) Recovery of ultrafine copper particles from metal components of waste printed circuit boards. Hydrometallurgy 121–124:1–6. https://doi.org/10.1016/j.hydromet.2012.04.015
113. Seif El-Nasr R, Abdelbasir SM, Kamel AH, Hassan SSM (2020) Environmentally friendly synthesis of copper nanoparticles from waste printed circuit boards. Sep Purif Technol 230:115860. https://doi.org/10.1016/j.seppur.2019.115860
114. Park JE, Kim EJ, Park M-J, Lee ES (2019) Adsorption capacity of organic compounds using activated carbons in zinc electrowinning. Energies (Basel) 12:2169. https://doi.org/10.3390/en12112169
115. Ma A, Sun C, Li G et al (2016) Kinetic studies for the absorption of organic matter from purified solution of zinc by coconut shell activated carbon. Characterization of minerals, metals, and materials 2016. Springer, Cham, pp 303–310
116. Bello WF, Valenzuela MB, Bernardes AM, Cifuentes G (2019) Removal of entrained organic matter in the copper electrolyte by ozonation. REM Int Eng J 72:79–86. https://doi.org/10.1590/0370-44672018720003
117. Abdelbasir SM, Hassan SSM, Kamel AH, El-Nasr RS (2018) Status of electronic waste recycling techniques: a review. Environ Sci Pollut Res 25:16533–16547. https://doi.org/10.1007/s11356-018-2136-6
118. Lebbie TS, Moyebi OD, Asante KA et al (2021) E-waste in africa: a serious threat to the health of children. Int J Environ Res Public Health 18:8488. https://doi.org/10.3390/ijerph18168488
119. Ghulam ST, Abushammala H (2023) Challenges and opportunities in the management of electronic waste and its impact on human health and environment. Sustainability 15:1837. https://doi.org/10.3390/su15031837
120. Kwarteng L, Baiden EA, Fobil J et al (2020) Air quality impacts at an e-waste site in Ghana using flexible, moderate-cost and quality-assured measurements. Geohealth 4(8):e2020GH000247. https://doi.org/10.1029/2020GH000247
121. Chen D, Liu R, Lin Q et al (2021) Volatile organic compounds in an e-waste dismantling region: from spatial-seasonal variation to human health impact. Chemosphere 275:130022. https://doi.org/10.1016/j.chemosphere.2021.130022
122. Rajesh R, Kanakadhurga D, Prabaharan N (2022) Electronic waste: a critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environ Chall 7:100507. https://doi.org/10.1016/j.envc.2022.100507
123. Lin S, Ali MU, Zheng C et al (2022) Toxic chemicals from uncontrolled e-waste recycling: exposure, body burden, health impact. J Hazard Mater 426:127792. https://doi.org/10.1016/j.jhazmat.2021.127792
124. Li W, Achal V (2020) Environmental and health impacts due to e-waste disposal in China—a review. Sci Total Environ 737:139745. https://doi.org/10.1016/j.scitotenv.2020.139745
125. Li K, Xu Z (2019) A review of current progress of supercritical fluid technologies for e-waste treatment. J Clean Prod 227:794–809. https://doi.org/10.1016/j.jclepro.2019.04.104
126. Salam MD, Varma A (2019) A review on impact of E-waste on soil microbial community and ecosystem function. Pollution 5:761–774. https://doi.org/10.22059/poll.2019.277556.592
127. Fang J, Zhang L, Rao S et al (2022) Spatial variation of heavy metals and their ecological risk and health risks to local residents in a typical e-waste dismantling area of southeastern China. Environ Monit Assess 194:604. https://doi.org/10.1007/s10661-022-10296-1
128. Acquah AA, D'Souza C, Martin BJ et al (2021) Musculoskeletal disorder symptoms among workers at an informal electronic-waste recycling site in Agbogbloshie, Ghana. Int J Environ Res Public Health 18:2055. https://doi.org/10.3390/ijerph18042055
129. Kumar P, Fulekar MH (2019) Multivariate and statistical approaches for the evaluation of heavy metals pollution at e-waste dumping sites. SN Appl Sci 1:1506. https://doi.org/10.1007/s42452-019-1559-0
130. Preeti M, Sayali A (2021) Scientometric analysis of research on end-oflife electronic waste and electric vehicle battery waste. J Scientometric Res 10:37–46. https://doi.org/10.5530/jscires.10.1.5
131. Liu K, Tan Q, Yu J, Wang M (2023) A global perspective on e-waste recycling. Circ Econ 2:100028. https://doi.org/10.1016/j.cec.2023.100028
132. Silva JAP, Lima GG, Camilo-Cotrim CF et al (2023) Impact of e-waste toxicity on health and nature: trends, biases, and future directions. Water Air Soil Pollut 234:320. https://doi.org/10.1007/s11270-023-06328-2
133. Rimantho D, Nasution S (2016) The current status of e-waste management practices in DKI Jakarta. Int J Appl Environ Sci 11:1451–1468
134. Collin MS, Venkatraman SK, Vijayakumar N et al (2022) Bioaccumulation of lead (Pb) and its effects on human: a review. J Hazard Mater Adv 7:100094. https://doi.org/10.1016/j.hazadv.2022.100094
135. Assi MA, Hezmee MNM, Haron AW et al (2016) The detrimental effects of lead on human and animal health. Vet World J 9:660–671. https://doi.org/10.14202/vetworld.2016.660-671
136. Awasthi AK, Zeng X, Li J (2016) Environmental pollution of electronic waste recycling in India: a critical review. Environ Pollut 211:259–270. https://doi.org/10.1016/j.envpol.2015.11.027
137. Hou R, Huo X, Zhang S et al (2020) Elevated levels of lead exposure and impact on the anti-inflammatory ability of oral sialic acids among preschool children in e-waste areas. Sci Total Environ 699:134380. https://doi.org/10.1016/j.scitotenv.2019.134380
138. Oe S, Miyagawa K, Honma Y, Harada M (2016) Copper induces hepatocyte injury due to the endoplasmic reticulum stress in cultured cells and patients with Wilson disease. Exp Cell Res 347:192–200. https://doi.org/10.1016/j.yexcr.2016.08.003
139. Mahurpawar M (2015) Effects of heavy metals on human. Int J Res Granthaalayah 3:1–7. https://doi.org/10.29121/granthaalayah.v3.i9se.2015.3282
140. Aendo P, Netvichian R, Thiendedsakul P et al (2022) Carcinogenic risk of Pb, Cd, Ni, and Cr and critical ecological risk of Cd and Cu in soil and groundwater around the municipal solid waste open dump in Central Thailand. J Environ Public Health 2022:1–12. https://doi.org/10.1155/2022/3062215
141. Begum W, Rai S, Banerjee S et al (2022) A comprehensive review on the sources, essentiality and toxicological profile of nickel. RSC Adv 12:9139–9153. https://doi.org/10.1039/D2RA00378C
142. Andeobu L, Wibowo S, Grandhi S (2023) Informal e-waste recycling practices and environmental pollution in Africa: what is the way forward? Int J Hyg Environ Health 252:114192. https://doi.org/10.1016/j.ijheh.2023.114192
143. Amponsah LO, Sørensen PB, Nkansah MA et al (2023) Mercury contamination of two e-waste recycling sites in Ghana: an investigation into mercury pollution at Dagomba Line (Kumasi) and

Agbogbloshie (Accra). Environ Geochem Health 45:1723–1737. https://doi.org/10.1007/s10653-022-01295-9

144. Ottenbros IB, Boerleider RZ, Jubitana B et al (2019) Knowledge and awareness of health effects related to the use of mercury in artisanal and small-scale gold mining in Suriname. Environ Int 122:142–150. https://doi.org/10.1016/j.envint.2018.10.059
145. McGrath TJ, Ball AS, Clarke BO (2017) Critical review of soil contamination by polybrominated diphenyl ethers (PBDEs) and novel brominated flame retardants (NBFRs); concentrations, sources and congener profiles. Environ Pollut 230:741–757. https://doi.org/10.1016/j.envpol.2017.07.009
146. Guo J, Zhang R, Xu Z (2016) Polybrominated diphenyl ethers (PBDEs) emitted from heating machine for waste printed wiring boards disassembling. Procedia Environ Sci 31:849–854. https://doi.org/10.1016/j.proenv.2016.02.094
147. Guo J, Zhang R, Xu Z (2015) PBDEs emission from waste printed wiring boards during thermal process. Environ Sci Technol 49:2716–2723. https://doi.org/10.1021/es5053599
148. Liu F, Zhang Y, Zhang M et al (2020) Toxicological assessment and underlying mechanisms of tetrabromobisphenol A exposure on the soil nematode *Caenorhabditis elegans*. Chemosphere 242:125078. https://doi.org/10.1016/j.chemosphere.2019.125078
149. Harrad S, Drage DS, Sharkey M, Berresheim H (2020) Perfluoroalkyl substances and brominated flame retardants in landfill-related air, soil, and groundwater from Ireland. Sci Total Environ 705:135834. https://doi.org/10.1016/j.scitotenv.2019.135834
150. Yu Y, Yu Z, Chen H et al (2019) Tetrabromobisphenol A: disposition, kinetics and toxicity in animals and humans. Environ Pollut 253:909–917. https://doi.org/10.1016/j.envpol.2019.07.067
151. Dutta D, Rautela R, Gujjala LK, Kundu D, Sharma P, Tembhare M, Kumar S (2023) A review on recovery processes of metals from e-waste: a green perspective. Sci Total Environ 859:160391. https://doi.org/10.1016/j.scitotenv.2022.160391
152. Manikkampatti PM, Myneni VR, Gudeta B, Komarabathina S (2022) Toxic metal recovery from waste printed circuit boards: a review of advanced approaches for sustainable treatment methodology. Adv Mater Sci Eng 2022:6550089. https://doi.org/10.1155/2022/6550089