Electronic Waste Reduction Through Devices and Printed Circuit Boards Designed for Circularity

Moupali Chakraborty, *Member, IEEE*, Jeff Kettle, and Ravinder Dahiya, *Fellow, IEEE*

***Abstract*— The development of printed circuit boards (PCBs) has so far followed a traditional linear economy value chain, leading to high volumes of waste production and loss of value at the end-of-life. Consequentially, the electronics industry requires a transition to more sustainable practices. This review article presents an overview of the potential solutions and new opportunities that may arise from the greater use of emerging sustainable materials and resource-efficient manufacturing. A brief contextual summary about how the international management of waste PCBs (WPCBs) and legalization have evolved over the past 20 years is presented along with a review of the existing materials used in PCBs. The environmental and human health assessments of these materials relative to their usage with PCBs are also explained. This enables the identification of which ecofriendly materials and new technologies will be needed to improve the sustainability of the industry. Following this, a comprehensive analysis of existing WPCB processing is presented. Finally, a detailed review of potential solutions is provided, which has been partitioned by the use of emerging sustainable materials and resource-efficient manufacturing. It is hoped that this discussion will transform existing manufacturing facilities and inform policies, which currently focus on waste management, toward waste reduction and zero waste.**

***Index Terms*— Biodegradable materials, electronic waste, life cycle assessment, recovery, recycling, sustainable electronics, waste electrical and electronic equipment (WEEE).**

I. INTRODUCTION

THE advances in electronics over the last more than 50 years have revolutionized all traditional socioeconomic sectors (e.g., health, agriculture, aerospace, manufacturing, and retail). Electronics form the backbone for advances in several emerging areas, such as automation, smart cities, connected everything, industry 4.0, robotics, virtual/augmented reality, and 5G/6G communication. It also underpins technologies such as wearable systems, which could help leapfrog the bureaucratic bottlenecks coming in the way of attaining United Nations (UN's) Sustainable Development Goals, such as universal education and affordable healthcare [1]–[7]. As a result of all the above, the demand for electronics continues to grow rapidly. For example, for the next four to five years, consumer electronics alone is expected to grow at an annual rate of 4.52% resulting in a projected market volume of US$538 billion by 2025 [8]. Yet, as revolutionary as electronics has been, in its current form, the production and the integration process it follows are inherently and unavoidably wasteful. The current "take-make-waste" model of production and consumption is unsustainable and a reboot is needed toward circular sustainable electronics. This is also important in view of the concerns related to the scarcity of critical rare metals (CRMs) and the dumping of electronic waste (e-waste) and Waste Electrical and Electronic Equipment (WEEE) [9].

A considerable part of WEEE (∼42%) comprises waste printed circuit boards (WPCB) [10], which typically use a substrate such as Flame Retardant 4 (FR4)—a composite material composed of woven fiberglass cloth with an epoxy resin binder. Such materials constitute a considerable part (∼70%) of WPCB and pose a major environmental challenge as they contain toxic substances, such as brominated flame retardants (BFRs) and nonmetallic materials (glass fiber and epoxy resin) [11]. The wastage of highly purified metals (copper, silver, and nickel), which have limited reserves, also raises concern related to sustainability. It is clear that there are advantages in transitioning away from such materials from a legal, environmental, and economic perspective [12]. The highly desirable aim is to reuse and achieve a 100% closed loop of materials, heat, and energy, as illustrated in Fig. 1. New methods should be explored with circular electronics, resource efficiency, and sustainable design principles at the core. This will also reduce the reliance on environmentally unfriendly materials and lead to a long-lasting solution [13].

The adverse impacts of WEEE have also been highlighted through several review articles, covering various facets of waste management, such as: 1) trends and scenarios of WEEE generation [14], [15]; 2) collection, recycling, and disposal by various countries [16]–[18]; 3) identification and classification of typical waste management scenarios; and 4) future WEEE management options [19]–[22] and so on. These articles have generally missed the waste reduction or ways for zero waste through design adaptations [23], [24]. Interestingly, the governments and policymakers are also focusing on the issues related to the management of WEEE, as now they are actively encouraging repair and extended life for electronics, thereby delaying the consigned to landfill [25]–[27]. The European

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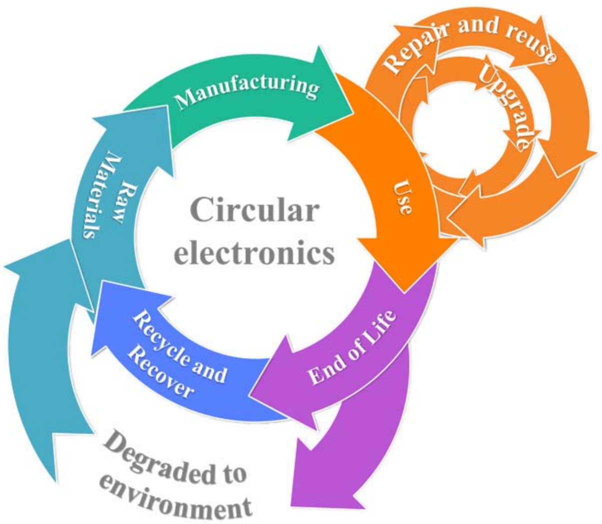


Fig. 1. Circular electronics as a way forward to manage WPCB and eventually lead to zero waste.

Union's (EU) WEEE Directive is one such example [28]. From 2021, the EU parliament set about establishing the "right to return" so that consumers can return the electronic product to the point of purchase, and then, it must be recycled responsibly. As a result, manufacturers are coming under greater pressure to innovate repair solutions. While these are steps in the right direction, it will be worthwhile to also consider a pro-active approach, involving switching to the development of electrical and electronic equipment (EEE) using more sustainable materials and resource-efficient manufacturing.

Considering the above developments, circular-economy strategies for electronics will be worthwhile, and therefore, this article provides a timely discussion, which also complements previous articles on WEEE. Herein, we focus on how new and emerging materials can be used to reduce the impact of WPCBs, which makes a significant part of WEEE. The article starts with the historical perspective on WEEE, explaining how the international management of WEEE and legalization has evolved over the past 20 years. This is followed by a short discussion in Section III on the materials currently used in information and communications technology (ICT) hardware along with an environmental assessment of these materials. For the first time, we report a "periodic table of sustainable electronics," assessing the environmental and human toxicity impact of different elements relative to their abundance within WPCBs. The motivation for this discussion is to identify which ecofriendly materials and new technologies will be needed to improve the sustainability of the industry. This is followed by a comprehensive analysis of WEEE processing in Section IV. The projection of expected future trends is also discussed in this section. Furthermore, we discuss current industry-scale technologies, their limitations, and future research directions. Finally, we discuss the challenges, potential solutions, and new opportunities that may arise from the greater use of sustainable materials and resource efficiency manufacturing. It is hoped that the researchers and practitioners from academia and industry will benefit from this in-depth discussion. Furthermore, this article is expected to stimulate the discussion about revising policies from the current focus on waste management toward waste reduction and zero waste—when there will be no need to develop a waste management strategy.

II. Historical Perspective

A. What Are WEEE and WPCB?

The EU's Directive 2012/19/EU defines EEE as: "…equipment which is dependent on electrical currents or electromagnetic fields in order to work properly and equipment for the generation, transfer, and measurement of such currents and fields" [14]. EEE is often designed to function for a period of time, after which operation ceases [end-of-life (EOL)] or performs suboptimally (obsolescence) [29]. When this occurs, the device may be discarded, and then, it becomes Waste EEE (WEEE) or "e-waste." WEEE is nonhomogenous and a complex mixture of components, such as power supplies, cabling, displays, and other accessories. New devices, such as photovoltaics (PVs) [30]–[32], smartphones, and electronic hardware for the Internet of Things (IoT) [33], are likely to make a big share of WEEE in the future. As mentioned in Section I, the WPCB makes a major part of WEEE. The composition of WPCB may vary with the design, functionality, manufacturing route, and application. For example, the planar printed circuit boards (PCBs) are sufficient for most EEEs, but emerging applications, such as wearable electronics, vehicles with interactive interiors, and robotics, require conformable and flexible PCBs (FPCBs) [34]–[38]. Typically, WPCBs comprise a mixture of materials that can be grouped into nonferrous and ferrous metals and plastics [14]. Ferrous metals tend to constitute the largest proportion of WEEE in size and weight, followed by plastics [14], [39]. Currently, the EU directive does not include medical devices, toys, leisure, and sports equipment and automatic dispensers as e-waste [40], but some of the materials they use can also be found in WPCBs.

B. WEEE Statistics and Highlights

One of the principal sources of data is the Global e-Waste Monitor, a collaborative effort between the International Telecommunication Union (ITU), the Sustainable Cycles (SCYCLE) Program, which is cohosted by the United Nations University (UNU) and the United Nations Institute for Training and Research (UNITAR), and the International Solid Waste Association (ISWA) [29]. Its latest report shows the current level of WEEE to be a whopping ∼60 million metric tons (Mt) [see Fig. 2(a)], and it is expected to rise to ∼75 Mt (excluding PV panels) in 2030. In 2019, the formal documented collection and recycling were 9.3 Mt, i.e., merely ∼17% of the generated WEEE. Thus, a large majority of WEEE (∼83%) is most likely not managed properly. The data show that the developing nations have larger ownership of EEE [see Fig. 2(b)] and, thus, are more likely to contribute to WEEE [see Fig. 2(c)] generation.

The WEEE issue has also attracted significant academic interest, as can be noted from Fig. 3 where the number of the article published [41] during the past 50 years are plotted using relevant keywords (e.g., "electronics waste," "recycling

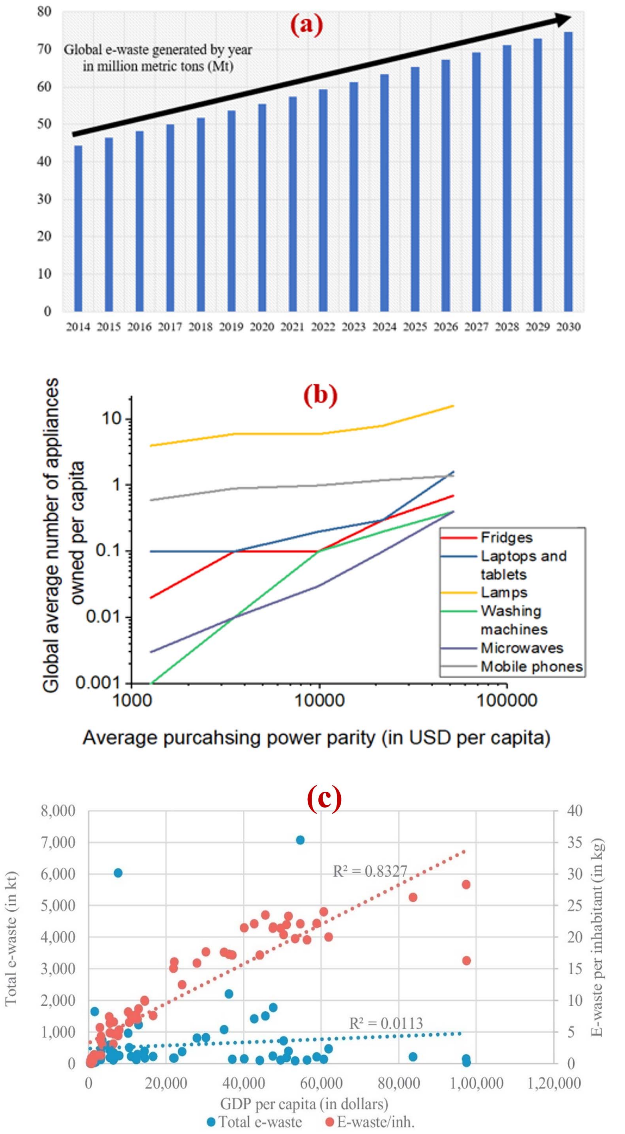


Fig. 2. (a) Global WEEE generated by year in Mt, (b) application owned per capita versus purchasing power parity, and (c) e-waste and e-waste/inhabitant versus gross domestic product (GDP) per capita, *reproduced with permission from* [40].

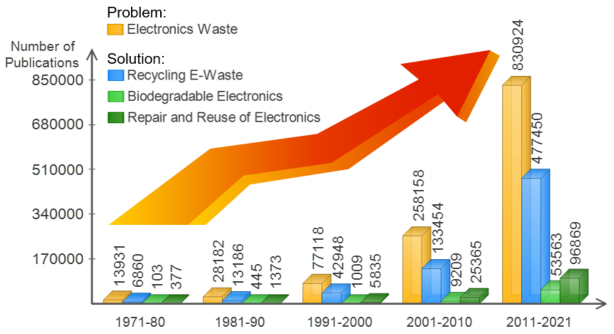


Fig. 3. Academic progress in tackling WEEE using a keyword search from dimension app [41].

e-waste,” “biodegradable electronics,” and “repair and reuse” of electronics). The figure shows that e-waste possibly became a pertinent issue around 20 years ago as the issue has attracted exponential attention by researchers since then. The figure also shows considerable growth, during the same period, in the number of publications on recycling WEEE. This growth is significantly higher than other alternative solutions, such as biodegradable or transient electronics and repair or reuse. The boost in repair and reuse papers, which has been seen recently, is probably due to new policies which promote repair or reuse. Nevertheless, the increasing number of papers on fully biodegradable electronics is a good sign as such solutions are expected to be relevant in the long term [42]–[44].

C. WEEE Management Approaches

Waste management is largely controlled and guided by regional or national governments. As a result, there is a wide variety of EOL management schemes [40]. Such variabilities, diffused nature of the industry, and variations in EOL scenarios make it difficult to measure the WEEE generation. As a result, the “production and trade” of EEE are used for monitoring waste generation as there is a strong link between trade statistics and national production statistics [29].

The collection is an important part of managing WEEE. “Formal collection” activities usually fall under the requirements of national or regional WEEE legislation, in which WEEE is collected by designated organizations. This happens via retailers, communal collection points, and/or government services. The final destination for the collected WEEE is a specialized treatment facility, which recovers the valuable materials in an environmentally controlled way and manages the hazardous substances in an environmentally sound way. A second scenario involves collection in an “informal” manner whereby WEEE is collected by individual waste dealers. Possible destinations for WEEE in this scenario include metal and plastic recycling; however, the hazardous substances are most likely not depolluted. In this scenario, WEEE is often untreated and might even be exported after the extraction of materials, such as aluminum or glass. Finally, a large proportion of collection activity is when WEEE is disposed of in mixed waste bins with other types of household waste. As a consequence, the disposed WEEE is then treated with the regular mixed waste from households. This waste is most likely incinerated or landfilled without material recycling, depending on the waste management infrastructure in a country.

In addition to these end of life (EOL) scenarios, several thousands of businesses and social enterprises operating in refurbishing/repair have emerged over the past ten years, where the product is returned to its original use, although the end product might not have the same quality as a new product [45]. Significant opportunities exist for innovation in the area such as modular smartphones designed for easier dismantling [46] or additive manufacturing based on emerging materials such as graphene to mend PCB assemblies [47], [48].

D. WEEE Legislation

International policies on WEEE management are varied and largely driven by developed nations [49]. The European WEEE Directive is the most well-known action that was developed to manage the EOL electronics and improve the collection and efficiency of the recycling chain. It is used alongside the restriction of hazardous substances (RoHS) Directive, which restricts the use of certain hazardous substances in EEE production. The WEEE Directive was updated in 2019 (2012/19/EC) and sets an overall WEEE collection target of 65% and individual targets for the reuse, recovery, and recycling of six different categories of WEEE. However, the recycling targets of WEEE in the EU do not promote the recovery of rare metals, which are present in small amounts, such as those used in electronics [50], but are immensely important for circularity in electronics. Outside the EU, Japan has launched the Home Appliance Recycling Law (HARL) and the Small Appliance Recycling Law to increase the recycling of WEEE. The USA and Canada do not have federal regulations to deal with the WEEE issue. Instead, they rely on policies imposed at the state level [51]. For example, in almost all the states of the USA, take-back programs are offered by private companies, nonprofits organizations, and/or local governments. At a federal level, the resource conservation and recovery act (RCRA) covers some toxic electronic waste, such as cathode ray tubes (CRTs). Australia has the National Waste Policy (2009) and the National Television and Computer Recycling Scheme (2011) to improve the recycling rate, but the WEEE management in Australia is not properly implemented based on outdated targets, and it lags behind the international best practices [52]. China placed the extended producer responsibility practice in 2011 for WEEE recycling and the "Collection and Treatment Decree on Waste Electrical and Electronic Equipment" in 2008. India developed the "The E-waste Management and Handling Rules" in 2010 to classify the WEEE according to the components and compositions. Most other developed nations have legalization in place to support WEEE processing [49]. The Basle convention is another initiative that was designed in 1992 under the UN Environmental program to monitor and control the flow of waste across countries. Several other international organizations, such as the mobile phone partnership initiative (MPPI), solving the E-waste problem (StEP), the Partnership for Action on Computing Equipment (PACE), and the National Electronics Product Stewardship Initiative (NEPSI), have been launched in recent years to contain the WEEE issue [53].

In 2021, the EU also released the "Right to repair" rules that are similar to other initiatives already in force in countries, such as the USA [54], [55]. For the first time, the measures include requirements for repairability and recyclability, contributing to circular economy objectives by improving the life span, maintenance, reuse, upgrade, recyclability, and waste handling of appliances. These rules give the users the right to decide what to do with their electronic products when they fail and before they have to be disposed of and thus empower consumers to behave more sustainably and, thus, help reduce the WEEE directly and indirectly [55].

III. ENVIRONMENTAL IMPACT OF PCBs

The main EEE, which led WPCBs after the EOL, is shown in Fig. 4. The major contributors are: 1) temperature exchange (TEE) equipment, such as air conditioners, refrigerators, and heat pumps; 2) large household equipment (LHE), such as vacuum cleaners, dishwashers, washing machines, Xerox, and printing machines; 3) the small household equipment (SHE), such as cameras, electric shavers, and electronic toys; and 4) ICT equipment, such as mobile phones, laptops, computers, radios, calculators, and telephones. Among these, the quantity of waste from ICT and SHE devices is on the rise due to increasing demand, short lifespan, and obsolescence. Altogether, the WEEE led to about 6 Mt of WPCBs in 2021. The key materials in WPCBs and their impacts on the environment are discussed in the following.

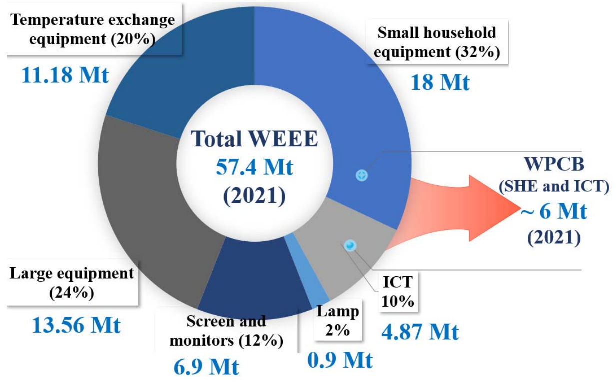


Fig. 4. Amount of waste PCBs from WEEE in the year 2021.

A. PCB Fabrication and Components

The current PCB manufacturing is a complex and wasteful subtractive process that includes the etching, drilling, masking, and plating of different materials, most of which contribute to the WEEE generation. Table I shows the key components of rigid and FPCBs along with the common materials that they are made of. The common set of materials used in PCBs is given in Table I. The legislation in the WEEE Directive requires the removal and recycling of electronics devices for PCBs bigger than 10 cm^2. Six materials of PCBs that are of immediate concern in the RoHS Directive (European Union 2003a) are cadmium (Cd), mercury (Hg), hexavalent chromium [Cr(VI)], lead (Pb), polybrominated biphenyls, and polybrominated diphenyl ethers and Octa-BDE [56]. The current tolerable limits of these materials are 0.01% w/w for Cd and 0.1% w/w for others [57]. Various substrates used in PCB, classified in different grades as per the standard of National Electrical Manufacturers Association (NEMA) [58], are given in Table II, along with solder or adhesives used to connect the integrated circuit (IC) and discrete components. The choice of solder alloys for a particular application depends on the properties, such as melting point, mechanical properties, chemical reactivity, and toxicity [59], [60].

Electronic packaging is needed for the interconnection of ICs and discrete components [61]. Basic standard packages in PCBs include transistor outline (TO), dual in-line package (DIP), small outline (SO), leadless chip carrier (LCC), thin small outline package (TSOP), B/C/L/PGA (pin grid array), quad flat package (QFP), quad flat no-lead (QFN), through

TABLE I
PCB COMPONENTS AND THEIR COMMON MATERIALS

PCB components	**Common materials**
Substrate grades	
XXXPC, FR2	Phenolic-Cotton paper
FR3	Epoxy-Cotton paper
FR4, FR5, G10	Epoxy-Woven glass
FR6	Polyester-Mat glass
CEM-1, CEM-2	Epoxy-Cotton Paper / Woven Glass
CEM-3, CEM-4	Epoxy-woven glass/Mat glass
CRM-5, CRM-6	Polyester-woven glass/Mat glass
CRM-7, CRM-8	Polyester-Mat glass/glass veil
PI (Kapton), PTFE	Common flexible substrates that are hazardous when incinerated
Pyralux (flexible foil)	PI-fluoropolymer composite
Conformal coating to protect board from corrosion & environment effects	Acrylic, urethane, PU, epoxy, parylene etc. They can cause health safety concern after EOL of PCB
Connecting tracks	
Conductive metals	Cu, Sn
Wire coatings	PVC
Discrete components	
SMT/THT Capacitor	Ta, Al, Nb, ceramic, Mica, Teflon, Glass, polychlorinated biphenyls
SMT resistor, Switch, semiconductors, battery	Toxic Cd, Hg, Pb acid, Zn
Infrared detector	InGaAs, PbS, SiO_2, HgCdTe, InSb
metal coatings/plating for corrosion protection	Toxic Hexavalent Cr ([Cr(VI)])
LEDs	Epoxy, Cu, III-V semiconductor
Integrated Circuits (ICs)	Si, Au wires, Phenol and epoxy resin, carbon black, Cu lead frame
Cleaner for fluxes	CFC solvent
Solders alloys	
Pb based (toxic)	Sn62/Pb36/Ag2, Sn63/Pb37, Pb55/Sn43.5/Sb1.5, Sn70/Pb18/In12
Sn based solder wire	Sn90/Zn7/Cu3,In50/Sn50, Sn98/Ag2
Pb-free solder paste (low temp. applications)	Sn42/Bi57.6/Ag0.4, In52/Sn48, Sn42/Bi58, Sn/Ag2.5/Cu.8/Sb.5, Sn42/Bi57/Ag1, Sn/Ag3.8-4/Cu.5-.7
Pb-free solder paste (high temp. applications)	Sn97/Cu3, Sn95/Sb5, Sn/Ag25/Sb10, Sn95/Ag5 etc.

Si - silicon; PU - Polyurethane; Pb – Lead; Sn – Tin; Cu - Copper, Zn - Zinc, Au - Gold; Ni - Nickel, Al – Aluminium; Ag – Silver; CFC - Chlorofluorocarbon; Ga -Gallium; Zn – Zinc; Cd – Cadmium; Fe – Iron; PI - Polyimide; PVC - Polyvinyl chloride; PTFE - Polytetrafluoroethylene; Bi - Bismuth; Pd – Palladium; In – Indium; As – Arsenide; Hg – Mercury; Ta – Tantalum; Nb – Niobium; Te – Tellurium; Sb – Antimony; Cr - chromium

TABLE II
ENERGY SAVING BY RECYCLING OF MATERIALS

Materials	**Energy saving (%)**
Aluminium (Al)	95
Copper (Cu)	85
Iron (Fe) and steel	74
Lead (Pb)	65
Zinc (Zn)	60
Paper	64
Plastics	>80

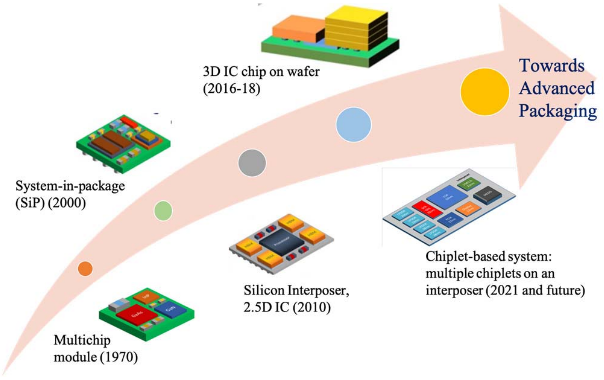


Fig. 5. Evolution of IC packaging and future directions.

hole, J-lead, gull wing, solder ball, and bumps, and so on. The advanced package families include flip-chip area array technologies, wafer-level packaging (WLP), fan-out WLP (FO-WLP), through silicon via (TSV) developments, embedded component/device technologies (ECP/EDT), and so on. The evolution of packaging over the past 50 years and the potential future advances are illustrated in Fig. 5. As can be observed in the figure, the packages have evolved from the traditional multichip module (MCM) to system in package (SiP) to recent trends of heterogeneous integration of chiplet-based systems [62]. The panel-level packaging is another example of heterogeneous packaging [63]. The heterogeneous integration is expected to improve the reliability so that ICs can operate for extended periods. Currently, there are no reports on how advanced packaging solutions would impact recyclability although the complexity of assembly limits the options for repair. New approaches will be needed to recover CRMs from such advanced packages.

B. Life Cycle Assessment

In order to evaluate the impact of material selection in PCBs used for ICT infrastructure, a case study using a smartphone has been applied. Material composition in smartphones has been shown to vary between smartphone types/manufacturers and age of manufacturer, but, in this work, data have been analyzed by averaging material compositions from several reports [64]–[67], as shown in Fig. 6(a). To assess the sustainability and potential for substitution; first, we evaluated the relative elemental abundance in the Earth crust or ocean (measured in ppm). The outcome in Fig. 6(b) shows the relative scarcity of the materials used in smartphones. Although Al, Fe, and Si are widely available, some of the more specialized materials, particularly those used for the RF IC or display, are much less abundant. Many of the abundant materials, such as Al and Fe, are recycled; for example, 60% of Al is recycled in the U.K. [68]. Statistics for the lesser abundant materials are much more difficult to source, and it is unlikely that many of them, particularly those in semiconductor dies, are currently recovered. This should be of pressing concern to the electronics industry as these materials are essential for many ICT applications. The costs of materials used in smartphones are shown in Fig. 6(c). Considering the volatility in the market, the data have been sourced to show the average market price over the last calendar year (November 2020–November 2021). It can be noted that the materials such as Au, Pt, and Pd have the highest base cost although these

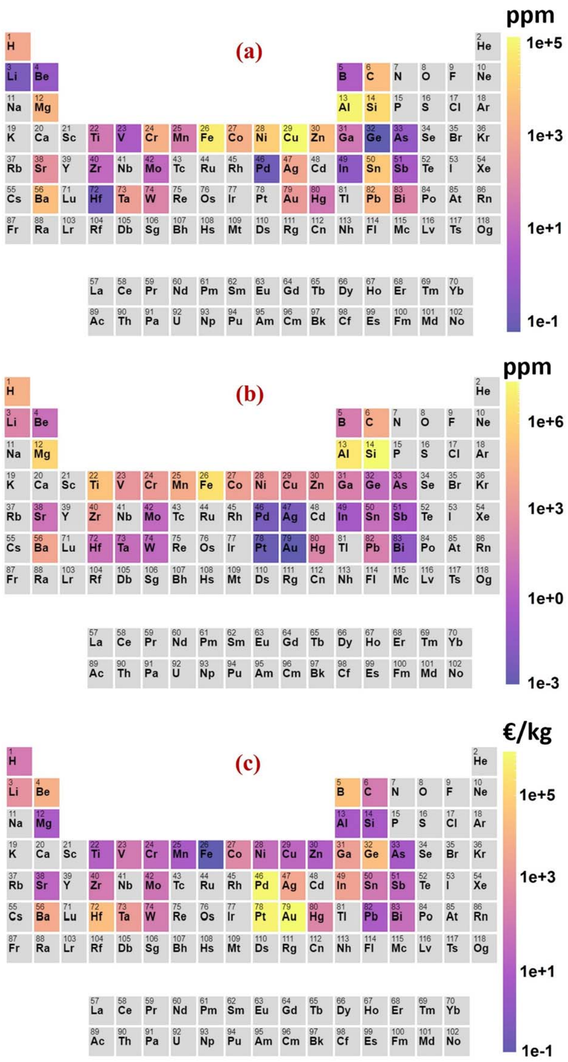


Fig. 6. (a) Relative abundance of materials in the mobile phone (ppm), (b) global abundance of materials used in smartphones within the Earth crust or ocean (ppm), and (c) cost (€/kg) of materials used in mobile phone.

are used sparingly [see Fig. 6(a)]. As the community moves to use more sustainable materials, it is vitally important to ensure that the value is not lost between manufacturing and reuse/recycling.

The data have also been used to apply a life cycle impact assessment using the USEtox model [69] to determine the potential impacts on human health and ecological toxicity [70], [71]. The results are useful for the ecodesign of electronic products and provide valuable information to cross-cutting WEEE management strategies. USEtox is a scientific environment model used to characterize the potential impact of toxic chemicals in products on human toxicology and ecotoxicology. The model outputs the environmental fate and describes the impact of various chemicals [72], [73]. The potential carcinogenic and noncarcinogenic impacts of ecotoxicity [see Fig. 7(a)] and human toxicity [see Fig. 7(b)] of the selected metals were calculated according to the formula

$$ISx = Cx \cdot W \cdot Cfx$$

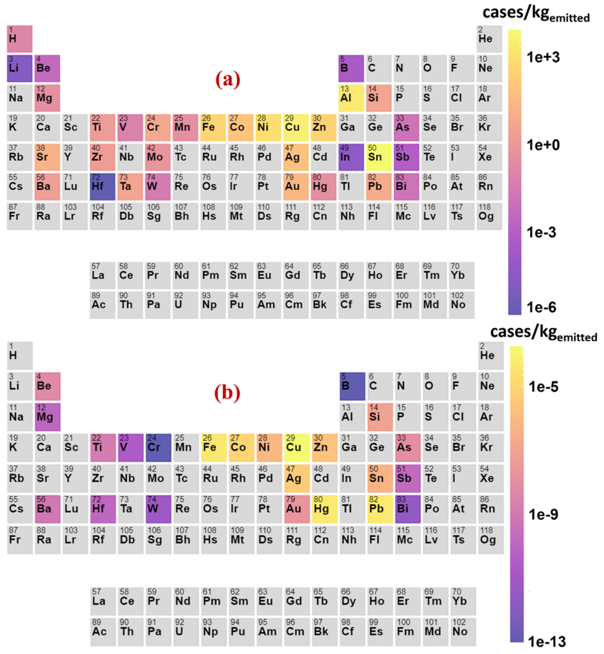


Fig. 7. Impact score of various PCB materials in terms of (a) ecotoxicity and (b) human toxicity (gray means no information or no impact).

where IS_x represents the impact score of metal x in the smartphone; C_x is the concentration of metal x in the WEEE (kg/kg); W is the total weight of the sample (in kg); and Cf_x is the characterization factor for the corresponding potential of metal x. The unit of the characterization factor for human toxicity and ecotoxicity is cases/kg$_{\text{emitted}}$, and it reflects the potentially affected fraction (PAF) of species due to change in concentration of toxic emissions. The characterization factors derived from USEtox were associated with the impacts of metals emitted to household indoor air, industrial indoor air, urban air, rural air, freshwater, seawater, natural soil, and agricultural soil. For USEtox calculations, data were sourced either from the standard libraries or via the EC's Ecotox page [74]. Results are displayed on a periodic table using code derived from GitHub [75].

In terms of the ecotoxicity impact of smartphones, tin (Sn), copper (Cu), and aluminum (Al) show the greatest impact. In the case of Sn (average 3200 PAF$\cdot$m$^3\cdot$day$\cdot$kg^{-1}), the impact is caused during the full life cycle. Cu, Al, and Ni [average between 3900 and 150 PAF$\cdot$m$^3\cdot$day$\cdot$kg^{-1})] are widely used in smartphones, which means these materials have some of the largest environmental footprints. Cu is used for conductive tracks in PCBs and lead frames in ICs. Al and Ni are mostly used in welding and the cover to provide internal strength. In terms of human toxicity, the principal sources of cancerous and noncancerous hazards arise from Cu, Pb, and mercury (Hg).

C. WPCB Impact on Health and Society

WPCB contains many hazardous materials, such as Hg, cadmium (Cd), Pb, Cr, BFRs, and ozone-depleting chemicals, such as chlorofluorocarbons (CFCs) [40]. Disposal of these

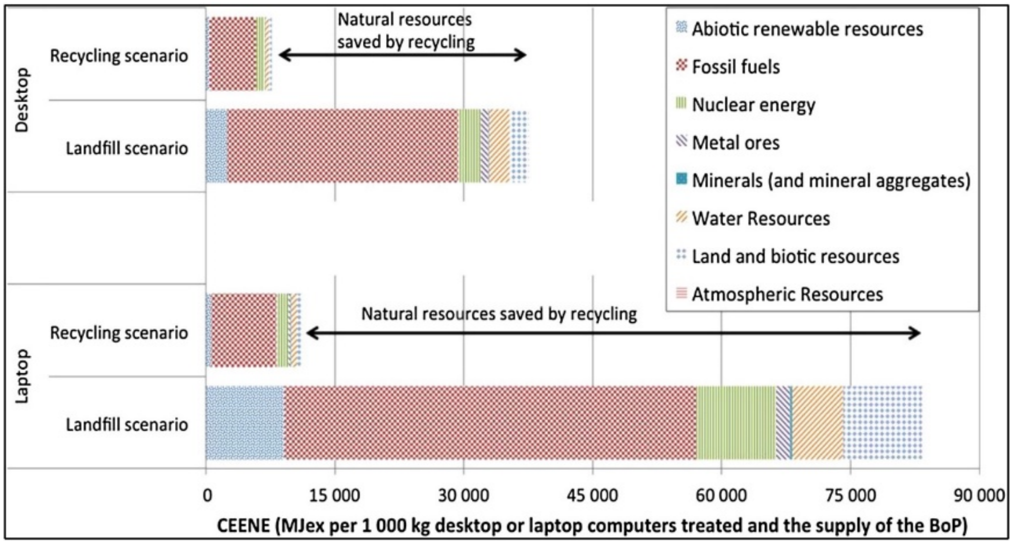


Fig. 8. Comparison of the cumulative exergy extracted from the natural environment (CEENE) analysis for the recycling and landfill scenario, *reproduced with permission from* [50].

chemicals/metals in the landfill or by incineration produces harmful effects to the environment. There are a wide variety of metals and organic/inorganic compounds that can impair mental and neonatal development, kidney, thyroid, and liver function and have carcinogens released into the air causing lung damage [18]. The lack of epidemiological data, weak associations, inconsistent findings across studies, and poor understanding of biological mechanisms preclude the establishment of a causal relationship between exposure to WEEE and adverse health outcomes [76]. However, the strong plausibility of an association between WEEE exposure and health outcomes needs further research.

Well-controlled and regulated landfills and incineration might provide a temporary solution to the global WEEE problem, but it may not be a viable long-term solution, especially for the countries with a scarcity of landmasses, such as Japan. Furthermore, this approach reduces the possibility of resource recovery, and therefore, recycling is a better alternative. WEEE recycling also reduces the total global demand for new metal production and eventually helps to reduce carbon footprints as recycling of metals could lead to significant energy savings. As an example, it requires 240 kg of fossil fuels, 22 kg of chemicals, and 1.5 tons of water to produce one computer and monitor. Table II summarizes the energy savings as a result of recycling when considering the direct impact on the greenhouse gas emissions due to new metal production [77]. For example, by recycling 10 kg of Al, it is possible to save 90% energy and prevent the creation of 13 kg of bauxite residue, 20 kg of CO_2 gas, and 0.11 kg of SO_2 gas [78]. Likewise, the recycling of desktops and laptops could lead to 80% and 87% resource-saving, respectively, as shown in Fig. 8 [50].

IV. RECYCLING APPROACHES

To date, there is no mainstream circular economy approach for electronics. Most commercial and research efforts have focused on the minimization of WEEE by way of recycling. To this end, a wide range of methods are being explored, including for WPCB [79], [80], and some of these are reviewed in this section.

A. Size Reduction and Separation Approaches

The general method of WPCB recycling is shown in Fig. 9. First, the easily removable components are manually dismantled from PCBs, and thereafter, the particle sizes are progressively reduced by applying the sequential processes of shredding, crushing, pulverizing, grinding, and (sometimes) ball milling [81]. In the process of shredding, WPCBs are fragmented into small pieces and, after that, granulated into fine particles in a pulverizer. Often the X-ray fluorescence spectroscopy (XRF) method is used to analyze the composition of the homogeneous metal alloys. However, the rough method of acid wash, heavy metal exposure, and noise in the dismantling process cause considerable environmental pollution [82], [83]. After the pulverization step, different separators are used for the separation of raw metal and nonmetal separation [84]. Some of these separation methods are summarized in Table III along with their principal mechanism and the separated elements. The process of separation produces a huge amount of dust and wastewater, which creates another environmental challenge.

B. Leaching of Waste PCBs

Leaching is an important step to recover base and precious metals from WPCBs. The output of the separator is a residue of fine-sized particles containing the precious metals, which can be extracted further by the leaching method. This is the main hydrometallurgical recycling process, which offers a selective separation between metal and nonmetals of WPCBs. However, the process of leaching leads to the formation of substantial waste. Therefore, a reliable and ecofriendly metal

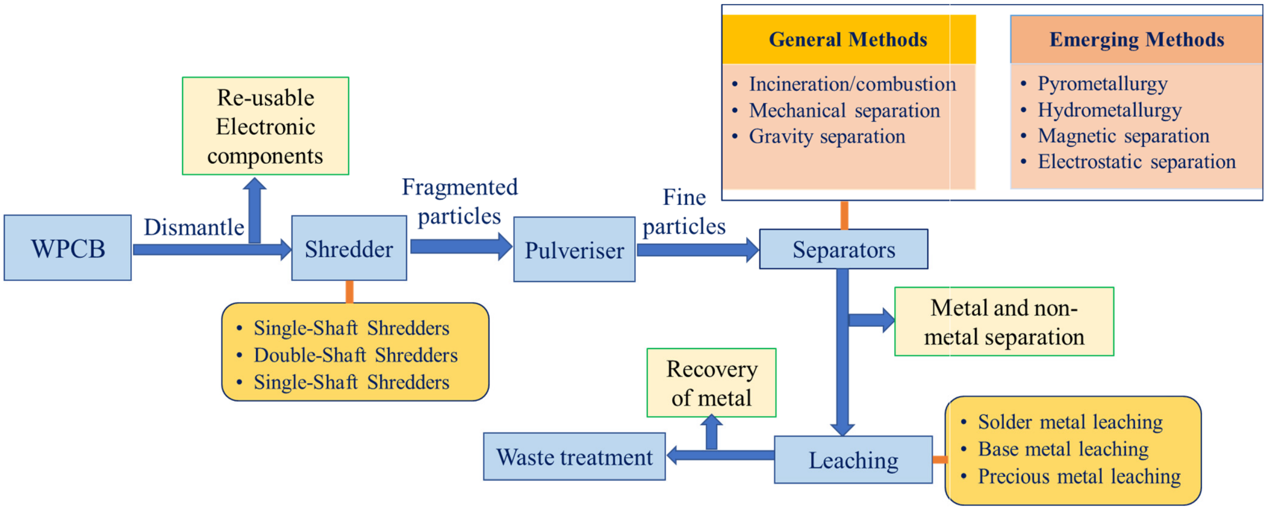


Fig. 9. General scheme for WPCB recycling.

TABLE III
METHODS FOR SEPARATION OF ELEMENTS

Separation Method	Principle of separation	Separated elements
Uncontrolled incineration	Combustion	Non-metallic part is removed
Mechanical separation	Depends on the material properties	Precious metals
Gravity separation	Specific gravity	Plastics, resins, glass from heavy metals
Pyrometallurgy	thermochemical treatment	Mineral and metallic phases from plastic
Hydrometallurgy	Strong acid treatment	Selectively dissolve and precipitate metals
Magnetic separation	Magnetic susceptibility	Ferrous metals from nonferrous metals
Electrostatic separation	Electric conductivity	Ferrous metals from nonferrous metals

TABLE IV
LEACHING AGENTS AND RECOVERED METALS FROM WPCBS

Leaching agents	Recovered metal	Ref
Solder metal leaching (SML)		
NaOH, HCl, and HNO_3	Pb and Sn	[85]
HNO_3	Pb	[86]
H_2SO_4, NaCl and NaOH	Sn, Pb, Zn	[87]
HBF_4	Pb, Sn, Fe	[88]
$SnCl_4$–HCl	Sn	[89]
$Fe_2(SO_4)_3$-H_2SO_4	Pb, Sn, Zn	[90]
Base metal leaching (BML)		
H_2SO_4 and H_2O_2	Cu, Au	[91]
Inorganic acids, organic sodium salts (EDTA and citrate), HCl, HNO_3, H_2SO_4	Cu	[92]
H_2SO_4 and H_2O_2	Cu, Fe, Zn, Ni, Al	[93]
H_2SO_4 and H_2O_2	Al, Zn, Sn, Cu	[94]
H_2SO_4–$CuSO_4$–NaCl	Cu, Ni, Ag, Fe	[95]
$Fe_2(SO_4)_3$-H_2SO_4	Cu, Fe	[90]
HNO_3	Cu	[86]
HCL-$FeCl_3$	Cu	[96]
Precious metal leaching (PML)		
$(NH_4)_2S_2O_3$, $CuSO_4$, and NH_4OH	Au, Ag	[93]
Alkaline sodium cyanide NaCN	Au, Ag	[97]
H_2SO_4, Thiourea ($SC(NH_2)_2$)	Au, Ag	[98]
Acid thiourea	Au, Ag	[99]
Iodine, H_2O_2	Au, Ag	[100]
Iodine-iodide lixiviant	Au, Ag, Pd	[101]
$(NH_4)_2S_2O_3$	Au, Ag, Pd	[102]
Aqua regia (3HCl + HNO_3)	Au, Ag, Pd	[103]

NaOH - Sodium hydroxide-alkali; HCl - Hydrochloric acid; HNO_3 - Nitric acid; Pb – Lead; Sn – Tin; Cu - Copper, Au - Gold; Ni - Nickel, Al – Aluminium; Ag – Silver; H_2SO_4 - Sulfuric acid; NaCl -Sodium Chloride; Zn – Zinc; HBF_4 – Fluoroboric acid; Fe – Iron; $SnCl_4$ - Tin Chloride; $Fe_2(SO_4)_3$ - Ferric sulphate; H_2O_2 - Hydrogen peroxide; $(NH_4)_2S_2O_3$ - Ammonium thiosulfate; Pd - Palladium

recovery method is necessary to avoid the secondary threat of environmental pollution from WPCBs. The leaching process itself requires the removal of several important components, such as lithium batteries, Al heat sinks, electrolytic capacitors, Cr, or Ni plated screws to avoid impurities and undesired chemical reactions. For example, batteries in contact with leaching solution may cause an explosion, polychlorinated biphenyls in Al capacitor may cause contamination of leaching solution, screws may slow down the leaching process, and the reaction between the capacitor and aqueous solution of bromine may increase the risk of explosion as they are exothermic in nature [84]. In general, the leaching process can be classified into three types: solder metal leaching (SML) [85]–[90], base metal leaching (BML) [86], [90]–[96], and precious metal leaching (PML) [93], [97]–[103], where acid or alkaline leaching agents are used to recover metals. Table IV summarizes some of the leaching agents and recovered metals from WPCBs.

C. Rare Metal Recovery

The rare-earth element (REE) or rare-earth metals (REMs) are the most valuable materials in WEEE and especially in WPCBs. These are a set of 17 elements: scandium (Sc), yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm),

TABLE V
LIST OF DEGRADABLE MATERIALS USED IN AN ELECTRONIC DEVICE

(Bio)degradable materials for substrates		
Natural polymers	**Synthetic polymers**	**Metal**
▪ Paper ▪ Nano-cellulose (CNF) ▪ Silk ▪ Shellac ▪ Gelatin ▪ Chitosan ▪ Silk fibroin-PVA composite	Polyvinyl alcohol (PVA) Polylactic acid (PLA), PLLA Polycaprolactone (PCL)-flexible Polyurethane (PU) Polybutylene succinate (PBS) Polyethylene glycol (PEG) Poly-lactic-co-glycolic acid (PLGA) Polydimethylsiloxane (PDMS) (with chemical) Poly(hydroxybutyrate-co-valerate) (PHBV)	Molybdenum (Mo) Ferrum (Fe) Tungsten (W) Zinc (Zn) Magnesium (Mg)
(Bio)degradable materials for conductors		
Chemically or electrochemically doped conjugated polymers		**Metal**
▪ Polypyrrole (PPy), ▪ Polyaniline (PANI) ▪ Poly(3,4-ethylenedioxythiophene) (PEDOT), conductivities can be changed up to 4.6 × 10^3 S/cm with the doping of poly(styrenesulfonate) i.e. (PEDOT:PSS) ▪ Poly(3-hexylthiophene) (P3HT) ▪ Melanin (doping via water absorption) ▪ Polyacetylene		▪ Molybdenum (Mo) ▪ Ferrum (Fe) ▪ Tungsten (W) ▪ Zinc (Zn) ▪ Magnesium (Mg)
(Bio)degradable materials for dielectric		
Natural	**Synthetic polymers**	**Inorganic**
▪ Nano-cellulose (CNF) ▪ Silk ▪ Shellac ▪ Gelatin ▪ Adenine ▪ Guanine thymine ▪ Cytosine ▪ Glucose ▪ Lactose ▪ Sucrose ▪ Caffeine ▪ Albumen ▪ Deoxyribonucleic acid (DNA)	▪ Polyvinyl alcohol (PVA) ▪ Polylactic acid (PLA) ▪ Polyurethane (PU) ▪ Polydimethylsiloxane (PDMS) ▪ PLGA−PCL composite	▪ Magnesium oxide (MgO) ▪ Silicon dioxide (SiO2) ▪ Silicon nitride (Si3N4) ▪ Spin-on-glass (SOG)
(Bio)degradable materials for Semiconductor		
Organic / Natural	**Synthetic**	**Inorganic**
▪ Indigo ▪ Melanin ▪ Tyrian purple ▪ Acridones ▪ Anthraquinones ▪ Terpenoids ▪ Phenazines ▪ Perylene diimide ▪ β-carotene	▪ Polythiophenes ▪ Poly (3-hexylthphene) ▪ P3HT	▪ Silicon Nano Membrane (30 - 300 nm) ▪ Polycrystalline silicon (poly-Si) ▪ Amorphous silicon (a-Si) ▪ Germanium (Ge) ▪ Silicon Germanium alloy (SiGe) ▪ Indium-gallium-zinc oxide (a-IGZO) ▪ Zinc oxide (ZnO)

ytterbium (Yb), and lutetium (Lu). Although some of these are not relevant to WPCBs, because of their unique electronic and magnetic properties, they are critical for devices such as PV cells, permanent magnets, fluorescent lamps, and rechargeable batteries. These elements are normally found in WEEE in their oxide forms, such as Eu_2O_3, In_2O_3, Ce_2O_3, and Y_2O_3 [84].

V. DEGRADABLE MATERIALS AND DEVICES IN PCBS

Encouraging the repair and reuse of WEEE is the best method to encourage circular electronics, but this may not be enough in the long term as the use of digital technologies is on the rise, and many ICT equipments (e.g., mobile phones) are the least recycled devices because of their small size and people's preference of privacy [104]. As an example, only 9% of the phones are properly recycled, and the rest is either kept unused at home because of data privacy or having no idea of recycling [105], [106]. Considering such challenges, the development of degradable or transient devices has been advocated in recent years. The bioderived and biodegradable electronics hold the potential to lead to zero WPCBs and can also open exciting new opportunities in the fields of agriculture or healthcare technologies. This section discusses the key components and materials (see Table V) needed for such devices, intending to attain degradable PCBs and EEE in the future. The discussion is structured around typical components, which includes: 1) substrates; 2) conductors; 3) dielectrics; and 4) semiconductors. They all should be the

TABLE VI

PARAMETER COMPARISON OF SUBSTRATE MATERIALS

Substrate materials	**Glass transition Temp (ºC)**	**Melting Temp. (ºC)**	**Young Modulus (Gpa)**
Biodegradable			
PLA	45-60	150-162	3.4
PLLA	55-65	170-200	3.7
PCL	60	58-65	0.4
PHBV	-1	153	3.6-5.2
PGA	35-40	220-230	7
Chitosan	203	290	0.95
Silk	140	283	14
Conventional			
FR4	-50	180	21-24
PI	-300	400	4

TABLE VII

COMPARISON OF CONDUCTIVE MATERIALS

Conductive materials	**Conductivity (S/m)**
Biodegradable	
Carbon black	$10^1 – 10^3$
Carbon nanotube (CNT)	10^1 - 10^4
PEDOT:PSS	10^1 - 10^4
Conventional	
Copper (Cu)	10^8
Silver (Ag)	10^8
Tin (Sn)	10^7

natural bridge between nature so that ecofriendly PCBs can be manufactured. Consequently, the sustainable manufacturing process and degradable devices are also discussed in this section.

A. Substrates

The substrate material has the greatest area and weight in a PCB; thus, the amount of WPCBs can be drastically reduced by replacing the traditional substrates with biodegradable materials, such as polylactic acid (PLA), poly(vinyl alcohol) (PVA), cellulose nanofiber (CNF), and silk [107]–[110]. In the past decade, conventional rigid substrates have been replaced by flexible, lightweight, stretchable biodegradable polymers [111], but most commercial PCBs still use FR4 (rigid) or polyimide (PI) (flexible). The primary limitations of current biodegradable polymers are: 1) lower glass transition temperature [112], [113] of the polymers (see Table VI); 2) their lack of fire retardancy; and 3) the incompatibility with existing PCB manufacturing processes. Therefore, while selecting a suitable substrate for a biodegradable PCB, it is also important to consider the ways to improve critical parameters, such as mechanical stability, thermal stability, dissolution, swelling rate, and ability to withstand harsh environments [114], [115].

B. Conductor

Conductive materials are used as connective tracks and contacts in PCBs. Typically, these are made of Cu, Ag, and Sn, but recently conjugated polymers and conductive nanocomposites (e.g., Ag paste) have also been explored (see Table VII) although they are not always degradable and ecofriendly. However, they do offer advantages such as resource-efficient printing directly on various types of flexible and stretchable substrates (e.g., paper and textile) [116], [117]. Therefore, there are both challenges and opportunities for new conductive polymers, which will be used in future biodegradable PCBs. To replace the traditional tracks on PCBs, they must possess stability and electrical functionality in part with current materials. For example, the conductivity should be more than 10^{-1} S/cm to build a high-performance biodegradable device [111]. However, most of the printable conductive materials known today exhibit poor performance, and there is a need for more research. With new material development with suitable doping, the performance of these materials could be improved to match the conventional metals though a substantial enhancement is needed. The compatibility of the doping process itself requires attention, and orthogonal solvents are needed while processing a layer to prevent damage or dissolution of the previous layer.

Furthermore, degradable conductive materials as needed to realize the fully degradable PCBs. Some of the degradable conductive materials being explored are given in Table V. The dissolvable materials, such as Mg and Mo, have also been explored for electrodes. Although Mg dissolves rapidly in phosphate-buffered saline (PBS) solution at room temperature, with suitable encapsulation, they could be used for longer periods as well. For example, encapsulating with a thin layer (100 μm) of biodegradable polymers, such as poly(L-lactide-co-glycolide) (PLGA), which is resistant to water for up to 30 days and allow tunable degradation [118].

C. Dielectric

The dielectric materials are important for active devices, such as field-effect transistors (FETs), and passive devices, such as capacitors and also for encapsulation. The dielectric loss or stability of these materials depends on the dielectric constant, where a low value indicates less energy dissipation. The dielectric constant can be increased by increasing the effective area where polymeric materials with conductive polymers, conductive fillers, metal particles, liquid metals, or carbon nanotubes (CNTs) are integrated [119]. However, device performance is degraded by the rise of leakage current due to high concentrations of conductive fillers [107]. The inorganic dielectric material of silicon dioxide (SiO_2) and silicon nitride (Si_3N_4) are widely adopted in electronic devices. Amorphous SiO_2 with high electrical resistivities also makes a suitable insulation layer [120]. Si_3N_4 and MgO are being used in microelectronics in the form of the gate dielectric in thin-film transistors (TFTs) and transistors [120]–[122].

D. Semiconductor

Biodegradable semiconductors fall into three categories: 1) silicon nanomembrane (Si-NM); 2) metal oxides (tin oxide, indium oxide, and so on); and 3) conducting polymers [123]. The charge carrier mobility defines the performance of these semiconductors. The conventional semiconductor industry depends on core silicon materials, and a vast number of fabrication methodologies have been developed for its deposition and growth mechanisms; however, the thick Si wafers are not easily decomposable. To overcome that, Si-NM shows new opportunities in terms of biodegradability, as demonstrated with electronic devices, such as degradable photodetectors and FETs [122], [124]–[128]. Metal oxides, such as zinc oxide (ZnO) semiconductors, show another new direction because of their simplistic synthesis, higher thermal stability, and adequate charge transport properties [129]–[132]. Using these new biodegradable materials and understanding their breakdown mechanisms can drastically help to reduce the problem of WEEE. The invention of semiconducting polymers, such as oligofurans, diketopyrrolopyrrole (DPP)-based polymer [24], beta-carotene, and indigo [133], provides a new class of organic semiconducting materials [114], [134].

E. Sustainable Manufacturing

The copper-etched fabrication of PCBs and conventional photolithography-based approaches (or subtractive processes) are slowly being replaced by additive manufacturing or printing electronic technologies, so as to improve resource efficiency. In this direction, innovative printing methods, such as contact printing [131], [132], [135], transfer printing [128], [136], [137], roll-based printing [122], [138], screen printing [139]–[141], and inkjet printing, have been developed to realize inorganic nano to chip-scale devices, circuits, and interconnects. The contact printing, for instance, enables the printing of vertically aligned 1-D materials mainly nanowires (NWs) onto the receiver substrate in a highly aligned manner [142]. The transfer printing, on the other hand, allows the integration of laterally aligned photolithography-defined arrays of nano/microstructures using elastomeric stamps [143]. Furthermore, the printing yield can be improved by direct roll transfer printing, which exploits the adhesive strength of the semicured PI layer. In the future, these innovative printing methods can be used to integrate biodegradable high-grade electronic layers on green substrates for the manufacturing of transient ICs. Additive manufacturing techniques, such as filament-based fused deposition modeling (FDM) [144], direct ink writing (DIW) [145], and multimaterial 3-D printing [146], are some other recent developments, which could be explored further for resource-efficient manufacturing of PCBs. Although the copper-based tracks and FR-4 substrates are still used extensively [144], [145], they can be eventually replaced by advanced research, such as a noncontact printing [147] for heterogeneous integration, where the less resistive and mechanically robust interconnections are formed using a high-resolution, noncontact extrusion printing methods [148].

F. Biodegradable Devices

A wide range of biodegradable devices developed using the above materials have been reported in the literature. A few of them are discussed here as such devices are likely to appear on PCBs in the future, leading to zero WPCB issues.

1) Solar Cells: Biodegradable and recyclable high-efficient solar cells are highly desirable for sustainable development as the conventional Si-based solar cell generates WEEE through the formation of photochemical oxidants. Thus, the substrate, electrode, and active layers of solar cells are being replaced by the biodegradable materials, and new-generation of organic solar cells (OSCs) [149], [150] and perovskite solar cells (PSCs) [151], [152] are produced which are having more than one biodegradable layers. However, it is also necessary to have a green fabrication process to overcome the intrinsic toxicity of the solvents used in PVs [24]. Fig. 10(a) shows an example of OSC with chitosan derivatives as cathode interlayer material.

2) Power Supply Circuit: The biodegradable wireless power supply circuit is gaining attention as the power supply is the primary component for any electronic device. An example, of a transient RF power scavenger circuit, is shown in Fig. 10(b). The circuit consists of an RF antenna, resistors, capacitors, inductors, diodes, and so on [153].

3) Organic FET: Biodegradable material-based organic FETs (OFETs) can provide a promising solution for the WEEE issue. An example of OFET shown in Fig. 10(c) uses the polypropylene carbonate (PPC) substrate, which is a biodegradable product of propylene oxide and copolymerization of CO_2 [154]. Other biodegradable materials, such as PLGA [155], CNF [156], and cellulose-based articles [157], are also used as substrates for OFETs.

4) Organic Light-Emitting Diodes: Ecofriendly optoelectronic elements, such as light-emitting diodes (LEDs), are currently fabricated with biodegradable materials for application in the healthcare and automotive sectors. Cellulose is one of the attractive substrate materials for organic LEDs (OLEDs) because of its flexibility, thermal stability, and sustainability. The cellulose nanocrystals (CNCs) [158] [see Fig. 10(d)] and multiwalled CNT-coated cellulose [159] are commonly used substrates, whereas cellulose acetate [160] is reported as encapsulating material for OLEDs. For the electrode in OLEDs, biodegradable silk fibroin (SF) [161], and photopolymer-based SF [162], poly(3,4-ethylenedioxythiophene) (PEDOT):polystyrene sulfonate (PSS)/single-walled CNT-based compound film [163] gives a satisfactory performance in terms of conductivity, and transmittance.

5) Transient Memory Device: Memory is one of the fundamental units for electronic devices, such as mobile, laptops, and cameras, and there is also a growing trend of biodegradable memory devices to reduce the WEEE [164]. For example, magnesium oxide (MgO) nanoparticles mixed with the polyvinylpyrrolidone (PVP) and graphene (as an active layer) have been used to develop transient memristors [165]. Although being a small step, the demonstration of a 4 × 4 crossbar memristor array is an important beginning toward the reduction of the WEEE. Cellulose [166] and silk composite [167] are also reported as substrates for memory devices.

6) Transient Piezoelectric Sensors and Energy Harvesters: With the advent of wearable systems for health monitoring, there is a tremendous need for biodegradable self-powered sensors to monitor the physiological state. To this end, piezoelectric materials have been explored as they can generate

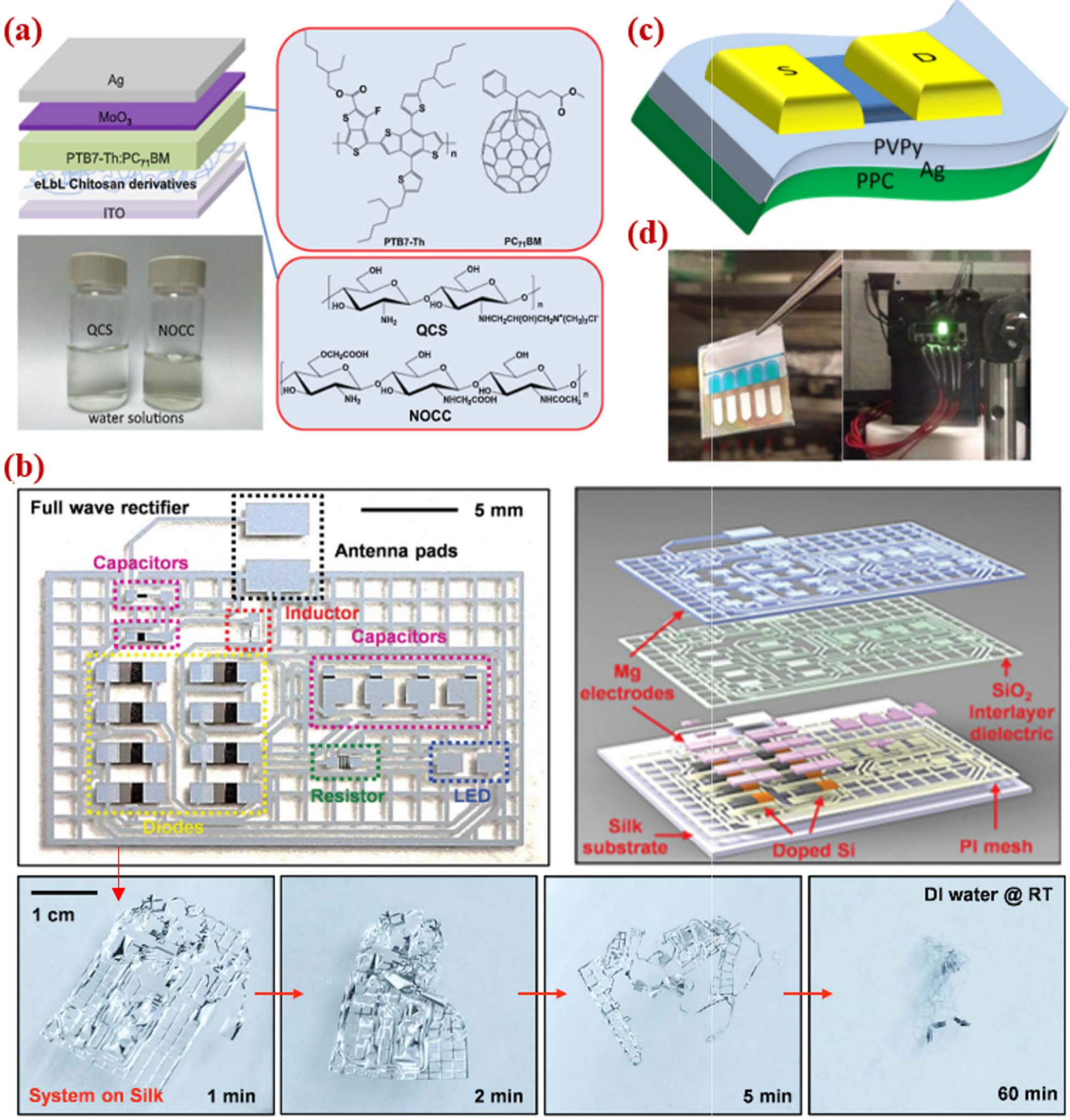


Fig. 10. Examples of biodegradable electronics: (a) OSC with chitosan derivatives as cathode interlayer materials, *reproduced with permission from* [150]; (b) transient RF power scavenging circuits with Si NMs as semiconductors, Mg as electrodes, SiO_2 as interlayer dielectrics, and silk as the substrates, *reproduced with permission from* [153], and biodegradability is proven by immerging the rectifying circuit in deionized water; (c) OFET on PPC substrate, *with Creative Commons Attribution 4.0 International license from* [154]; and (d) OLEDs on CNC substrate mounted on glass (left) and exploded view (right), *reproduced with permission from* [158].

electrical charges under mechanical stress and, hence, can be used for force/pressure sensing applications. The commonly used piezoelectric materials, such as lead zirconate titanate (PZT) and lithium niobate, exhibit strong piezoelectric properties, but they also contain toxic, nonrenewable, and nonbiodegradable components. In this regard, the bio-based piezoelectric materials, such as amino acids, collagen, cellulose, and peptide nanotubes, are attractive as they are biocompatible, renewable, low cost, and simple and low temperature processable [107], [168], [169]. An example of a flexible piezoelectric pressure sensor based on free-standing biodegradable glycine-chitosan film and its dissolution is shown in Fig. 11(c) [169] fabricated by self-assembly of biological molecules of glycine within a water-based chitosan solution, the piezoelectric films in this sensor consist of stable spherulite structure of β-glycine embedded in amorphous chitosan polymer.

7) Energy Devices: Power supplies and energy storage are vital for the operation of any electronic device. However, they are the current major challenge as conventional batteries use nonbiocompatible chemical power, generate environmental pollution, and cause risks to humans [169]–[171]. Sustainable power sources are much needed to reduce WEEE, and important first steps have been taken in this direction as well [172]. For example, the biodegradable triboelectric nanogenerator (TENG) [see Fig. 11(a)], based

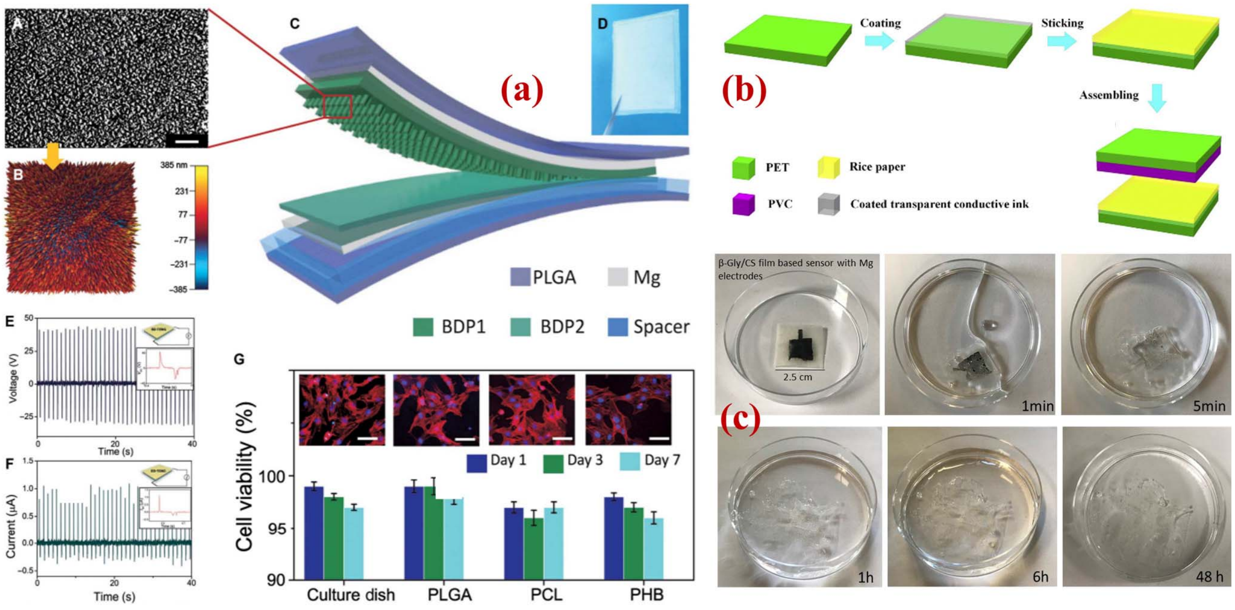


Fig. 11. Biodegradable energy harvesting devices: (a) biodegradable TENG, *with Creative Commons Attribution-NonCommercial license from* [118]; (b) biodegradable TENGs made of powder RP and supports the structure of PVC and PET, *reproduced with permission from* [172]; and (c) glycine-chitosan-based biodegradable piezoelectric sensors and its dissolution, *with CC-BY license from* [169].

on synthetic polymers PLGA, poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), polycaprolactone (PCL), PVA, and resorbable metals, has been reported recently [118]. Natural biodegradable TENGs with all the materials collected from nature, e.g., chitin (from shells of crab and shrimp), cellulose (from wood and cotton), SF from egg and cocoon, rice paper (RP) from wheat, corn, and rice, and egg white (EW), have also been reported recently [173]. Another example of natural polymer-based TENG is RP-TENG, which is made from powder RP and supports the structure of polyvinyl chloride (PVC) and polyethylene terephthalate (PET), and conductive ink-based electrodes [see Fig. 11(b)] [172]. The edible TENGs are also interesting developments toward renewable energy developed with natural materials [172], [174]–[179].

VI. OPPORTUNITIES AND CHALLENGES

There are already significant volumes of PCBs waste that it will take decades to manage material recovery properly. Furthermore, the rise in the use of digital technologies means that more WPCB will need to be handled in the coming decades. Considering these, the recycling and reuse of WPCB are practical ways forward to apply the brake and help delay the arrival of new WEEE. Meanwhile, new approaches, such as degradable electronics, could be explored to complement and bridge the gaps and eventually take over the current recycle and reuse approach in the long term. Thus, the circular electronics connect the recycling and degradable approaches—both at the device and part or system level, as summarized in Fig. 12. By combining these two levels, the device could be designed to confirm the rebirth of the materials and, thus, prevent new waste at its end of life. To build the circular device, it is crucial to determine how the device will be recycled, and accordingly, what materials and manufacturing steps will be incorporated. Some of the potential ways and opportunities are discussed in this section.

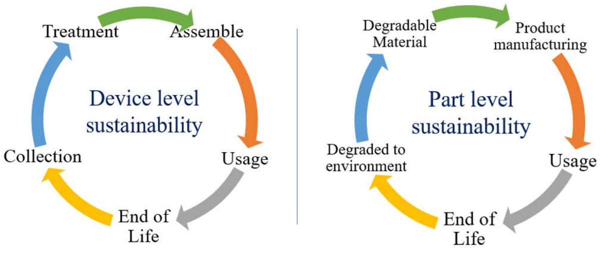
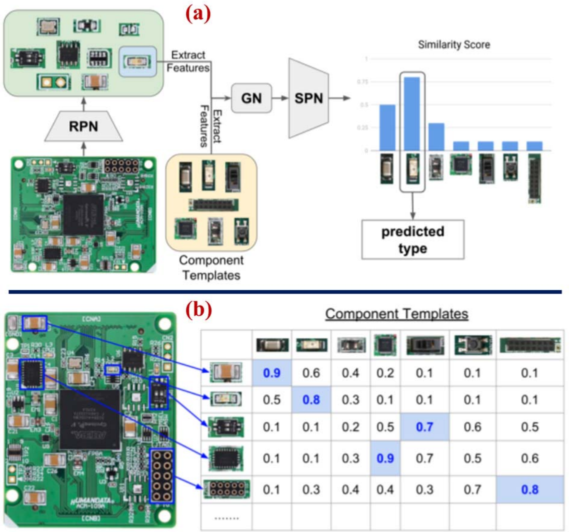


Fig. 12. Device- and part-level sustainabilities of PCB.

A. *Employing Advanced Sensing Technologies for Recycling and Recovery*

Computer vision is becoming a promising technology for efficient and selective recycling of WPCBs [180], [181]. In this method, the distinct features of electronic components or PCBs are recognized optically by their colors, shape, size, and topography [182]. Optical sensors are also employed to accrue the relevant information regarding WPCB. This enables automatic sorting of specific PCBs (such as PCBs from mobile phones and laptops), and preknowledge of mounted components in those PCBs improves the recycling rate by selective recycling of ICs. For example, the presence of particular ICs can be detected, and they can be recycled and reused easily. However, these methods require a high-quality predataset for the smooth classification of the detected components in PCBs. Various machine learning algorithms, such as neural networks [183], principal component analysis [184],



	0.9	0.6	0.4	0.2	0.1	0.1	0.1
	0.5	0.8	0.3	0.1	0.1	0.1	0.1
	0.1	0.1	0.2	0.5	0.7	0.6	0.5
	0.1	0.1	0.3	0.9	0.7	0.5	0.6
	0.1	0.3	0.4	0.4	0.3	0.7	0.8
…….							

Fig. 13. Example of (a) and (b) three-stage neural network algorithm-based PCB sorting for efficient recycling, *reproduced with permission from* [186].

and nearest neighbor [185], reported in the literature for classification, can help automate the recycling process. An example of a three-stage pipelineneural network for PCB sorting is given in Fig. 13. The region proposal network (RPN), the graph network (GN), and the similarity prediction network (SPN) are used here to compute a similarity score for the efficient classification of electronic components on PCB [186].

Multisensor data fusion with the help of blockchain tools is another approach that could advance the recycling and recovery process for WEEE. An example of a multisensor-based segregation process uses three sensors based on visual, near-infrared (NIR), and far-infrared (FIR) sensors [187]. As each sensor images light at different frequencies, different information (attributes) about the plastic waste can be deduced, such as color, physical, chemical compositions, and shapes, all of which contribute to classifying the waste type. Another example of multisensor-driven technology consists of a color-based cullet sorter, where the glass samples are supplied uniformly through a vibration feeder, a high-resolution charge-coupled devices (CCD) line camera measures the quantity of light, and the color sorter collects the color data, which allows for an air nozzle to separate the waste [188]. Using this technology, intelligent robots can be trained for various tasks, such as identification, handling, and segregation of plastic waste [189]. A blockchain tool can also be used to trace the movement of products from manufacturing to their EOL disposal [190]. By this technology, an automatic event can be generated when the device reaches its EOL. Furthermore, they could also be employed to improve the recovery processes, which, otherwise, may lead to additional chemical waste by providing product information at the point of recycling [191]. For example, typical metal recovery processes, such as open burning, produce toxic furans and dioxins. Likewise, the hydrochloric and nitric acid wash for precious metal recovery generates hazardous gas and acid solution. These chemicals eventually contaminate the air, soil, and water body, and leave a serious danger to human health. The recycling process should follow viable design rules as more than 80% of the environmental impact of a product is determined at the design stage [192].

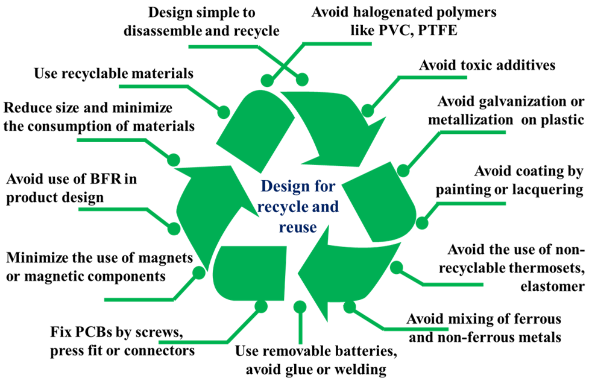


Fig. 14. Key design guidelines for recycling and reuse of PCBs.

B. Sustainable Designs and Degradable 3-D Printed PCBs

The biodegradability-related discussion in Section VI-A indicates that a majority of devices are based on organic materials. The fundamental advantage of using these materials is their availability in viscous solutions, which makes them attractive for direct printing. This also opens new avenues for using resource-efficient manufacture to develop the next generation of ecofriendly PCBs. For example, PCBs manufactured using the conventional metal-etch approach lead to 70k tons of Cu waste in the core etching step [193]. Such wastage could be prevented by printing as also demonstrated in some recent works [144], [146], [194]. However, some of the materials currently in use for printing may still be the same as in conventional PCBs.

For example, FR4 is still used as a substrate for printing conductive tracks using silver paste. As a result, with current approaches, there is limited gain in terms of addressing the issue of WPCBs. This could be improved by using materials that are sustainable and ecofriendly so that the 3-D printed PCB can be made greener and degradable. This approach will advance various initiatives around the world focusing on sustainability and WEEE such as the right to repair and imposing a carbon tax to attain "net-zero." This will be beneficial to consumers and governments, as the reused electronic items are likely to be more affordable. Research shows that up to 50% of users would prefer to use refurbished products [195], [196], and tapping this potential with new business models could generate new jobs and strengthen the (European) economy by an additional €115–325 billion [197].

The greener PCBs will also require sustainable designs, and to this end, there is a need to gain more understanding about the materials, placement of devices, and scalability. Primary challenges in green-PCB involve implementation issues, such as electrical interconnects, materials compatibility, and current-carrying capacity. Accruing a smooth signal conditioning as with copper in conventional PCBs is one of the main challenges as the printed conductive materials usually have

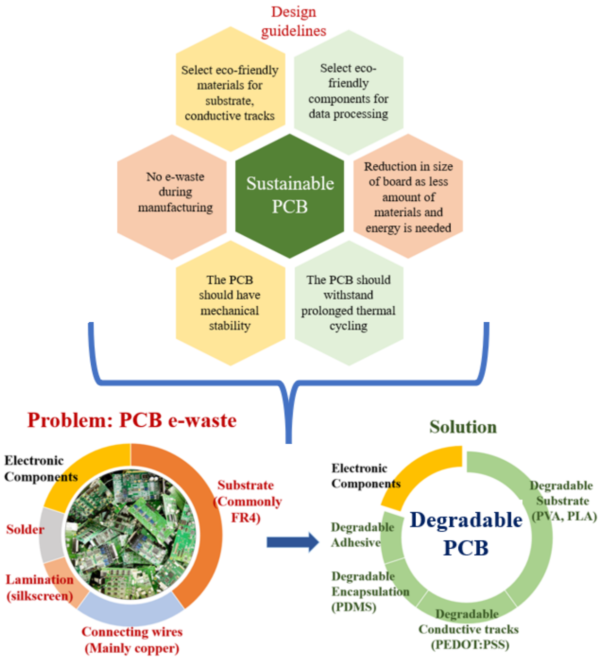


Fig. 15. Design guidelines of future degradable PCBs.

larger sheet resistance. Other challenges lie in maintaining the mechanical and thermal stabilities of the degradable substrate. Therefore, an optimization in materials and methods needs to be carried out carefully. This should start from the prototyping stage itself and then be followed during every fabrication step. For example, one could reduce the number of components on the PCBs by following a design that requires 3-D printing in such a way that the elements such as capacitors become an inherent part of the substrate, instead of soldered distinct elements. This approach has been used to develop a robotic hand with intrinsic sensing and embedded electronics [48]. The synergistic interdisciplinary inputs from material science, electronic engineering, electrochemistry, and environmental engineering are needed to advance such approaches. The PCB design should also consider easy disassembly and embedded sustainability, as summarized in Fig. 14. The design step requires a comprehensive knowledge of both PCB development and recycling processes. Design guidelines of a sustainable PCB and the potential future PCBs are also shown in Fig. 15. When PCB will reach its EOL, the layers of ink, adhesive, and polymers will degrade naturally or be easily recovered, and the electronic components will be available for reuse.

VII. CONCLUSION

Domestic and industrial WEEE is an issue that adversely impacts economic, environmental, and health and, hence, requires urgent attention. Considering the challenges associated with the processing of WPCBs, it is important to explore alternative methods, which can help maintain sustainability without adversely impacting the environment. Green electronics, based on a green manufacturing process and biodegradable materials, could be an effective solution for WEEE management. The circular-economy strategies are worthwhile for the electronics industry to investigate; though numerous business and regulatory challenges must be addressed. As an example, it must be ensured that the full environmental burden based on life cycle assessments of new materials is lower than incumbent technologies. New materials need to be rigorously tested, and potentially certified, for performance, safety, and reliability, as well as designed for repair/reuse. Furthermore, the low environmental impact materials may not provide as much economic value to recycling centers compared to traditional electronics because of their shorter lifetime and lower cost, a problem that is exasperated when coupled with low consumer electronic costs. Nevertheless, the area of ecofriendly materials is particularly pertinent given the rise of flexible, mouldable, and 3-D printed electronics. In all cases, there is an opportunity to "reset" the WEEE problem and deliver products that could substitute the incumbent technologies, creating products with a lower impact environmental profile. By using alternative solutions that will prevent waste through the supply chain (e.g., toxic chemicals, electronic waste, or e-waste), materials that can improve recycling efficiencies, the creation of conditions for workable circular electronics is achievable.

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