



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

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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 $\text{NH}_3/\text{NH}_4^+$ 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

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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 land-filled 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 ($\text{NH}_3/\text{NH}_4^+$). 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 coil-able. 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

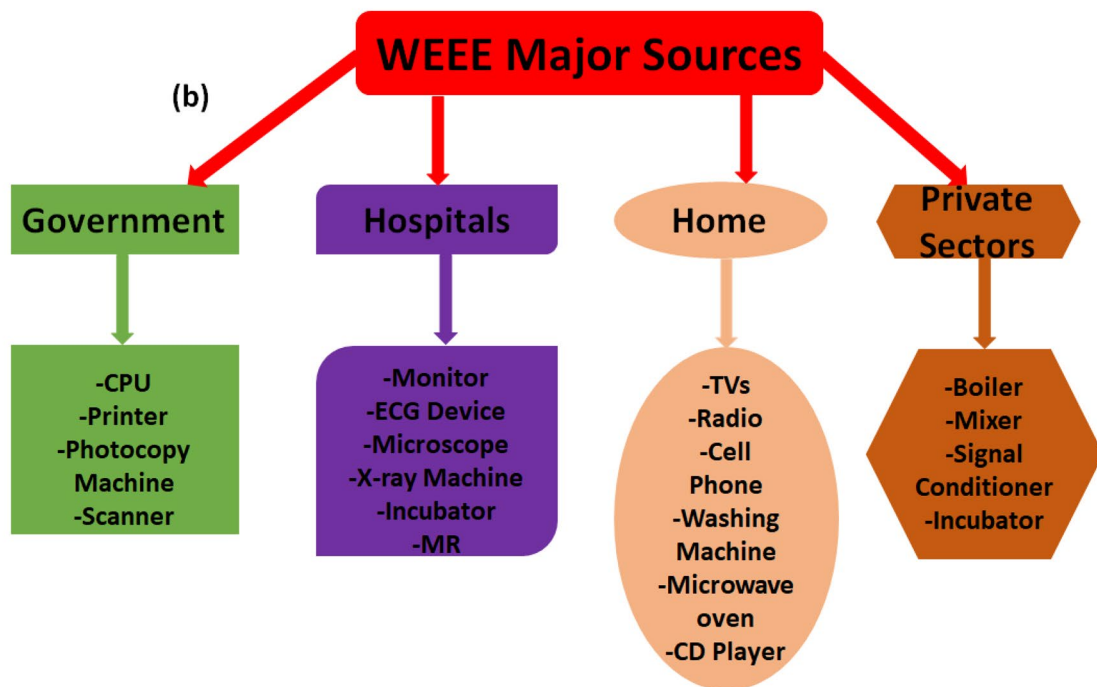
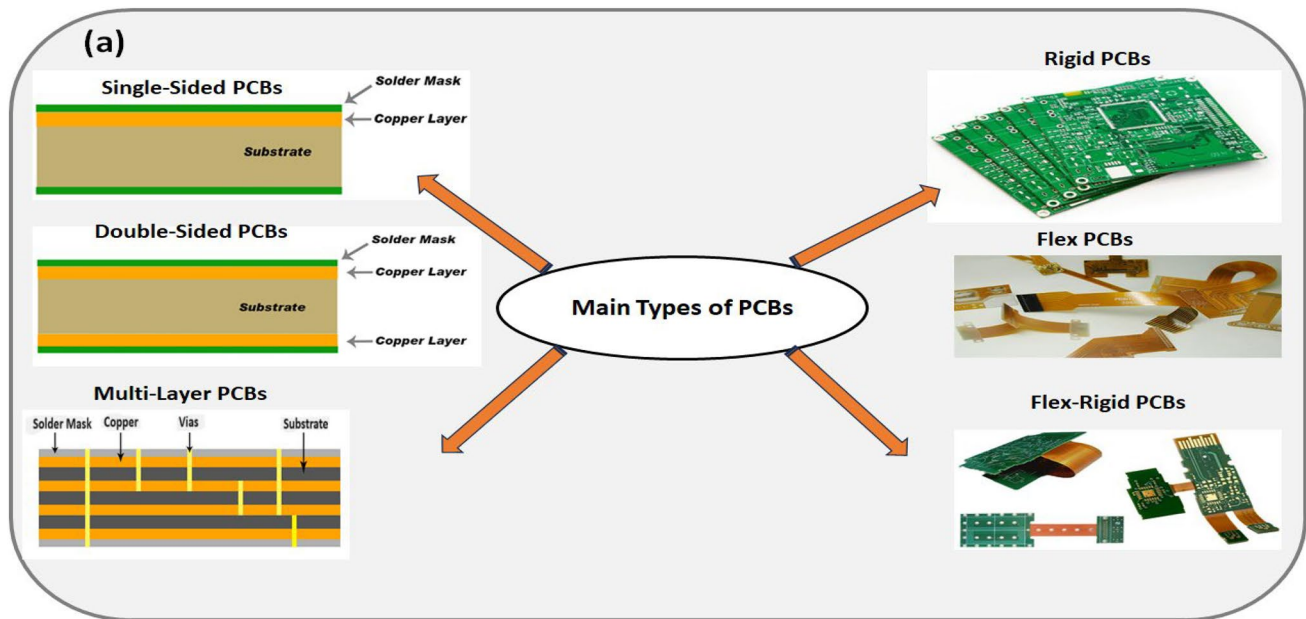


Fig. 1 a Geometric structure of six main types of PCBs, adapted from [37]; b four major sources of DPCBs

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 scarce 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

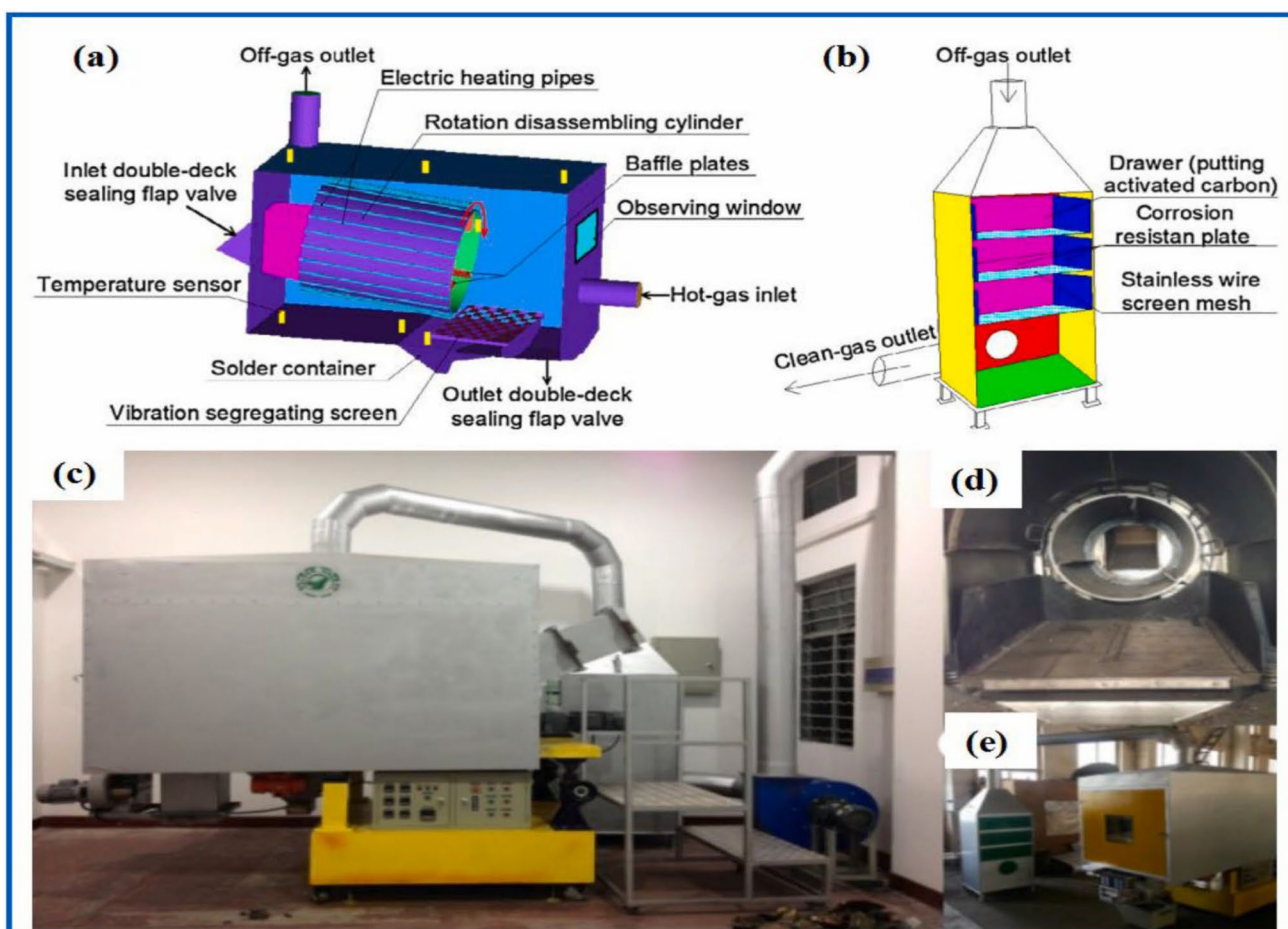


Fig. 2 Structures of **a** electronic components (ECs) automatically disassembling machine and **b** off-gas purification device; photographs of **c** ECs disassembling system, **d** internal structure and **e** feed inlet. Copyright 2023, with permission from Elsevier [62]

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, HNO₃, 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 HBF₄ with H₂O₂ 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 H₂O₂ 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 H₂O₂, 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 HBF₄, 0.40 mol/L H₂O₂ and 3.0% HNO₃. 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 FeCl₃ 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 H₂SO₄–CuSO₄–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 $\text{NH}_3/\text{NH}_4^+$ 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 PCBs 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

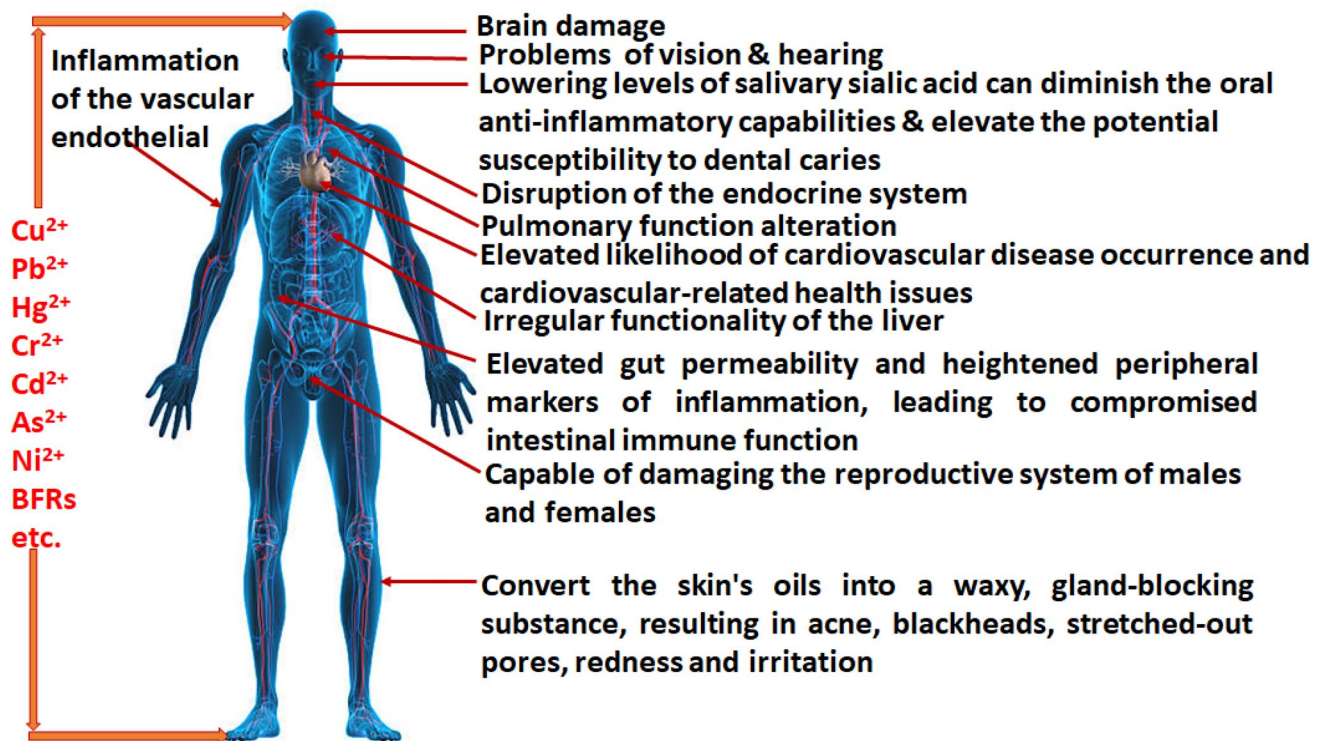


Fig. 3 Additional adverse effects of toxic metals/compounds from DPCBs on humans [47, 151, 152]

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 $\text{NH}_3/\text{NH}_4^+$ 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 $\text{NH}_3/\text{NH}_4^+$ 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.

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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.

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