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Upcycling E-waste for sustainable innovation: functional materials, toxicity reduction, and circular design

Pranav Prashant Dagwar, Debajyoti Kundu and Deblina Dutta *

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The exponential growth in electronic waste (E-waste) driven by digitalization, urbanization, and rapid technological turnover presents an urgent global challenge due to its complex composition of valuable and toxic materials. While conventional recycling methods often fail to recover critical resources efficiently and contribute to environmental pollution, upcycling has emerged as a transformative approach that not only recovers metals and polymers but also converts them into value-added functional materials. This review provides a comprehensive assessment of the composition and embedded resource potential of E-waste, highlighting the upcycling of printed circuit boards, wires, plastics, and rare earth element-rich components into high-performance catalysts, energy storage electrodes, sensors, and environmental remediation materials. Emphasis is placed on bio-assisted and green processing technologies, including bioleaching, deep eutectic solvents, and biomimetic synthesis, which offer low-impact alternatives for material recovery. The study also integrates life cycle safety, toxicity mitigation, and circular design frameworks to align material innovation with global sustainability goals. Industrial translation challenges, including technological scalability, market readiness, regulatory gaps, and informal sector integration, are critically discussed. By reframing E-waste as a resource-rich feedstock, this review presents upcycling as a viable pathway toward the circular economy transition and sustainable materials innovation.

Environmental significance

The rapid growth of electronic waste poses a significant environmental challenge due to its heterogeneous composition of toxic constituents and different valuable resources. Conventional recycling practices are often energy-intensive or rely on informal methods such as open burning and acid leaching, leading to hazardous emissions, soil and water contamination, and risks to human and ecological health. Upcycling presents a sustainable alternative by converting E-waste into high-value functional materials while reducing landfill dependency and pollutant release. Recovery of critical metals, polymers, and rare earth elements conserves natural resources and lowers the environmental burden of primary extraction. The integration of bio-assisted and green recovery technologies, supported by life-cycle assessment, aligns E-waste management with circular economy and sustainability objectives.

1. Introduction

Rising global population and the constant urge of civilization to march towards digitalization, urbanization, and rapid technological advancements have led to an unprecedented surge in electronic waste (E-waste) generation.[1] As defined by Dey[2] any electronic product or item that has reached its end of life or has fulfilled its purpose and which is deemed no longer necessary for the user can be determined as electronic waste *i.e.*, E-waste. Easy access to resources and global industrialization has made the production chain more rapid, leading to an unprecedented rise in E-waste.[3] According to Elgarahy[3] the global economies have generated an estimate of 62 billion kilograms (62 Mt) of E-waste equivalent in the year 2022 which is an average of 7.8 kg per capita marking a continuous upward trajectory. It was once recorded to be 34 Mt in the year 2010 and projections indicate that global E-waste could reach about 82 Mt by 2030, with generation rising several times faster than documented recycling.[4] Despite growing awareness, only 22.3% of the total generated E-waste has been formally documented as collected and recycled in an environmentally sound manner, leaving the majority subject to informal handling, landfilling, or open burning, particularly in low- and middle-income countries.[1] With the intensified imbalance in E-waste generation and recycling, a stressful gap has developed between them.[2] The growth in E-waste generation across the globe has significantly outpaced improvements in formal recycling rates over the past decade, as depicted in Fig. 1.[4] E-waste has a complex composition of both valuable and hazardous materials including

Department of Environmental Science and Engineering, SRM University-AP, Amaravati, Andhra Pradesh, India. E-mail: deblina.d@srmap.edu.in

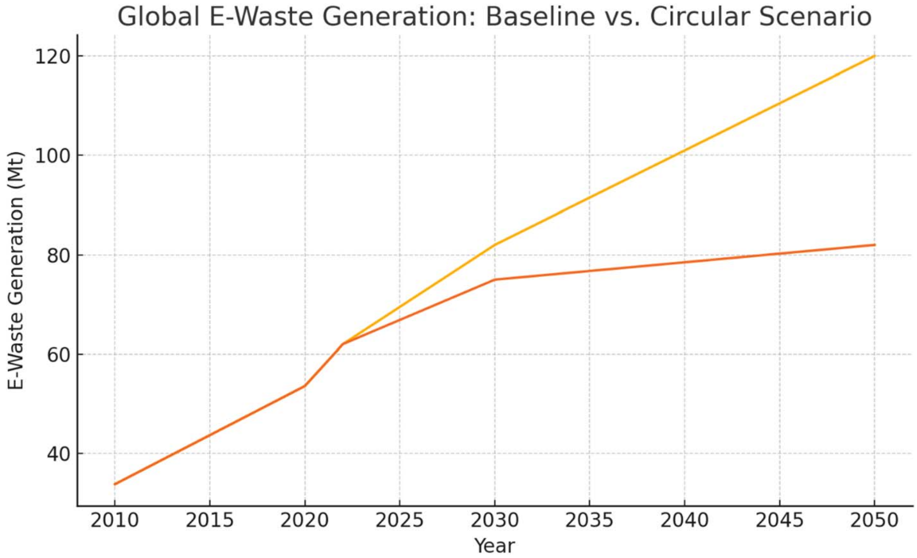


Fig. 1 Global trends in E-waste generation and formal recycling rates (2010–2050).

different metals, plastics, wires, glasses, ceramics and other components.[5] According to Elgarahy[3] E-waste has been distributed into different electronic items including household appliances, IT and telecom devices, consumer electronics, and other electronic materials, in which the composition has been distributed as over 60% of metals, 15% of plastics, metals and plastic mixtures of 5% and other components of 20%. As reported in the Global E-waste Monitor[4] it has been estimated that in the year 2022, 31 Mt of metals, 17 Mt of plastics, and 14 Mt of other components such as glass and ceramics were found in different discarded E-waste items. Despite the economic potential valued at USD 91 billion, with copper (USD 19 billion), gold (USD 15 billion), and iron (USD 16 billion) forming the largest shares, this potential remains largely untapped due to insufficient collection and recovery systems.[4,5]

According to the reports by the Global E-waste monitor[4] developed economies are found to be the highest producers of E-waste products, with regions like Europe producing 17.6 kg per capita, followed by America at 16.1 and Oceania at 14.1 kg per capita respectively, yet only Europe exceeds 40% in documented recycling rates.[1,4] In contrast to the developed regions of the globe, the developing regions such as the Asian continent, are the largest total generators of E-waste at 30 Mt, followed by Africa, with the lowest recycling infrastructure, struggling with proper waste management and policy enforcement.[1] The regional distribution of E-waste generation and formal recycling rates in 2022 along with the projected production until 2030 is summarized in Table 1, highlighting the disparity between developed and developing regions in both volume and collection efficiency.[4]

This trend reflects over-consumption and planned undesirability, whereas the persistent digital divide shows a lack of access to basic technology for millions across the globe.[6] As described by Sandwal[7] the low recycling ratio amplifies environmental and health hazards, particularly from toxicants such as lead, mercury, cadmium, and brominated flame retardants released into the environment.[7] In developing nations informal recycling processes are found to be extremely vulnerable as they expose vulnerable populations, including children and women, to long-term health risks such as cancer, neurotoxicity, and reproductive disorders.[7,8] Conventional E-waste disposal practices such as open burning, acid leaching, landfilling, crushing, grinding, screening, and sieving generate severe environmental and human health impacts through toxic releases, hazardous dust, and persistent contamination. The environmental and human health impacts associated with these traditional disposal and recycling practices are illustrated in Fig. 2.[9]

Table 1 Regional distribution of E-waste generation and recycling rates in 2022 and projected share in 2030 (ref. 1 and 4)

Region/continent	E-waste (2022, Mt)	Projected 2030 (Mt)	Share of global total (%)	Per capita (kg, 2022)	Growth trend
Asia	32.7	43	53%	6.7	+6% per year
America	10.5	14	17%	13.0	Moderate
Europe	9.3	12	15%	17.6	Slow
Africa	2.5	4.5	4%	2.1	Slow
Oceania	∼0.7	∼1.0	1%	17–19	Stable
Global total	62 Mt	82 Mt	100%	7.8	+5.7% YoY

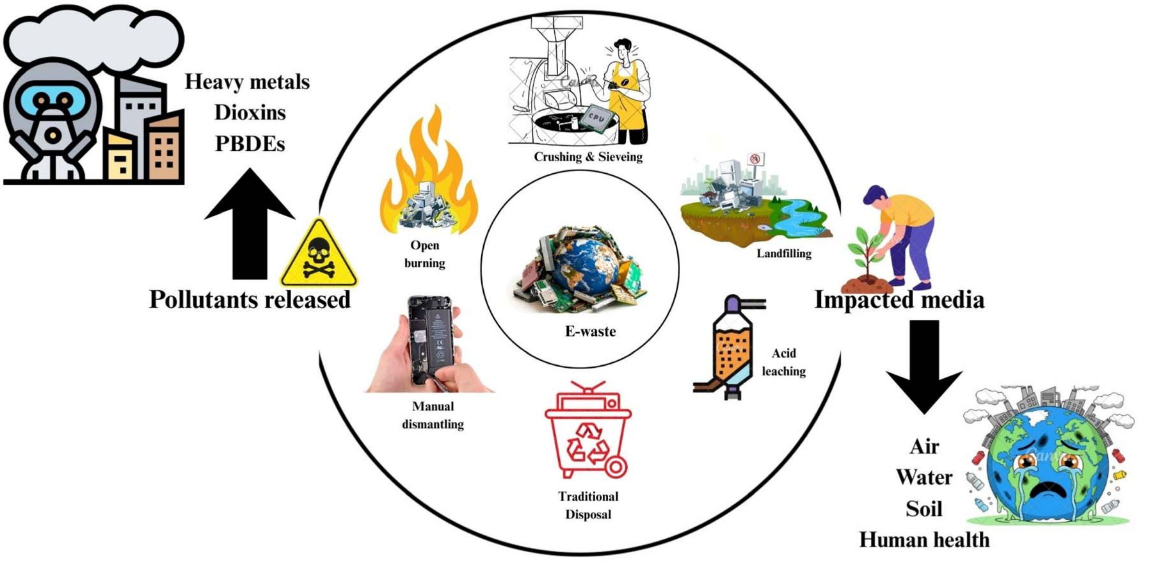


Fig. 2 Environmental and human health impacts associated with traditional and conventional E-waste disposal methods such as open burning, acid leaching, and landfilling.

Different precious and rare earth elements are found in E-waste which often exist at higher concentrations than in mined ores; for instance, in smartphone PCBs the concentration of gold is found to be 1071 ppm whereas in the primary ores it is observed to be merely 5.29 ppm making E-waste a veritable "urban mine".[10] It has been estimated that over 80% of E-waste doesn't get recycled despite the clear economic and environmental advantages.[1] According to Dagwar[11] E-waste is an opportunity as it represents a potential source of critical raw materials, despite being a crisis for the global nations in terms of pollution and health risk. Recycling opposes sustainability. Different researchers have considered upcycling as a new unconventional method towards recycling opposing the conventional or traditional recycling methods, offering a novel path forward transforming waste into value-added functional materials while supporting environmental sustainability, circular economy goals, and the recovery of critical resources.[12,13] As described by Iqbal[14] the recycling sector has seen a significant rise due to the skyrocketing demands to meet the supply of electronic items into the urbanized market. Conventional E-waste recycling methods face significant limitations due to various challenges in dismantling complex modern products, with intensive limitations in terms of environmental safety, resource efficiency, and social sustainability.[10] In many low- and middle-income countries, widespread use of informal practices such as open burning, manual dismantling, and acid leaching remains persistent, leading to the release of hazardous substances like lead, mercury, cadmium, brominated flame retardants, dioxins, and furans into the environment.[1,8] These pollutants contaminate soil, air, and water and pose severe health risks including respiratory issues, neurotoxicity, reproductive disorders, and cancer, especially for unprotected workers and nearby residents.[15] Current recovery technologies often operate with low efficiency, particularly in informal settings or with outdated techniques despite the presence of valuable materials in E-waste such as gold, copper, palladium, and rare earth elements.[9] Moreover, conventional recycling processes are also resource- and energy-intensive, with transportation and logistics adding to costs and carbon footprints, while insufficient infrastructure and underinvestment restrict scalability.[16] Conventional techniques include the pyrometallurgical process which is an energy intensive method used in formal sectors. This method uses high thermal treatment which emits toxic gases if not well-controlled,[17] whereas the hydrometallurgical process utilizes different solvents and aqueous solutions to recover metals from E-waste.[11] The lack of proper infrastructure, economic incentives, energy resources, equipment and regulatory enforcement further limits the adoption of safer and more efficient recycling practices, especially in developing nations.[18] E-waste is a rich reservoir of metals such as Au, Ag, Cu, Pd, different rare earth elements and polymers that can serve as precursors for advanced materials when processed through innovative approaches like green synthesis, selective leaching, or bio-assisted techniques.[5,19] As described by Gollakota[20] the adoption of sophisticated E-waste recovery methods such as bioleaching, upcycling, and green-solvent processing remains severely constrained in developing countries due to barriers like those faced by conventional recycling systems. Critical limitations have been observed in infrastructure and equipment such as specialized bioreactors, controlled environments for enzymatic recovery, and precision separation tools that are largely unavailable in countries like India, Ghana, and Nigeria which is reinforcing dependence on informal dismantling practices.[21] The absence of modular and scalable infrastructure further makes it a challenging task for transitioning from pilot-scale techniques into full-scale operations, whereas the economic constraints present a challenge for these nations.[9] High capital

Table 2 LCA-based comparison of environmental impacts for PCB processing routes[26,27]

Route	GWP (kg CO_2e)	Energy use (MJ)	Toxicity indicators	Key characteristics
Pyrometallurgy	15–45	150–400	High	High-temperature furnaces and slag and flue-gas treatment
Hydrometallurgy	8–25	80–200	Medium–high	Acid leaching and wastewater treatment dependent
Upcycling (component reuse + recyclable PCB)	~5–10	30–80	Low	Direct functional reuse; reduced material and chemical inputs
Upcycling *via* bio/DES routes	~2–12	25–80	Low–very low	High selectivity, solvent reuse, and minimal emissions

investment plays a very crucial role in technologies such as biotemplating and hydrometallurgical processing particularly in markets where existing incentive subsidies and tax exemptions cannot offset the low cost of virgin materials.[22] As studied by Liu[17] different regulatory weaknesses hinder the progress, due to the limited enforcement of different frameworks such as Extended Producer Responsibility (EPR) which allows the informal sector to dominate E-waste handling, thereby marginalizing formal initiatives that employ advanced recovery methods, whereas the inadequate coordination among different governmental, industrial, and research sectors restricts the flow of technical knowledge needed for effective technology transfer.[23] Addressing these systemic barriers requires the development of hybrid recovery models that formally integrate informal-sector workers, the mobilization of targeted international funding to support pilot-scale demonstrations, and the design of tailored economic incentives that can catalyze broader adoption of advanced upcycling technologies.[24] While traditional recycling methods often reduce electronic waste into base materials through energy-intensive processes, upcycling offers a more sustainable and innovative alternative by converting E-waste into functional materials of higher value.[10,11] Unlike conventional techniques that commonly degrade material quality, upcycling aims to retain or enhance material properties by transforming waste streams into catalysts, sensors, electrodes, or structural composites thus aligning with the principles of a circular economy.[9,19] It has been studied that upcycled E-waste has been successfully used to fabricate supercapacitor electrodes with high electrochemical performance, sensors for environmental monitoring, and catalytic supports for industrial reactions.[9] Compared to conventional recycling, upcycling significantly reduces environmental burdens.[3] Upcycling eliminates the need for energy intensive smelting and mitigates the release of toxicants like dioxins and heavy metals often generated during incineration or acid leaching.[15] Moreover, it enables localized value recovery, which is important for regions lacking centralized high-tech recycling infrastructure thereby promoting decentralized circularity and green entrepreneurship.[4] Furthermore, functional reuse supports design innovations such as modularity, remanufacturing, and extended product life.[2] Upcycling E-waste not only conserves resources but also transforms the waste paradigm shifting from end-of-life treatment to materials valorization thus integrating environmental sustainability with technological innovation.[25] Upcycling embodies the principles of a circular economy, transforming what would otherwise be discarded into products with renewed purpose and meaning. Global policy trends increasingly recognize these advantages: the EU Circular Economy Action Plan and India's E-waste Management Rules (2022) now advocate for eco-design and material circularity over linear material flows.[1,4] It can be understood that upcycling demonstrates substantially lower environmental burdens, with life cycle assessments reporting 50–63 percent reductions in global warming potential, 30–70 percent lower energy consumption, and an 84 percent reduction in marine aquatic ecotoxicity compared with conventional recycling, highlighting its superior environmental performance,[26] whereas bio-based and deep eutectic solvent (DES)-assisted recovery and upcycling pathways show consistently low environmental footprints, typically within 2–12 kg CO_2e and 25–80 MJ per kg PCB, corresponding to approximately 60–70% lower GWP and ~70% lower cumulative energy demand relative to pyrometallurgical processing. Toxicity indicators are reduced by 80% or more, primarily due to avoided high-temperature emissions, reduced mineral acid use, and solvent recyclability.[27] Table 2 highlights the comparison of environmental impacts related to processing of PCBs.

This study explores the potential of upcycling E-waste into functional, high-value materials through environmentally conscious and technologically advanced approaches, moving beyond conventional recycling, which often prioritizes bulk recovery, highlighting the untapped resource potential of E-waste for applications such as electrocatalysts, energy storage materials, environmental sensors, and soil conditioners. The work reviews material composition, bio-assisted and green processing strategies, and circular design principles, while addressing toxicity mitigation, life cycle safety, and regulatory challenges. By integrating insights from materials science, environmental engineering, and policy, the study highlights how upcycling can simultaneously tackle resource depletion, pollution, and waste mismanagement, while supporting innovation, market readiness, and global sustainability goals.

2. E-waste composition and resource potential

Electronic waste constitutes a complex, multi-material urban ore dominated by metals and plastics, with metal grades that frequently exceed those of primary mineral ores.[1] On an aggregated mass basis, E-waste is composed primarily of iron and steel (∼50%), followed by plastics (∼20–30%) and non-ferrous metals (∼10–15%), mainly copper, aluminum and other REEs.[28] When compared to a device-level, it has further been highlighted that its high metal density, such as desktop computers roughly containing 43–44% metals, is substantially higher than most municipal or industrial waste streams.[11] This different non-ferrous fraction includes elements such as copper, aluminum, lead, tin, zinc, and nickel, with copper acting as a major value driver holding the electronic item together.[14] In printed circuit boards, copper contents commonly reach 15–20 wt%, whereas precious metals such as gold, silver, palladium, and platinum occur at ppm to sub-wt% levels.[28] These precious elements dominate intrinsic value, with copper and precious metals together accounting for up to ∼90% of PCB material value.[5] E-waste also contains critical and strategic elements including elements such as cobalt, indium, antimony, and REEs, particularly in magnets and phosphors.[11] However, global REE recovery from E-waste remains below 5%. The metals embedded in 2022 E-waste are valued at approximately USD 90–95 billion, yet current systems recover only a fraction, with <60% of copper and ∼20% of precious metals effectively recycled.[4] E-waste represents a strategically important secondary resource, justifying targeted recovery and advanced upcycling within circular-economy frameworks.

2.1. Metallic fractions in PCBs and wires

According to Marques,[29] the constant rise in the production of different electronic devices and persistent technological advancements lead to a surge in E-waste. Printed circuit boards (PCBs) and internal wiring are among the most valuable fractions of E-waste due to their high content of precious and base metals.[30] PCBs typically contain more than 40 elements, with concentrations that often far exceed those found in primary ores.[17,31] In PCBs the metals account for roughly 30–40% of total weight, dominated by copper (16–25%) used in tracks, connectors, and base plates, alongside tin-based solders, iron, nickel, and chromium in structural and contact components.[1] Though present in trace amounts, precious metals such as gold, silver, and palladium add significant recovery value, while minor metals like aluminum and zinc play additional structural and conductive roles.[29] Table 3 provides the metallic fractions in PCBs with approximate ranges and their primary roles.

Au and Pd occur at concentrations of 100–250 ppm and 5–10 ppm respectively, levels up to 50–100 times higher than those in natural deposits.[34,35] It is estimated that the total recoverable value of metals from E-waste globally surpasses USD 57 billion annually, with PCBs contributing disproportionately to this total.[36] Mobile phones, computer motherboards, and TV PCBs exhibit particularly high concentrations of precious metals, which make them prime targets for urban mining.[37] Table 4 provides representative metal concentrations found in different E-waste components, demonstrating the potential of PCBs and wires as a high-grade secondary resource.

In addition to their economic value, the recovery of metals from E-waste is also environmentally beneficial. When compared to primary mining, recycling metals from PCBs saves significant amounts of energy and reduces greenhouse gas emissions.[17] With PCBs holding a central position in all the electronic devices, the inclusion of additional E-waste categories such as household appliances, information devices, and medical equipment expands the spectrum of urban mining opportunities, as these streams collectively account for roughly 60 percent of global E-waste generation, such as appliances: 42 percent, small IT: 10 percent, and medical: 2–5 percent.[5] The richness of metals varies significantly, shaping targeted recovery and upcycling strategies.[38] As described by Jandric[39] household appliances are dominated by ferrous metals (50–65 percent Fe/steel) with moderate Cu content, providing high-volume but low-precious metal yields that suit bulk recycling into construction steel or wiring, while compressors and motor magnets offer selective REE recovery. As described by Holgersson[38] information devices such as smartwatches, printers, and routers contain concentrated Cu (up to 25 percent) and precious metals comparable to those in mobile phones, making them attractive for high-value upcycling pathways including catalyst and sensor fabrication.[23] Medical equipment represents a critical hotspot for REEs, with neodymium–iron–boron (NdFeB) magnets enriching components in monitors, MRI, and CT systems at levels 10–100 times higher than those in typical consumer electronics, highlighting its strategic relevance for circular supply chains amid global supply risks.[5] Table 5

Table 3 Metallic fractions in PCBs[32,33]

Metal	Approx. fraction (by weight)	Primary role in PCBs
Copper (Cu)	∼16–25%	Tracks, connectors, and base plates (primary conductor)
Tin (Sn)	∼3–4%	Solder (often alloyed with Pb or Ag)
Lead (Pb)	∼0–4%	Older solder compositions
Silver (Ag)	∼0.05–0.2%	Contacts, solder, and multi-layer capacitors
Gold (Au)	∼0.03–0.1%	Contacts, connectors, and surface plating
Palladium (Pd)	∼0.01%	Multi-layer ceramic capacitors and connectors
Iron (Fe)	Part of ∼3–5% (with Ni and Cr)	Transformer cores and mechanical parts
Nickel (Ni)	Part of ∼3–5% (with Fe and Cr)	Contacts, coatings, and alloys
Chromium (Cr)	Part of ∼3–5% (with Fe and Ni)	Structural alloys and corrosion resistance
Aluminium (Al)	Trace – minor fraction	Structural support and conductive roles
Zinc (Zn)	Trace – minor fraction	Coatings and alloys
Other minor metals	Trace	Antimony, bismuth, *etc.* (in solders or flame retardants)

Table 4 Concentrations of key metals in various E-waste components

Device type	Cu (wt%)	Au (ppm)	Ag (ppm)	Pd (ppm)	References
Mobile phone PCB	12–20	200–300	100–200	8–10	17
TV circuit board	10–15	80–150	70–120	5–7	34
Computer motherboard	18–25	200–250	150–200	6–8	31
Wire/cable (Cu core)	40–90	<1	<1	<1	17

Table 5 Typical metal composition ranges for selected device categories[5,17,38]

Device category	Dominant metal fractions	Critical/valuable elements
Refrigerators	Fe ∼50–65%, Cu ∼10–20%, and Al ∼5–10%	Precious metals typically at trace levels; minor Nd/Pr in motor magnets
Washing machines	Fe ∼45–60%, Cu ∼6–12%, and Al ∼10–20%	Low precious metal content with bulk metals to dominate recovery value
Routers/mini-IT PCBs	Cu ∼15–20%, Fe ∼1–5%, and Al ∼3–8%	Au often at 200–1000 ppm, Ag >1000 ppm, and Pd in tens of ppm
Printers/MFDs	Cu ∼10–20% (in PCBs) and high Fe in frames and motors	Au and Ag typically in the low hundreds of ppm
Smartwatches	High-density PCBs with Cu comparable to that in smartphones	Au, Ag, and Pd present in connectors and coatings; low absolute mass per device
Patient monitors and similar medical devices	Cu-rich PCBs plus magnet assemblies	NdFeB or SmCo magnets lead to very high localized REE concentrations

provides representative figures of metal fractions in household electronics.

These gradients highlight clear recovery priorities: appliances for large-scale Cu/Fe recycling, small IT devices for PM-rich bioleaching or hydrometallurgical upcycling, and medical systems for advanced REE recovery.[22,40] The resulting economic hierarchy ranges from bulk recovery worth $1200–2500 per tonne to high-value upcycling streams reaching $10 000–25 000 per tonne, reinforcing both the economic viability and life-cycle advantages of differentiated processing. This evidence supports policy expansion of Extended Producer Responsibility (EPR) frameworks to include appliances and medical electronics, which currently achieve less than 20 percent formal collection in India and collectively reveal a $100–300 billion global urban mining opportunity. However, challenges remain in achieving high recovery efficiencies, especially in informal recycling

Table 6 Uses of different plastic types in electronic products[31,34,42]

Plastic type	Common applications in electronics	Key properties	Associated concerns
FR-4 (epoxy resin and glass-reinforced)	PCB substrates	High thermal stability and strong insulation	Difficult to recycle and often combined with toxic flame retardants
Acrylonitrile butadiene styrene (ABS)	Casings and housings	Tough, impact-resistant, and easy to mold	Non-biodegradable and may release toxic fumes when burned
Polycarbonate (PC)	Lenses, screens, and enclosures	Transparent, strong, and heat-resistant	BPA concerns and poor recyclability
Polyamide (PA/nylon)	Connectors and cable ties	Durable and abrasion-resistant	Energy-intensive to produce and limited recyclability
Polyethylene (PE)	Wire insulation, cable harnesses	Flexible, light weight, and good insulation	Persistence in the environment and microplastic pollution
Polyvinyl chloride (PVC)	Cable sheathing and insulation	Flexible and flame-resistant (with additives)	Releases dioxins and chlorine compounds when burned; toxic additives
Polybutylene terephthalate (PBT)	Connectors and housings	High strength and electrical insulation	Difficult to recycle and often blended with flame retardants
Polyethylene terephthalate (PET)	Films, insulation, and casings	Light weight, strong, and transparent	Downcycling is common and can retain contaminants
Polymethyl methacrylate (PMMA)	Displays and light guides	Transparent and scratch-resistant	Brittle, low chemical resistance, and limited recycling options
Flame retardants (BFRs and OPFRs)	Added across many plastics	Fire safety and thermal stability	Persistent, bioaccumulative, toxic and health and environmental risks

sectors where primitive techniques lead to environmental contamination and health hazards.[1]

2.2. Plastic components and flame retardants

According to Westec[41] plastics are considered essential to the structure and safety of modern electronics, providing insulation and mechanical support. Plastics constitute a significant fraction of electronic waste, accounting for approximately 15–25% of the total E-waste mass depending on the device category.[31,34] The most encountered polymers in E-waste include high-impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS), polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). These plastics are used in casings, connectors, circuit board laminates, and insulation for wires and cables.[42] Table 6 explains the use of different plastics in electronic devices.

The plastic components present in E-waste are frequently treated with flame retardants particularly brominated flame retardants (BFRs) such as tetrabromobisphenol A (TBBPA), decabromodiphenyl ether (DecaBDE), and hexabromocyclododecane (HBCD) to test and implement fire safety functionality.[43] While these additives increase fire resistance, they also present serious environmental and health risks, particularly when released through informal recycling processes like open burning or low temperature dismantling.[31,34] The co-presence of polymers and toxic additives complicates the recycling of E-waste plastics.[44] Techniques such as compatibilizer blending, pyrolysis, or incorporation into polymer composites and geopolymers have been explored to valorize these materials while mitigating environmental risks.[31] However, challenges remain in completely removing or neutralizing BFRs during processing due to their tendency to migrate into household dust, water, and food chains and to be released during unsafe E-waste recycling intensifies both occupational and environmental hazards, especially in informal sectors.[1,45] Regulatory efforts, particularly in the EU and US, have already restricted some of the most hazardous flame retardants, driving innovation toward safer alternatives and clearer material labelling.[46]

2.3. Rare earth elements and critical metals

Rare earth elements (REEs) are a group of different metallic elements, comprising 17 lanthanides along with scandium and yttrium, which are essential for many modern and green technologies including electric vehicles, wind turbines, permanent magnets, LED lighting, and smartphones.[11,42] Regardless of their technological importance, the recovery of REEs from end-of-life electronics is often observed in low concentrations, due to their complex bonding matrices and the lack of mature recovery infrastructure.[35] Electronic waste offers a promising secondary source of REEs, especially from components such as NdFeB magnets in hard drives, phosphors in display screens, and lamp powders.[47] However, less than 1% of global REE demand is currently met through recycling.[48] This contrasts sharply with the increasing demand, which is projected to exceed 190 000 tonnes annually by 2026, driven largely by the clean energy transition.[11] Recent studies have shown that REEs like yttrium (Y), lanthanum (La), and gadolinium (Gd) are enriched in the finer particle fractions of mechanically pre-treated waste PCBs, suggesting that size-selective separation could enhance recovery yields.[35] Table 7 gives a detailed

Table 7 Rare earth elements (REEs) and critical metals in E-waste, their common sources, applications, and recovery significance[11,49]

Element/metal	Main sources of E-waste	Key applications	Recovery significance
Neodymium (Nd)	Hard disk drives, speakers, and magnets	Permanent magnets (EV motors and wind turbines)	High-value REE and critical for clean energy tech
Dysprosium (Dy)	Magnets in HDDs and EV motors	Enhances magnet heat resistance	Vital for EVs and renewable energy
Terbium (Tb)	Magnets and phosphors	Green phosphors and magnet alloys	Limited global supply
Europium (Eu)	Lamp phosphors and displays	Red/blue phosphors in screens & lighting	Critical for display tech and concentrated supply
Yttrium (Y)	Phosphors, LEDs, and lasers	Optical materials and displays	High demand for energy-efficient lighting
Lanthanum (La)	Batteries, optics, and displays	Rechargeable NiMH batteries and camera lenses	Important for optics and storage devices
Cobalt (Co)	Lithium-ion batteries	Cathode material in batteries	Critical for battery supply chains
Lithium (Li)	Batteries	Energy storage (LIBs and EVs)	Essential for energy transitions and limited reserves
Nickel (Ni)	Batteries, alloys, and PCBs	Battery cathodes and structural alloys	Economically valuable and widely used in LIBs
Gallium (Ga)	Semiconductors and LEDs	Integrated circuits and photovoltaics	Critical for electronics & solar technologies
Indium (In)	LCDs and touchscreens	Indium tin oxide (ITO) coatings	Key for displays, rare and supply-sensitive
Tantalum (Ta)	Capacitors (PCBs and phones)	High-performance capacitors	High-value metal and vital for miniaturized electronics
Gold (Au)	PCBs and connectors	Conductors and corrosion-resistant contacts	High economic value and a critical recovery target
Silver (Ag)	PCBs, switches, and solders	Conductors, solders, and sensors	Valuable and widely recoverable
Palladium (Pd)	Multi-layer ceramic capacitors and connectors	Catalysts, sensors, and electronics	High-value, scarce precious metal

understanding about the application of REEs in electronic devices. However, extraction technologies such as hydrometallurgy, bioleaching, and ion-exchange resins are still being optimized for economic and environmental performance.[42] Recovering REEs from discarded electronics not only mitigates supply chain risks but also reduces the toxic footprint of mining while securing inputs for green technologies.[11]

As per Keal[48] the strategic importance of REEs and other critical metals like cobalt, indium, and antimony has led to increasing interest in circular economy approaches that prioritize material recovery from end-of-life electronics, supported by digital tracking and eco-design principles. By turning E-waste into a secondary source for these critical resources, research can build more resilient supply chains, support renewable energy transitions, and significantly cut the environmental costs of technology, making waste a cornerstone of sustainable progress. Fig. 3 below illustrates the growing global demand for REEs and the current recovery potential from E-waste sources, highlighting the urgency and opportunity for developing scalable recycling solutions.[31,42]

3. Strategies for upcycling E-waste into functional materials

With the need for functional materials observing a rise in the upcycling of E-waste, it has seen a steep rise in recent years.[50] Based on targeted separation and transformation pathways it can be converted into metal- and carbon-rich fractions such as catalysts, energy-storage electrodes, and sensor platforms.[51] With appropriate designs these routes can deliver materials with performance comparable to that of conventionally synthesized items and can exhibit lower environmental footprints than both primary material production and conventional recycling.[52] Metal recovery-to-catalyst pathways represent one of the most developed upcycling strategies.[10] Metals recovered from printed circuit boards and connectors are transformed into oxides, alloys, metal–organic frameworks or supported nanoparticles,[53] whereas carbon and composite recovery pathways focus mostly on converting carbonaceous fractions from spent supercapacitors, plastics, or mixed E-waste into porous carbons, reduced graphene oxide, or carbon–metal composites.[17] Different materials are reused from the recovered pathways with the structural integrity of glass, polymer, and metal components recovered from displays, PCBs, and printed electronics.[54] As described by Carpnell[55] these different materials which are refurbished into functional materials for electrochemical and resistive sensors present a closed-loop approach in which end-of-life sensor components are remanufactured into new conductive or insulating filaments. Routes which involve green processing techniques such as hydrometallurgy, bioleaching, and deep eutectic solvent-based extraction can provide selective metal streams under milder conditions and reduced toxicity relative to strong-acid leaching.[56] The combination of high copper and precious-metal grades, recoverable carbon fractions, and specialty metals gives e-waste significant circular-economy value.[57] As described by He[58] meta-analyses indicate that when upcycled materials displace raw catalysts or electrodes, life-cycle assessments have frequently reported 50–70% reductions in global warming potential and energy demand relative to pyrometallurgical or conventional hydrometallurgical routes.[50] Collectively, this can support repositioning E-waste from a disposal challenge to a strategic feedstock for high-performance functional materials within circular-economy frameworks.

3.1. Metal recovery and catalyst fabrication

The valorization of metals from E-waste for catalyst fabrication is emerging as a key pathway within the broader paradigm of sustainable materials chemistry and the circular economy.[59] According to Grandhi,[1] E-waste is a complex matrix composed of metal-rich components such as PCBs, central processing units (CPUs), capacitors, mobile phones, batteries, and even printed inks. These components contain critical and precious metals all of which are essential for industrial catalysis but suffer from limited geological availability and high extraction costs.[2] Conventional recycling often focuses on bulk metal

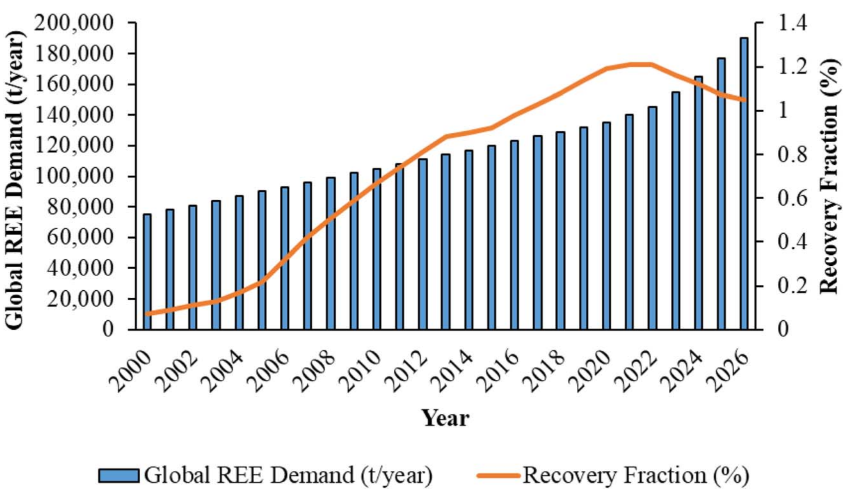


Fig. 3 Global demand for REEs and the current recovery potential from E-waste sources.[11]

recovery *via* smelting or acid leaching, and these processes are energy-intensive and environmentally damaging.[14] As per Xia and Ghahreman[10] upcycling these metals directly into functional catalysts presents a high-value, low-footprint solution by eliminating the intermediate step of refining and transforming waste streams into active materials for chemical synthesis, energy conversion, and environmental remediation. Recovery of gold from PCBs and its transformation into homogeneous catalysts can be considered a prominent case of high-value metal upcycling, as McCarthy[60] developed a ligand-assisted solvometallurgical method that selectively extracts Au(III) ions from shredded electronic components under mild conditions. The recovered gold was subsequently complexed into organometallic frameworks capable of catalyzing oxidative coupling reactions with high selectivity, stability, and recyclability, all while avoiding the use of aqua regia or cyanide-based leaching. Building upon selective recovery principles, Zadehnazari[61] demonstrated the use of CO_2-assisted carboxylation of alkynes using Au(III)-embedded covalent organic frameworks (COFs) fabricated from CPUs. The COF structure enhanced stability and electron transfer, while enabling photochemical activation. This innovative route supports valorization of gold from E-waste and simultaneously supports carbon capture and utilization. In a shift from metal refinement to direct reuse, Ryabchuk[62] recovered copper from mobile phone PCBs and employed it directly in hydrogenation catalysis following physical fragmentation and thermal processing. The resulting Cu-based materials exhibited high activity and reusability in the selective hydrogenation of nitroarenes, illustrating the potential of minimal pre-treatment pathways for E-waste-derived catalysts. Similarly, Hossain and Sahajwalla[50] proposed a green smelting approach using hybrid electric arc furnaces to extract Cu and Fe from multi-component E-waste such as cables and PCBs. The recovered metals are directly used to fabricate functional matrix composites and iron-based catalysts suitable for high-temperature applications. The use of embedded plastics as reducing agents further reduced the need for external reagents and minimized slag generation. Mechanochemical techniques offer a solvent-free, scalable route for upcycling non-metallic and ceramic-rich E-waste fractions. Niu[63] utilized one-step ball milling to produce self-doped $BaTiO_3$ catalysts from discarded capacitors and then synthesized photocatalysts which demonstrated high efficiency in dye degradation and organic pollutant breakdown under visible light. This method avoided energy-intensive calcination or precursor synthesis, making it especially attractive for low-resource settings. Beyond metals, non-metallic E-waste components such as plastics, glass fibers, and ceramics have also been utilized as catalyst supports or active-matrix materials.[64] As Paone and Mauriello[65] demonstrated polymeric or oxide-rich battery components could serve as dopants or structural templates in mixed-metal oxide catalysts. This can be shown using Co- and Ni-containing residues from lithium-ion batteries that were thermally treated with ceramic substrates to produce redox-active materials suitable for heterogeneous oxidation reactions. The diversity of E-waste sources, recovery strategies, and catalyst types is summarized in Fig. 4, highlighting the potential of upcycling to drive circular innovation across multiple chemical applications and it also provides the understanding of different upcycling pathways for metal recovery from E-waste into functional materials.

According to Farooq[66] it can be further extended in concept by recovering Ni, Co, and Cu from discarded batteries and converting them into bimetallic nanoparticles for catalytic water treatment. These catalysts exhibited superior performance in degrading pharmaceutical contaminants and retained structural integrity over multiple cycles, outperforming their monometallic analogs. An innovative electronic-ink upcycling approach was introduced by Zhang,[67] in which the study recovered silver from printed E-waste using low-temperature plasma methods. Ag nanoparticles were integrated into flexible membranes that acted as on-chip catalytic microreactors. These systems enabled real-time reaction monitoring and miniaturized synthesis, opening new applications in bio-catalysis, lab-on-chip technologies, and portable chemical diagnostics. These collective advancements reflect a transformative shift in E-waste management from traditional bulk recycling to functional upcycling strategies that prioritize value creation.[3] Rather than returning recovered metals to the conventional supply chain, these approaches engineer metals and other active components directly into advanced catalytic systems.[64] These different studies demonstrate that metals such as gold, copper, nickel, and cobalt, derived from PCBs, CPUs, batteries, mobile phones, and printed electronics, can be selectively extracted and utilized for applications ranging from oxidative coupling and CO_2 fixation to hydrogenation reactions and wastewater remediation. Importantly, several of these catalysts exhibit comparable or superior performance to those produced from virgin materials, while also offering enhanced selectivity, durability, and reusability.[10] By circumventing the need for high-energy processing or chemical purification, techniques such as ligand-assisted solvometallurgy, mechanochemical synthesis, and green smelting significantly reduce the environmental and economic costs of catalyst production.[68] These innovations align strongly with circular economy principles, minimize hazardous by-products, and contribute to resource efficiency. Ultimately, the upcycling of E-waste into high-performance catalysts not only supports sustainable materials science but also reinforces global efforts toward cleaner production, reduced mining dependence, and environmentally responsible technological advancement.[46]

3.2. Conductive materials for supercapacitor electrodes

The development of high-performance supercapacitor electrodes from E-waste represents a sustainable and technologically promising pathway for addressing both electronic waste accumulation and energy storage demands.[59] E-waste streams such as printed circuit boards (PCBs), cables, and electronic housings contain a range of metals and polymeric materials that can be transformed into functional electrode materials through thermochemical, hydrothermal, or electrochemical techniques.[14] These approaches yield conductive carbon frameworks, redox-active metal oxides, or composite hybrids with tailored porosity, surface area, and electrochemical

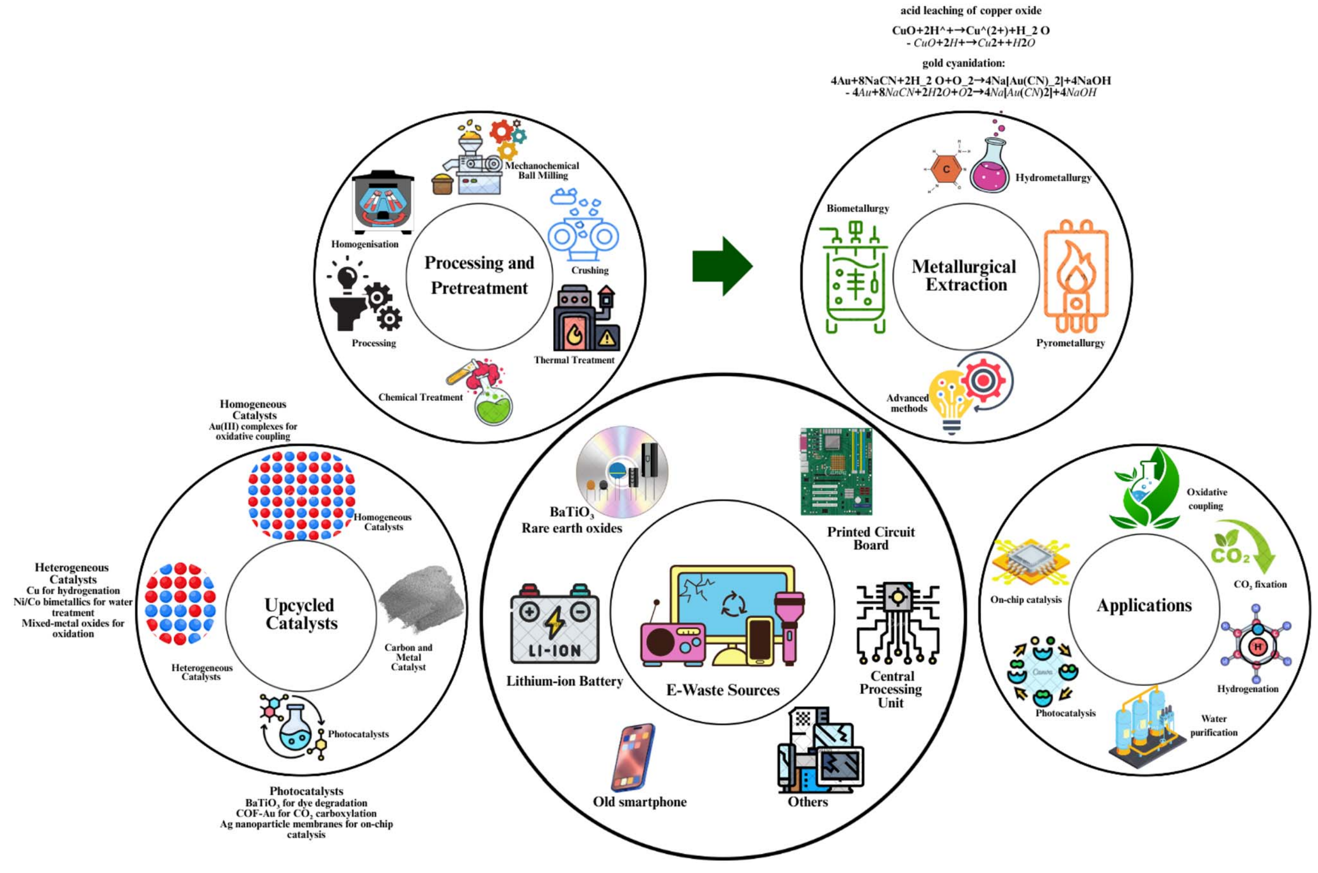


Fig. 4 Upcycling pathways for metal recovery from E-waste into functional materials.

activity.[64] Recent studies have demonstrated the successful upcycling of copper from PCBs into Cu/CuO@C-rGO composites, which serve as high-capacitance electrodes.[51] As studied by Mathaiyan[69] it recovered copper ions from PCB leachate and incorporated them into a reduced graphene oxide matrix, producing a hierarchical porous nanostructure with a surface area of 184 $m^2\ g^{-1}$. The resulting material achieved a specific capacitance of 432.5 F g^{-1} at 1 A g^{-1}, with an energy density of 17.8 Wh kg^{-1} and a power density of 250 W kg^{-1} in a two-electrode asymmetric cell. Similar advances were reported by Chen,[70] who synthesized $NiCo_2O_4$ nanoflakes from industrial and E-waste-derived metal sludges. The spinel oxide structure facilitated reversible faradaic reactions, yielding a capacitance of 278 F g^{-1} at 0.5 A g^{-1} and cycling stability above 90% over 3000 cycles. Carbon-based materials derived from pyrolyzed E-waste plastics and casings also offer high surface areas (up to 1600 $m^2\ g^{-1}$) and good capacitive behavior when activated using KOH or phosphoric acid.[71] According to studies conducted by Ragupathi[72] and Sivaprakash[73] it was highlighted that tetragonal MnF_2 shows high supercapacitor performance with specific capacitances of 406 F g^{-1} (three-electrode) and 80 F g^{-1} (two-electrode), retaining 82% capacitance after 5000 cycles at 1.8 V and delivering 35.99 Wh kg^{-1}. In comparison, the present biomass-based composite activated carbon exhibits superior performance, achieving 290.47 F g^{-1} and 99.92% retention over 5000 cycles, highlighting its promise for high-performance supercapacitor devices.[74] The oxygenated surface functionalities and graded pore distribution facilitate enhanced charge storage through electric double-layer and pseudocapacitive mechanisms. Moreover, Nagaraju[75] demonstrated the feasibility of using waste cable wires to fabricate flexible fiber-based hybrid electrodes. These systems, composed of nickel-coated conductive fibers combined with electrochemically deposited MnO_2 and carbon, achieved capacitances of ∼300 F g^{-1} and retained over 90% performance under repeated mechanical bending, highlighting their potential for wearable electronics. As per the research of Zhu[76] and Adhikari[77] the scope was extended by incorporating hybrid nanostructures such as CuO/graphene and metal-doped MnO_2, which provide synergistic charge storage *via* combined surface adsorption and faradaic reactions. These materials exhibit energy densities ranging from 10 to 22 Wh kg^{-1} and demonstrate stable performance in Na_2SO_4 and KOH electrolytes. Factors influencing performance include the nature of the metal oxide, crystallinity, surface functionalization, and the conductivity of the supporting carbon matrix. The electrochemical behavior of these materials is tightly linked to their surface area, pore structure, and composition.[78] As shown in Table 8, a range of E-waste-derived electrode materials have been benchmarked, demonstrating that tailored synthesis strategies can yield materials with performance metrics comparable to those of commercial supercapacitor electrodes.

Table 8 Electrical, surface, and structural properties of E-waste-derived supercapacitor electrode materials

Material	Source	Surface area ($m^2 g^{-1}$)	Specific capacitance ($F g^{-1}$)	Energy density ($Wh kg^{-1}$)	Power density ($W kg^{-1}$)	Cycle stability	Electrolyte	Reference
Cu/CuO@C-rGO composite	PCB-derived Cu + rGO	184	432.5 @ 1 A g^{-1}	17.8	250	92% retention after 5000 cycles	1 M KOH	69
$NiCo_2O_4$ nanoflakes	Metal sludge from E-waste	~110	278 @ 0.5 A g^{-1}	22.1	312	>90% after 3000 cycles	3 M KOH	70
Activated carbon	Pyrolyzed E-waste plastics	1200–1600	120–250	6–14	~200	85–95% after 5000 cycles	H_2SO_4 and Na_2SO_4	72 and 73
MnO_2/graphene composite	Leached PCB + GO	~110	285 @ 1 A g^{-1}	10.6	230	93% after 3000 cycles	Na_2SO_4	72 and 77
Ni/C flexible fiber	Waste cable wires	~170	~300 @ 0.5 A g^{-1}	~12	~200	>90% under repeated bending	PVA-H_2SO_4 gel	75
CuO/graphene hybrid	PCB scrap Cu + GO	145	315 @ 0.5 A g^{-1}	15.2	288	~90% after 4000 cycles	1 M KOH	76
MnO_2/biomass carbon	Mn from PCBs + biochar	~130	260 @ 0.5 A g^{-1}	13.7	275	88% after 5000 cycles	Na_2SO_4	77
Mixed oxide@carbon hybrid	Mixed PCB oxides + AC	~200	240–270	11–16	220–300	90–95% after 5000 cycles	KOH	79

3.3. Sensor development from upcycled materials

Repurposing E-waste into sensor platforms represents a transformative opportunity for sustainable materials science, offering a dual benefit of pollution mitigation and resource circularity.[71] In recent years, substantial advancements have been made in upcycling diverse E-waste components ranging from compact discs and printed circuit boards to mobile batteries and display panels into high-performance electrochemical and biosensing devices.[59] These efforts have not only reduced environmental liabilities associated with end-of-life electronics but also created economically viable pathways for fabricating next-generation sensing technologies.[78] As described in the study of Brown,[80] it was presented with a pioneering strategy wherein discarded compact discs (CDs) were being transformed into functional, stretchable, and flexible bioelectronic devices. Using an accessible, solvent-free, and low-cost fabrication process, the metallic reflective layers from CDs were mechanically harvested and patterned with certain altercations and wave-shaped geometries *via* a craft cutter, eliminating the need for photolithography or cleanroom infrastructure.[81] The resulting upcycled CD electronics (UCDEs) are capable of real-time biopotential measurement, temperature sensing, and metabolite detection.[82] The electrical resistance was reported at approximately 0.03 Ω cm^{-2}, and the sensors retained their performance even after repeated mechanical deformations such as stretching and bending, whereas these sensors, costing as low as $1.50 per device, were integrated into Bluetooth-enabled modules for real-time physiological monitoring, highlighting their potential as scalable, wearable, and disposable sensor platforms.[80] In a different approach to sensor fabrication, Oestreicher[83] developed plasmonic gold nanoparticles (AuNPs) from gold-containing microprocessor pins recovered from E-waste. These extractions were conducted using a hydrometallurgical leaching process that yielded a high-purity Au(III) solution. More often this solution was then used to synthesize colloidally stable gold nanoparticles *via* reduction with sodium citrate and ascorbic acid, followed by stabilization with polyvinylpyrrolidone (PVP). The synthesized nanoparticles showed well-defined spherical and triangular shapes and strong responsiveness to refractive index changes. Their sensitivity to dielectric environments confirms their suitability for surface plasmon resonance sensors and related optical systems, which helps in highlighting urban mining as a sustainable alternative to conventional gold sourcing for precision sensor fabrication.[83] Another promising study by Pathan[51] demonstrated the upcycling of copper foil extracted from dead lithium-ion mobile phone batteries into copper-based metal–organic frameworks (CuBTC). These MOFs were synthesized through a salt-free, solvothermal process using benzene-1,3,5-tricarboxylic acid as the organic linker. CuBTC was then used to modify screen-printed carbon electrodes for the non-enzymatic electrochemical detection of bilirubin, a clinically significant biomarker for liver function. The resulting sensors exhibited a notably low oxidation potential of 0.04 V and a limit of detection of 0.36 μM, with a dynamic linear range spanning from 5 to 130 μM. The sensor also showed exceptional selectivity in complex biological matrices such as artificial urine. These findings highlight the potential of E-waste-derived CuBTC as a versatile material for medical point-of-care diagnostics.[51] Expanding the scope of E-waste-derived sensing platforms to environmental applications, Saadaoui[81] introduced an electrochemical sensor for mercury (Hg^{2+}) detection based on cerium–cobalt oxide nanostructures fabricated directly on substrates recovered from liquid crystal displays (LCDs). The Ce@Co nanocomposite, featuring abundant oxygen vacancies, was immobilized onto LCD-derived substrates to construct an electrochemical sensing interface using square wave stripping voltammetry. The fabricated sensor demonstrated a low detection limit of 2.8 ppb, a wide linear detection range between 16 and 620 ppb, and an excellent sensitivity of 158.28 $\mu A\ cm^2\ ppm^{-1}$. Application tests in real seawater samples confirmed the sensor's practical viability and high recovery rates. The use of recycled LCDs not only minimized hazardous waste streams but also offered a new route for high-surface-area electrode development for environmental monitoring.[81] In a recent study, Vaishag[84] presented an innovative method for fabricating an electrochemical dopamine sensor by utilizing electronic waste and modifying the sensing surface with Ti_3C_2 MXene. Liquid crystal display glass waste was recovered and integrated into the sensor fabrication process. The MXene-enhanced electrode significantly improved the electron transfer rate and active surface area, resulting in high sensitivity (0.174 $\mu A\ \mu M^{-1}$) and a low limit of detection of 0.46 μM. The sensor showed excellent selectivity in the presence of interfering species such as uric acid and ascorbic acid and was successfully applied in real biological samples. This work demonstrates the value of combining E-waste upcycling with emerging 2D nanomaterials to enhance electrochemical performance and expand application scope in neurochemical sensing.[84] While material transformation is a common theme in upcycled sensors, Li[85] emphasized a relatively underexplored yet highly impactful approach which involved the reuse of intact and functioning electronic components from waste printed circuit boards (WPCBs). The study also provides information that many electronic components, including resistors, capacitors, and integrated circuits, remain operational well beyond the disposal point of their host devices. These components, if selectively disassembled and requalified, can be reintegrated into sensor circuits, thus substantially reducing manufacturing energy consumption and carbon emissions.[85] Collectively, these studies illustrate a paradigm shift in sensor development, one that embraces circular economic principles and closes material loops in the electronics sector. The diversity of materials ranging from metal nanoparticles and MOFs to flexible metal films, MXenes, and functional components demonstrates the flexibility and promise of E-waste as a raw material.[84] By integrating systematically upcycled materials into modular, multifunctional, and decentralized sensors these solutions can offer scalable solutions to global health, environmental, and industrial challenges.[10] Fig. 5, illustrates the transformation of diverse E-waste streams into functional sensor platforms through sustainable upcycling strategies.[86]

3.4. Critical life cycle assessment and safety study

E-waste upcycling has demonstrated a strong technical capacity making it possible to be scalable across different catalysts, energy-storage materials, sensors, and metal-recovery routes.[54] Upcycling tends to offer a lower environmental burden than conventional recycling routes which can be supported by LCA data that rely on complex synthesis routes, short durability testing, and techno-economic or life-cycle evaluation.[58] It was described by Seif[52] that upcycled noble-metal and base-metal catalysts derived from PCBs and mobile-phone scrap commonly achieve 70–100% of the activity of commercial benchmarks, for reactions such as 4-nitrophenol reduction, the oxygen reduction (ORR), and the hydrogen evolution (HER).[87] According to Tatrari,[53] with nanoscale metal dispersion which is widely recognized for enhancing atom efficiency, various previous studies were found to be limited to gram-scale synthesis, ligand-intensive routes, and short durability assessments of fewer than 100 cycles. Encouragingly, recent progress in waste-derived carbon nanomaterials and advanced supercapacitor systems demonstrates scalable, cost-effective, and environmentally supportive fabrication strategies with substantially improved cycling stability and device-level performance. These developments signal a promising transition toward sustainable, high-performance energy storage technologies, where material innovation is increasingly aligned with long-term durability, economic feasibility, and life cycle sustainability considerations for practical large-scale implementation.[88] Maintaining performance as a perspective, Au- and Pd-based nanoparticles which are derived from PCB leachates deliver the highest mass-specific activity but are constrained due to precursor cost and complex synthesis.[87] Base-metal catalysts such as CuO, NiO, and Co-based oxides produced from connectors and coils show slightly lower intrinsic activity but offer greater scalability and lower cost per unit mass, making them more realistic for large-volume applications.[69] Technology readiness level (TRL) holds a crucial importance. When described in terms of technology, simple oxide and mixed-oxide catalysts prepared *via* co-precipitation and calcination approaches show a TRL of 5–6, whereas MOF-derived and single-atom catalysts remain at a TRL of 3–4 due to synthesis complexity and dependence on organic ligands.[52] As described by Liu[17] the key bottlenecks include impurity control such as Pb, Sb, halogens and others, with limited solvent recycling. The use of ionic liquids or DESs shows insufficient benchmarking against commercial catalysts. Bioleaching or DES extraction shows a promising direction that includes integrated flowsheets which can be linked directly to catalyst formation and the development of robust base-metal or bimetallic systems, which can be tailored for wastewater treatment and CO_2 conversion.[89] E-waste-derived carbons and carbon–metal composites typically exhibit specific capacitances of 200–600 F g^{-1}, with some rGO- or MOF-derived hybrids exceeding 800 F g^{-1} in three-electrode configurations.[90] According to Mathaiyan[69] thermal activation to derive materials from refurbished activated carbons, spent supercapacitors, and polymer-derived waste offers the most balanced trade-off between

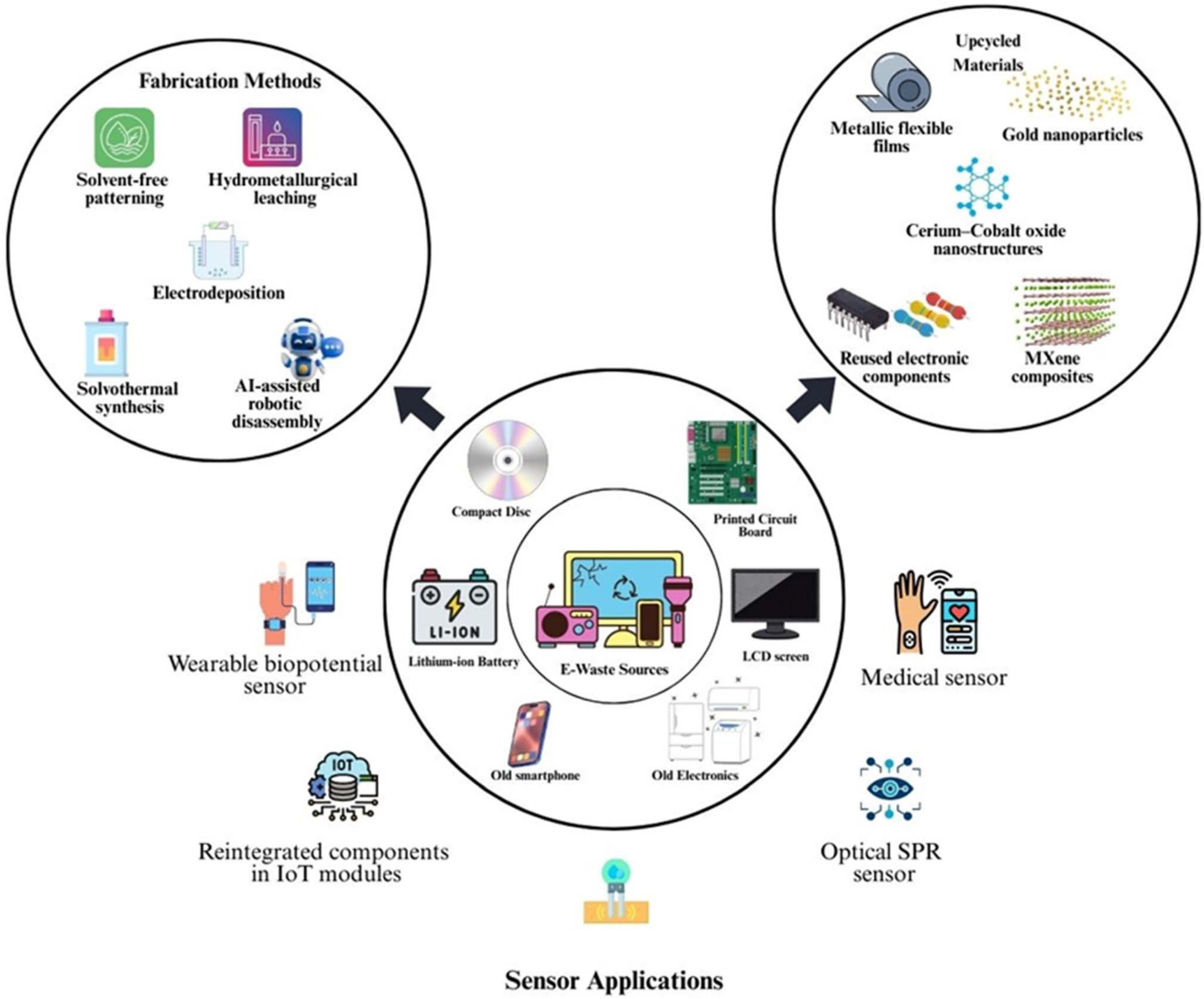


Fig. 5 Transformation of E-waste into functional sensors through upcycling and sustainable fabrication routes.

performance, scalability, and cost, typically achieving 250–350 F g^{-1}.[71] In contrast, pseudocapacitive hybrids such as rGO–$NiCo_2O_4$ can reach higher gravimetric capacitance but suffer from lower volumetric performance and more complex processing. This from a TRL standpoint shows that refurbished carbons are approaching a TRL of 6–7, whereas advanced composites based on mixed e-waste streams remain at a TRL of 3–4.[91] Cu- and Au-based platforms derived from high-value E-waste deliver the best electroanalytical performance, while carbon-only sensors emphasize low cost and flexibility at moderate sensitivity.[69] According to Castro[89] bioleaching consistently achieves 80–95% recovery of Cu and Zn and 40–80% recovery of precious metals, with energy demand substantially lower than that in conventional hydrometallurgy. However, slow kinetics and inhibition by plastics and additives remain major scale-up barriers.[92] Enzymatic systems offer higher selectivity but are costly and largely confined to laboratory studies.[56] As described by Wu[93] bioleaching for low-grade ores is observed at a TRL of 7–8, whereas application to E-waste is found to be at a TRL of 4–6.[94] Whereas DES-based leaching achieves >90% recovery of several base and critical metals under mild conditions, solvent degradation, viscosity-driven mass-transfer limits, and regeneration costs constrain scalability, with most systems remaining at a TRL of 4–5, with limited industrial demonstration.[95]

Application of LCA remains rigorous across all the domains including the assessment of toxicity and safety. It has been concluded that LCAs suggest 50–70% reductions in GWP and energy use when upcycled products replace virgin materials, but inconsistent system boundaries limit comparability.[96] Routes combining simple unit operations with high material recovery currently offer the best balance of TRL, cost, and environmental benefits, while highly engineered materials remain largely at the laboratory scale.[88] The integration of design-for-disassembly and repair principles is mainly under study for improving upcycling efficiency and circularity.[52] Table 9 summarizes the TRL, challenges and opportunities in E-waste recycling.

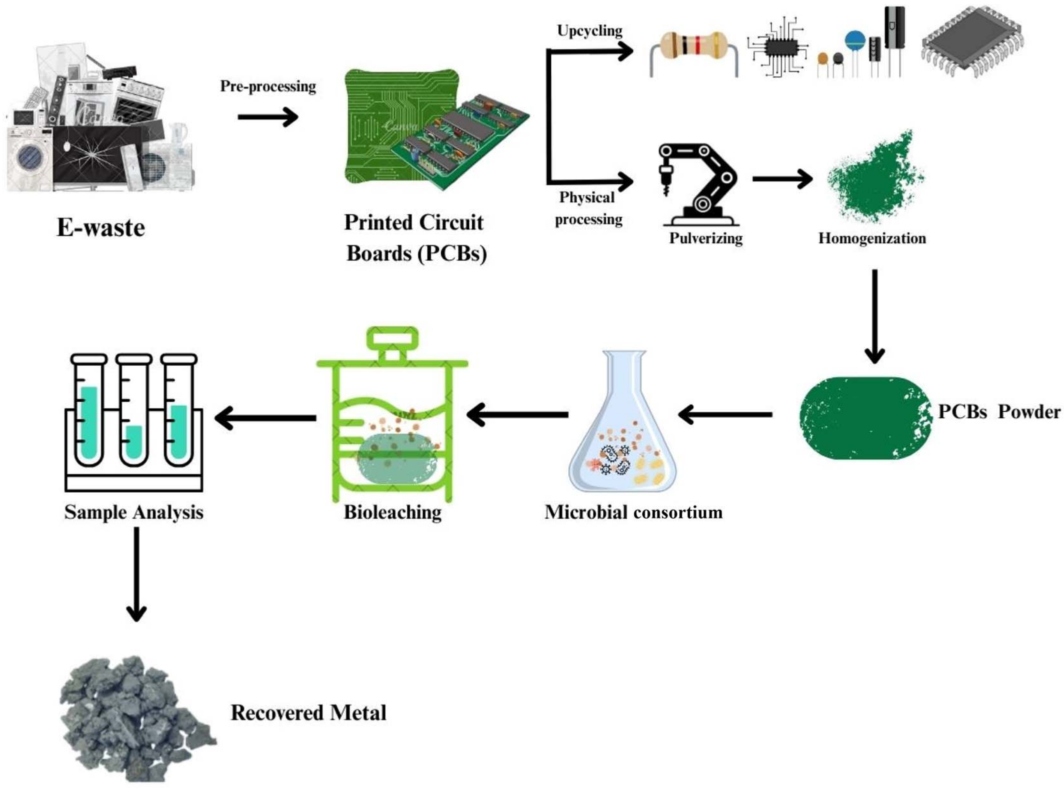
Table 9 Technology readiness, challenges, and opportunities in E-waste upcycling[52,53,96]

Application area	Processes	TRL	Challenges	Results
Catalysts	Cu/Ni oxides, Au/Pd NPs, and MOF-derived catalysts	3–6	Ligand/reductant cost, impurity poisoning, and limited durability data	Robust base-metal or bimetallic catalysts; direct coupling of metal recovery with catalyst synthesis
Supercapacitor electrodes	Refurbished activated carbons and rGO–metal oxides	3–7	Non-standardized testing, low mass loading, and scale-up of nano-architectures	Refurbished carbons; integrated metal recovery–electrode fabrication; device-level benchmarking
Sensors	Cu-MOFs, rGO, MXenes, and upcycled carbons	3–6	Feedstock variability, limited robustness and lifetime testing	Printable/laser-written platforms with standardized recognition layers
Bioleaching & enzymatic recovery	Chemolithotrophic bacteria and enzyme systems	3–6	Slow kinetics, inhibition by plastics/additives, and downstream separation	Hybrid bio-electro-hydrometallurgical systems; reuse of metal-loaded biomass
DES/green solvent routes	Choline chloride-based DESs	4–5	Solvent degradation, viscosity, and regeneration cost	DES-enabled direct synthesis of functional materials; membrane or electro-dialysis recovery
Cross-cutting (LCA & design)	LCA-linked upcycling and modular design	2–4	Inconsistent system boundaries and limited safety/toxicity data	Standardized LCA/LCC frameworks; design-for-disassembly and repair integration

4. Bio-inspired and green processing techniques

4.1. Bioleaching and enzymatic recovery

According to Baniasadi,[94] sustainable metal recovery has observed significant changes and modifications in the recycling techniques, from traditional or conventional techniques to advanced methods. Bioleaching or biometallurgy, the biologically mediated solubilization of metals, has been gaining attention as a sustainable alternative to conventional chemical leaching for E-waste recycling.[11] It leverages the use of bacteria or fungi to recover metals such as copper (Cu), gold (Au), nickel (Ni), cobalt (Co), zinc (Zn), and lithium (Li) from complex matrices under ambient or near-ambient conditions.[47] As an advanced method when compared with traditional leaching with sulfuric acid or cyanide, bioleaching achieves comparable metal yields with drastically reduced environmental impact, lower energy input, and minimal chemical waste.[97,98] Acidophilic bacteria such as *Acidithiobacillus ferrooxidans*, *A. thiooxidans*, and *Leptospirillum ferrooxidans* are widely used for E-waste bioleaching due to their robust metal oxidation capabilities.[11] Microbial organisms oxidize Fe^{2+} to Fe^{3+} and S^0 to H_2SO_4, which in turn facilitate metal solubilization *via* redox-driven and acidic dissolution pathways.[99] According to Natarajan[100] *A. ferrooxidans* achieved 97.4% Cu and 85.3% Zn recovery from PCBs at 30 °C, pH 2.0, and 5% pulp density, over 12 days of incubation.[100] The study by Kwok[101] determined that *A. thiooxidans*, when applied to mobile phone PCBs, yielded 96.3% Cu and 81.4% Zn in 10 days, at slightly lower pulp density (2%) but under similar thermal conditions.[101] In the context of lithium-ion battery (LIB) cathodes, *A. ferrooxidans* facilitated the recovery of 92% Co and 75% Li at 35 °C, pH 2.5, and 4% pulp density, within 10 days.[102] These high yields are attributed to the microbial oxidation of ferrous ions and sulfur, enhancing the leaching of transition metals from oxide lattices.[103] A comparative trial using a mixed culture of *A. ferrooxidans* and *L. ferrooxidans* demonstrated up to 99% Cu and 88% Zn solubilization from pulverized PCB waste, but only when the oxygen supply (*via* aeration or agitation) was retained above 0.2 vvm.[98] Fungi such as *Aspergillus niger*, *Penicillium simplicissimum*, and *Trichoderma atroviride* offer a different route by secreting organic acids (*e.g.*, citric, oxalic, and gluconic) that chelate metal ions.[104] In a study on fungal leaching, *A. niger* achieved 81.2% Cu, 68.4% Zn, and 15.5% Pb recovery from PCB powder at pH 4.5, with organic acid titers reaching 0.24 M.[105] In the study leaching time was longer (∼15 days), but the system required no pH adjustment or oxidizing agents. Fungal systems are also more resistant to metal toxicity than bacteria but exhibit slower kinetics.[106] Hence, pretreatment of PCBs *via* pyrolysis or grinding (<75 μm) significantly improves leaching performance.[14] Emerging studies now combine anaerobic digestion with bioleaching, using volatile fatty acids (VFAs) such as acetic, propionic, and butyric acids as bio-derived lixiviants. Russo[98] reported that VFA-rich fermentation liquor achieved 95.8% Co, 86.4% Ni, and 80.1% Li leaching from spent LIB cathodes at pH 4.2, a temperature of 37 °C, and 7-day contact time. The integrated process improved overall waste valorization, enabling both metal recovery and methane generation from residues. Microbial engineering has enabled direct enzymatic targeting of specific toxic or valuable metals. *E. coli* expressing the MerA (mercuric reductase) gene showed >95% reduction of Hg^{2+} to volatile Hg^0 within 24 hours in reactors



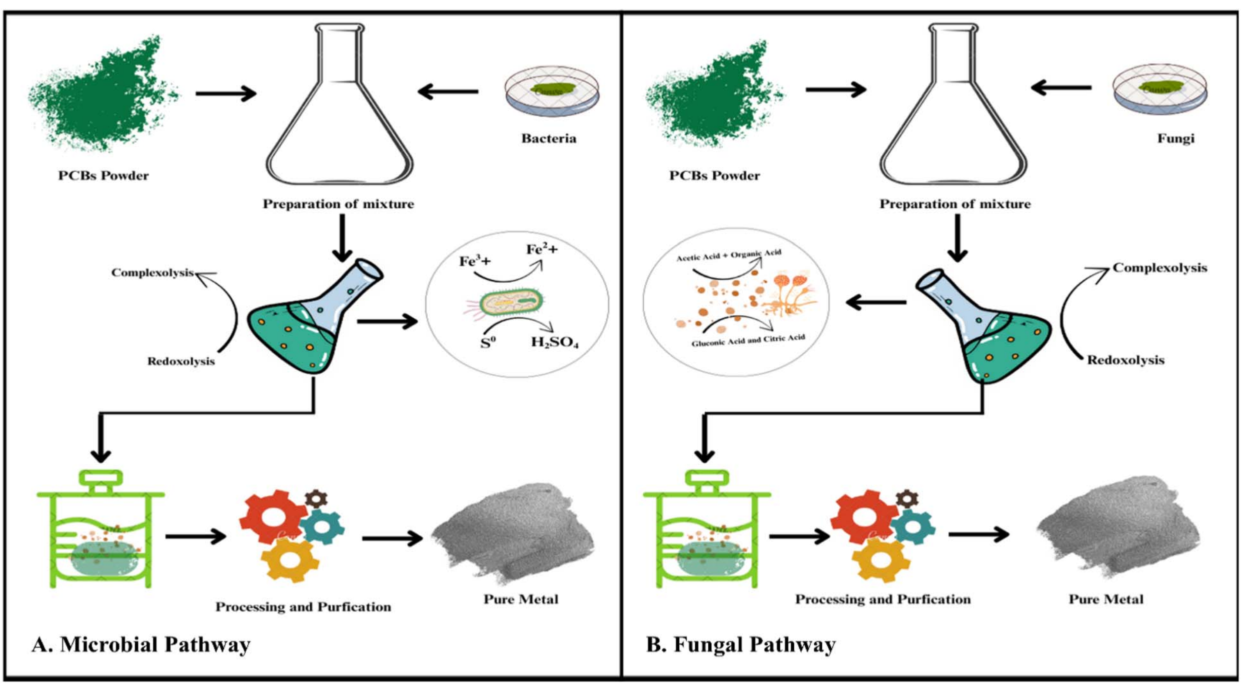


Fig. 6 Microbial-mediated metal solubilization from printed circuit boards: bacterial and fungal pathways.

operated at pH 6.5 and 30 °C, with PCB-derived leachates.[107] Additionally, *Chromobacterium violaceum* utilizes its natural cyanogenic pathway to produce HCN, leaching Au from PCBs. Under controlled conditions (pH 7.2, 28 °C, 6 days), up to 90% Au recovery was achieved, with minimal cyanide accumulation due to metabolic feedback inhibition.[101] An engineered

Table 10 Synthesis conditions and properties of nanoparticles prepared *via* bio-templating from E-waste

Nanomaterial	E-waste source	Bio-template/green agent	Calcination temp. (°C)	Particle/crystallite size (nm)	Surface area (m^2 g^{-1})	Bandgap (eV)	Photocatalytic activity	Reference
SnO_2	WPCBs (Sn leachate)	*Camellia sinensis* and *Aloe vera*	400	28–45 (XRD)	78	3.67	>95% degradation of RhB and MB in 120 min under visible light	112
Cu/CuO	WPCBs (Cu leachate)	Ascorbic acid (bioreductant)	300	52–460 (SEM and DLS)	—	~2.1	96.2% RhB removal in 120 min; antibacterial against *E. coli*	113
ZnO	CRT phosphors and PCB powders	Egg albumin and banana peel (biotemplates)	500	20–50 (TEM)	50–100	3.2–3.4	80–90% dye degradation in 100 min (visible light)	115
Fe_3O_4	Fe-rich PCB dust	Gelatin and corn starch	550	30–60	100–180	2.7–3.0	85% MB degradation within 90 min	115
CuO/ZnO composite	PCB (mixed oxides)	Citrus peel extract	350	35–70	—	~2.0–2.3	90% Cr(VI) removal in 60 min	115
SnO_2 quantum dots	PCB-derived Sn	Orange peel extract	400	3.8–7.6 (TEM and HR-TEM)	92	4.01	88% MB degradation under solar light in 100 min	114
Ag/CuO nanocomposite	PCB scrap	*Withania somnifera* root extract	350	~42 (XRD)	—	~2.2	Excellent photoantibacterial effect and dye degradation	114
CuO nanoparticles	PCB-derived copper	Glucose and urea (biomimetic agents)	450	20–80	—	2.0–2.4	91% degradation of MB in 70 min under visible light	116

Shewanella oneidensis strain with enhanced electron transfer proteins has also been shown to reduce metal oxides and enable Co recovery from waste LIBs, reaching 78.5% Co within 5 days at neutral pH and 30 °C.[108] Bioleaching and enzymatic metal recovery are now entering a mature phase, supported by promising experimental recoveries and pathway optimization.[11] While process times remain longer than traditional leaching, recovery rates exceeding 90% for Cu, Co, Zn, and Au are now achievable under optimized biological conditions.[14] Integration with renewable bioresources such as dark fermentation and advances in synthetic biology are expected to accelerate industrial adoption, especially for low-volume, high-value metals and decentralized E-waste treatment systems.[109] Fig. 6 provides the understanding of microbial pathways for metal solubilization from PCBs, where the microbial pathway is defined in Fig. 6A and fungal pathway is defined in Fig. 6B.

4.2. Bio-templating and biomimetic synthesis

Bio-templating and biomimetic synthesis have emerged as promising strategies to fabricate nanostructured materials from E-waste, aligning green chemistry principles with circular economy goals.[110] These methods utilize biologically derived agents such as plant extracts, fruit peels, polysaccharides, and proteins as reducing, capping, or structure directing agents to synthesize metal oxides and composite nanomaterials under mild, environmentally favorable conditions.[111] According to Liu[110] bio-assisted processes not only eliminate the need for toxic reagents but also yield materials with enhanced different functional characteristics. Different studies have validated the potential of this approach across different material systems. Ghosh[112] synthesized SnO_2 nanoparticles from WPCBs using *Camellia sinensis* and *Aloe vera* leaf extracts, in which the resulting particles, obtained *via* calcination at 400 °C, exhibited high surface area (78 m^2 g^{-1}), narrow crystallite size (28–45 nm), and strong photocatalytic performance >95% dye degradation within 120 min under visible light. Similarly, Abdelbasir[113] used ascorbic acid to reduce copper extracted from PCB leachate, yielding Cu/CuO nanoparticles ranging between 52 and 460 nm with antibacterial effectiveness and photocatalytic degradation of Rhodamine B exceeding 96%. The use of egg albumin, banana peel, and citrus peel extracts has also been demonstrated to guide the formation of metal oxides like ZnO, Fe_3O_4, and CuO/ZnO composites with bandgaps ranging from 2.0 to 3.4 eV, suitable for environmental remediation. In these systems, bio-templates act as carbonaceous matrices or nucleation scaffolds, improving surface-active site density and charge carrier mobility. Ayyappan[114] synthesized SnO_2 quantum dots (3.8–7.6 nm) and Ag/CuO composites using orange peel and *Withania somnifera*, respectively, achieving enhanced solar-light-driven photocatalysis and antimicrobial activity due to quantum confinement and surface functionalization effects. In addition to size control and eco-friendliness, these approaches often achieve comparable or superior catalytic efficiencies relative to conventional thermal or chemical methods, with lower energy input. The particle characteristics, including surface area, morphology, crystallite size, and bandgap, directly influence the photocatalytic degradation rates of common dyes like methylene blue (MB) and Rhodamine B (RhB) and contaminants like Cr(VI), as summarized in Table 10.

4.3. Use of green solvents and low-impact processing

Deep eutectic solvents (DESs) have observed a steep rise in implementation of green solvents; this has revolutionized metal recovery from E-waste by replacing traditional mineral acids with tangible, biodegradable systems that offer both environmental compatibility and process efficiency.[68] According to Zhou,[117] DESs, composed of a hydrogen bond acceptor (commonly choline chloride) and a hydrogen bond donor (*e.g.*, ethylene glycol and oxalic acid, urea), create a highly polar, low-vapor-pressure medium that facilitates selective complexation and dissolution of target metals without the need for aggressive redox reagents or high energy inputs. Recent studies have demonstrated the ability of DESs to efficiently leach metals such as Cu, Co, Li, Ni, Mn, Zn, and REEs from a variety of E-waste sources under mild thermal and kinetic conditions.[118] Zhou[117] reported that ChCl/EG (1 : 2) could extract 91.6% Co and 80% Li from $LiCoO_2$-based batteries at 180 °C over 24 h, whereas ChCl/OA (1 : 1) achieved significant recovery of both metals at the same temperature within just 10 h. The enhanced dissolution kinetics in oxalic-acid-based DESs are attributed to strong bidentate coordination of oxalate ions with Co^{2+} and Li^{+}, promoting rapid lattice collapse and solubilization.[119] Beyond Li-ion batteries, DESs have been employed for PCB recycling, achieving >95% Cu recovery with ChCl/citric acid systems at 90 °C for 2 h.[68] Similarly, Zn and Mn leaching from Zn–C batteries has been demonstrated using ChCl/urea (1 : 2), yielding >90% recovery of both metals at 150 °C over 90 minutes.[120] Notably, such systems avoid chlorine gas evolution, commonly associated with HCl-based hydrometallurgy, and reduce the environmental load of secondary effluents.[121] A critical parameter influencing DES performance is viscosity, which affects mass transfer during leaching, as the addition of co-solvents like water or ethanol reduces viscosity and enhances diffusivity, while retaining the hydrogen-bond network essential for metal chelation.[122] Zhou[117] showed that adding water (10–20 wt%) to ChCl/OA significantly improved Li and Co recovery kinetics without compromising solvent recyclability. As per the study by Zhang[123] ChCl/EG was combined with ozone bubbling (O_3) to oxidize Fe^{2+} and release Li^{+} from $LiFePO_4$ cathodes at only 40 °C, achieving 92.2% Li recovery in 6 h.[123] As per Okeke[124] microwave-assisted DES extraction is a technologically advanced method that assists in reducing the reaction time. Using ChCl/benzenesulfonic acid (1 : 1) for Nd–Fe–B magnet recycling under microwave irradiation[117] resulted in 94% Nd and 87% Fe recovery at 140 °C within 16 h. Similarly, HDES (hydrophobic DES) systems such as decanoic acid/trioctylphosphine oxide (TOPO) have been developed for selective extraction of Au and Ag from E-waste. These systems exhibit strong metal–ligand interactions in a non-aqueous phase, eliminating the need for toxic organic solvents like toluene or kerosene while attaining >98% selectivity for Au over Cu and Zn.[125] Table 11 summarizes various DES systems with their molar ratios, operating conditions, and metal recovery yields. Most systems operate at sub-boiling temperatures (<180 °C) and short durations (10 minutes to 24 h) and with high recovery efficiencies (>90%), reflecting their technical viability and environmental preference over mineral acid leaching.[126]

The growing body of evidence supports DESs as credible, sustainable alternatives to traditional solvents, particularly when coupled with low-energy leaching aids like ultrasound or microwave heating. Moreover, most DES components are inexpensive and accessible. Choline chloride, for instance, is produced at the industrial scale and derived from biomass, making DESs economically viable for industrial application.

5. Toxicity reduction and environmental risk management

5.1. Sources and fate of hazardous substances

The rising generation of E-waste and the constant improper handling of hazardous materials have released a complex mixture of hazardous substances into the environment.[1] Different materials originate from the diverse chemical constituents of electronic components and exhibit a wide spectrum of toxicological behaviors, including bioaccumulation, endocrine disruption, and genotoxicity.[11] Understanding their sources and environmental fate is essential for assessing exposure risks and developing effective remediation strategies.[2] E-waste contains over 1000 different hazardous compounds, which include heavy metals such as Pb, Hg, Cd, and Cr^{6+}, persistent organic pollutants (POPs), flame retardants (PBDEs and TBBPA), and dioxins/furans as prominent polluters. Open burning and crude acid leaching emit dioxins, furans, heavy metals and PBDEs, which contaminate

Table 11 Selected deep eutectic solvent systems for metal recovery from E-waste

E-waste source	Target metals	DES composition	Temp. (°C)	Time	Recovery efficiency (%)	Reference
Li-ion batteries (LCO)	Co, Li	ChCl/EG (1 : 2)	180	24 h	91.6% Co and 80% Li	117
Li-ion batteries (LCO)	Co, Li	ChCl/OA (1 : 1)	180	10 h	100% Co and 100% Li	117
$LiFePO_4$ batteries	Li	ChCl/EG + O_3 (1 : 8)	40	6 h	92.2% Li	123
PCBs	Cu, Zn, and Sn	ChCl/citric acid (1 : 1)	90	2 h	>95% Cu and 85% Zn	68
Zn–C batteries	Zn and Mn	ChCl/urea (1 : 2)	150	90 min	95% Zn and 92% Mn	120
Nd–Fe–B magnets	Nd and Fe	ChCl/succinic acid/EG (1 : 1 : 1)	140	16 h	94% Nd and 87% Fe	117
Mixed E-waste (PCBs)	Au, Pd, and Cu	ChCl/malonic acid (1 : 2)	120	4 h	>98% Au, 99% Pd, and 80% Cu	125
PCBs (HDES)	Cu and Ag	Decanoic acid/TOPO (1 : 1)	100	4 h	99% Cu and 96% Ag	125

air, soil, and water and are linked to respiratory illnesses, cancers, and neurological disorders among workers and nearby communities. According to Robinson[127] PCBs can contain up to 20–30 wt% brominated flame retardants (BFRs), while cathode-ray tubes hold up to 20% PbO. Cadmium (Cd), commonly found in rechargeable Ni–Cd batteries and SMD chip resistors, is highly mobile in soil and leaches under acidic conditions, with leachate concentrations reported as high as 4.5 mg L^{-1} under unmanaged landfill conditions, far exceeding the WHO limit of 0.003 mg L^{-1} for drinking water.[14] Landfilling further exacerbates pollution, with leachate containing Pb concentrations 254–461 times above permissible limits, threatening groundwater quality and food chains. Similarly, mercury (Hg) used in CCFL backlights and relays is readily methylated by aquatic microbes, forming methylmercury, a potent neurotoxin known to biomagnify across trophic levels.[5] According to the study by Wang[128] it has been estimated that improperly processed LCDs can release up to 1.2 mg Hg per unit, primarily *via* volatilization and leaching routes. Brominated flame retardants (BFRs) like PBDEs and TBBPA, commonly embedded in PCB resins and plastic casings, are semi-volatile, enabling atmospheric transport and long-range deposition.[117] Mechanical processing steps release dust enriched with Pb and Cu often up to 300 times background levels along with flame retardants, increasing inhalation exposure, soil degradation, and morbidity in informal recycling areas. Atmospheric measurements in informal E-waste recycling areas have detected PBDE concentrations as high as 1.35 ng m^{-3}, which can undergo photolytic degradation into more toxic polybrominated dibenzofurans (PBDFs).[129] Leachate from E-waste dumps in South Asia reported PBDE levels exceeding 5000 ng L^{-1}, threatening aquatic biota through chronic endocrine interference.[130] Lead (Pb), one of the most abundant toxicants in E-waste, is present in solder (Sn–Pb alloys), CRT glass, and cable sheaths.[2] Soil samples near informal dismantling sites in Ghana showed Pb concentrations ranging from 600–2500 mg kg^{-1}, compared to background levels below 40 mg kg^{-1}.[131] Such contamination poses severe risks of developmental neurotoxicity, particularly in children, and is aggravated by low soil mobility, resulting in long-term persistence.[11] Additionally, emerging contaminants such as per- and polyfluoroalkyl substances (PFASs) and organophosphate flame retardants (OPFRs) are now increasingly detected in E-waste plastics and dust.[132] These chemicals are persistent, resistant to degradation, and interfere with hormone regulation and cellular metabolism. As per Zhao[133] indoor dust from E-waste workshops in China showed PFAS concentrations between 54 and 289 ng g^{-1}, suggesting direct occupational exposure. The fate of these hazardous substances depends on multiple parameters including waste composition, local climate, disposal method, and physicochemical properties.[28] In landfills, hydrophilic substances like Cd and Cr^{6+} leach into groundwater, while hydrophobic BFRs and PAHs accumulate in sediments and biota.[134] Atmospheric emissions through open burning introduce dioxins and heavy metals into air-suspended particulates, increasing inhalation risks. Thermal processing, particularly open burning, greatly enhances environmental dispersion, as temperatures in informal burning activities range from 300 to 600 °C, insufficient for complete combustion and conducive to formation of polychlorinated dibenzo-*p*-dioxins (PCDDs) and polybrominated dibenzofurans (PBDFs).[135] Evidence from major E-waste site in Africa, Agbogbloshie in Ghana, shows soil PBDE levels reaching 4250 ng g^{-1}, while bottom ash contains Pb concentrations of 3560–6450 mg kg^{-1}, collectively heightening mortality risks through particulate exposure and bioaccumulation. Samples collected from Guiyu, China, one of the largest informal E-waste hubs, revealed PCDD/F concentrations in fly ash as high as 450 ng I-TEQ per kg, a level over 1000 times the EU soil limit for agricultural land.[130] Bioavailability and long-range transport result in global contamination. Studies have detected E-waste-derived BFRs and Pb isotopes in Arctic marine mammals and Antarctic ice cores, confirming the planetary-scale footprint of improper E-waste handling.[127,133] Given these risks, accurate monitoring of contaminant release pathways is crucial. Modern tools like life cycle impact assessment (LCIA), geochemical modeling, and biomonitoring using sentinel species are increasingly employed to trace the fate of toxicants and assess their cumulative impact on human health and ecosystems.[14] Table 12 summarizes key hazardous substances in E-waste, their primary sources, pathways, environmental behavior, and toxicological implications.

5.2. Detoxification approaches: physical, chemical, and biological

The removal or neutralization of hazardous substances in E-waste streams is critical for mitigating their environmental and health impacts.[1] As per Punia[136] detoxification strategies can be broadly classified into physical, chemical, and biological categories, each with specific mechanisms, applicability ranges, and operational efficiencies. These techniques are often integrated into pre-treatment or post-recovery stages of E-waste management to reduce emissions of toxicants such as heavy metals, persistent organic pollutants (POPs), dioxins, brominated flame retardants (BFRs), and polycyclic aromatic hydrocarbons (PAHs).[5] According to Saha[28] physical detoxification methods typically involve mechanical separation, thermal treatment, and stabilization, in which thermal desorption and vitrification are widely used to immobilize or destroy volatile and semi-volatile toxicants. As per Abdoli,[137] vitrification of lead-rich cathode-ray tube (CRT) glass at >1200 °C effectively condenses Pb within a silicate matrix, reducing leachability to below 0.01 mg L^{-1}, well under the US EPA threshold of 5 mg L^{-1}.[137] However, open burning or low-temperature incineration common in informal recycling is counterproductive, releasing brominated dioxins and furans.[134] Controlled pyrolysis at 600–800 °C under oxygen-limited conditions has been shown to degrade BFRs by up to 90%, though energy input remains a constraint.[138] Chemical detoxification methods include acid or alkaline leaching, oxidation, precipitation, and solvent extraction. Advanced oxidation processes (AOPs), such as using Fenton's reagent, ozonation, and photocatalysis, have been developed to degrade toxic organics. In a recent study, Wang[139] demonstrated the photocatalytic degradation of TBBPA in E-waste leachates using a TiO_2–CeO_2 nanocomposite under

Table 12 Key hazardous substances in E-waste: sources, environmental fate, and risk profiles

Substance	Common sources	Pathways	Fate & behavior	Toxicological risks	Reference
Lead (Pb)	Solder, CRTs, and PVC cables	Leaching, dust, and air	Persistent in soil; immobile; bioavailable	Neurotoxicity and kidney damage	131
Mercury (Hg)	LCDs, relays, and switches	Vaporization and leaching	Methylated in water; bioaccumulative	Neurotoxicity and fetal risk	128
Cadmium (Cd)	NiCd batteries and SMD resistors	Leaching	Mobile in acidic soil; plant uptake	Renal toxicity and bone disease	127
PBDEs/TBBPA	PCB resin and plastics	Leaching and volatilization	Persistent, semi-volatile, and endocrine disruptor	Thyroid disruption and liver toxicity	129
Dioxins/furans	Open burning of BFRs	Airborne, particulate	Lipophilic and long-range transport	Carcinogenic and immune toxicity	130
PFASs/OPFRs	Plastics and coatings	Dust inhalation and ingestion	Very persistent and accumulate in humans	Endocrine and immune dysfunction	133
Cr^{6+}	Anti-corrosion coatings	Leaching	Strongly oxidizing and water soluble	Carcinogenic and respiratory issues	127

visible light, and over 95.4% degradation was achieved within 90 minutes at neutral pH, with minimal by-product formation. Similarly, the use of biochar-supported nZVI (nanoscale zero-valent iron) has shown high efficiency in reducing Cr^{6+} and Pb^{2+} concentrations in WPCB ash leachate by >98% through redox and adsorption mechanisms.[140] These methods are particularly suitable for detoxifying aqueous waste streams or spent acid solutions from leaching operations. Stabilization and encapsulation are essential for immobilizing heavy metals. Phosphate-based binders and cementitious materials are often used to treat metal-rich residues. For instance, stabilizing incinerator fly ash with Portland cement and Na_2SiO_3 reduced Pb leachability by 86% and Zn by 72%, without compromising compressive strength.[141] According to Dixit[142] biological detoxification is becoming a cost-effective and eco-friendly approach, particularly for complex and low concentration E-waste residues. Microbial consortia and specific enzymatic systems have been used to transform or degrade toxic substances.[11] White-rot fungi such as *Trametes versicolor* and *Phanerochaete chrysosporium* produce extracellular ligninolytic enzymes such as laccase. Manganese peroxidase can degrade BFRs and PAHs.[28] In a notable study, laccase derived from *T. versicolor* achieved 78% degradation of TBBPA in WPCB extract within 48 hours at pH 4.5 and 30 °C.[143] Additionally, bacterial strains such as *Pseudomonas putida* and *Cupriavidus metallidurans* have demonstrated capabilities to bioaccumulate and biotransform heavy metals like Cd, Pb, and Hg.[136] In bioreactor systems, immobilized *P. putida* achieved 93% Pb(II) removal from simulated leachate within 72 hours.[138] Enzyme-mediated reduction of Cr^{6+} to the less toxic Cr^{3+} using chromate reductases has also been reported, with reduction efficiencies over 90% under optimal redox conditions.[141] Hence, hybrid systems integrating physical, chemical, and biological treatments are being developed. As per Chakraborty[5] sequential photocatalysis–biosorption systems have shown enhanced detoxification synergy, first oxidizing complex BFRs to smaller intermediates and then removing them *via* microbial uptake. Table 13 summarizes the key detoxification techniques, their mechanisms, target pollutants, and removal efficiencies as reported in recent studies.

5.3. Life cycle assessment (LCA) and safety considerations

Life Cycle Assessment (LCA) provides a critical framework for evaluating the environmental impacts of upcycled E-waste technologies across their entire life span from material sourcing and processing to end-of-life disposal.[144] In the context of E-waste valorization, LCA is pivotal to identifying environmental trade-offs and optimizing recovery strategies to minimize emissions, toxicity, and energy consumption.[145] Recent studies have demonstrated that current E-waste recycling systems, especially in developing nations, suffer from poor regulatory oversight, informal processing, and significant environmental challenge.[1] The study by Dutta[144] provides a comprehensive LCA of E-waste management in Thailand

Table 13 Detoxification approaches for toxicants in E-waste streams

Method type	Technique	Target pollutants	Removal efficiency (%)	Key conditions	Reference
Physical	Vitrification	Pb (CRTs)	>99% immobilization	>1200 °C	137
Physical	Controlled pyrolysis	BFRs and PAHs	∼90% degradation	600–800 °C, O_2-limited	138
Chemical	TiO_2–CeO_2 photocatalysis	TBBPA	95.4%	Visible light, pH ∼7	139
Chemical	nZVI with biochar	Cr^{6+} and Pb^{2+}	>98%	Redox + adsorption	140
Chemical	Cement-based stabilization	Pb and Zn	Pb: 86% and Zn: 72%	Na_2SiO_3, curing for 28 days	141
Biological	Laccase degradation (*T. versicolor*)	TBBPA	78%	pH 4.5, 30 °C	143
Biological	*P. putida* bioreactor	Pb^{2+}	93%	72 hours, neutral pH	138

Table 14 Key findings from LCA and safety studies on E-waste management

Location	Focus	Key findings	Recommendations	Reference
Thailand	LCA and LCC of E-waste systems	High GHG emissions from informal logistics; poor recycling economics	National-level policy is needed for reverse logistics and domestic recycling capacity	147
Cameroon	LCA + system dynamics	IEMS reduces GWP (−27%) and toxicity (−34%)	Levy on producers; subsidies for formal recyclers	148
Ghana	Occupational health	Poor safety practices despite awareness; exposure to heavy metals	Develop tailored safety training and regulation for informal workers	149
India	Consumer disposal behavior	Awareness, convenience, and norms drive disposal intentions	Strengthening EPR, awareness campaigns, and consumer-targeted infrastructure	150

which revealed that informal recycling practices, such as improper dismantling and uncontrolled refrigerant release, significantly contributed to greenhouse gas (GHG) emissions. Quantitative life-cycle assessments (LCAs) provide strong evidence that upcycling pathways outperform conventional smelting-centric recycling when appropriate design and process choices are made.[55] Most comparative studies apply gate-to-gate or cradle-to-gate system boundaries, with a functional unit of 1 kg of PCB or E-waste treated, excluding upstream use phases.[24] In different studies related to pyrometallurgical routes typically 15–45 kg CO_2e and 150–400 MJ per kg were reported, driven by high-temperature furnaces and off-gas treatment.[129] Conventional hydrometallurgy reduces thermal demand but still shows 8–25 kg CO_2e and 80–200 MJ per kg, with elevated toxicity impacts from acid use and wastewater treatment.[14] In contrast, bioleaching- and DES-based upcycling routes consistently fall in the ∼2–12 kg CO_2e and 25–80 MJ per kg range, corresponding to 60–70% lower global warming potential and energy demand and ∼80% lower ecotoxicity indicators relative to pyrometallurgy.[69,89] Device-level LCAs reinforce the role of circular design: studies on modular, recyclable PCBs with integrated-circuit reuse report ∼63% reductions in total GWP and ∼84% lower marine aquatic ecotoxicity compared with conventional FR-4 designs.[26] Critically, these gains are enabled by design for disassembly, modularity, and material transparency, which increase the yield and purity of fractions entering upcycling routes.[146] Material passports and repairability standards facilitate pre-sorting of high-value streams and enable low-impact bio- or DES-based recovery, while extended product lifetimes reduce functional E-waste generation. Together, policy integration and quantitative LCA evidence demonstrate that upcycling, when coupled with circular design, delivers substantially lower environmental burdens than conventional smelting-dominated recycling.

Transport-related inefficiencies and the export of hazardous components like printed circuit boards further intensified these impacts.[147] Similarly, Esopere[148] used integrated LCA and system dynamics modeling in Cameroon to show that an optimized, policy-driven formal recycling system could reduce global warming potential by 27%, carcinogenic toxicity by 34%, and fine particulate matter formation by 16.3%. Moreover, safety considerations are critical, particularly in regions where informal E-waste processing dominates. A study conducted in Ghana's Agbogbloshie region found that informal workers engaged in crude recycling methods such as open burning faced significant occupational hazards, including respiratory issues, thyroid dysfunction, reproductive impairments, and heavy metal poisoning,[149] and the study also revealed a negative correlation between workers' safety knowledge and actual safety practices, emphasizing the urgent need for context-sensitive safety training and policy interventions. Policy efficiency in formalizing recycling pathways is a recurring recommendation across multiple studies.[1] Esopere[148] proposed levies on producers and subsidies for formal recyclers as effective instruments to incentivize sustainable practices. Furthermore, consumer behavior significantly influences the success of recycling frameworks.[104] Laeequddin[150] highlighted that awareness, convenience, and social norms were strong predictors of responsible E-waste disposal behavior among consumers, highlighting the need for proactive regulations; even well-intentioned consumers often resort to unsafe or non-compliant disposal pathways. LCA and safety assessments must be tightly integrated into the design of circular systems for E-waste upcycling.[151] A hybrid approach combining environmental impact modeling such as LCA, economic metrics including Life Cycle Costing (LCC), and behavioral insights can enable complete decision-making and guide the design of safe, resource-efficient recovery infrastructures.[152,153] A comparative overview of key findings from recent LCA and safety-related studies on E-waste is presented in Table 14.

6. Circular design principles and sustainability integration

6.1. Design for reuse, modularity, and disassembly

Designing plays a crucial role in the development of different electronic products making their life cycle more combined with the further end of life practices.[5] Circular design is central to closing material loops in the electronic product lifecycle.[154] The integration of design for reuse, modularity, and disassembly

(DfRMD) enables material recovery, component upcycling, and resource efficiency while minimizing environmental impacts.[146] These principles are particularly critical in managing the projected rise of E-waste, which is estimated to reach 74.7 million metric tons by 2030.[155] Design for reuse (DfR) aims to extend product life and preserve the functionality of high-value components.[156] Modern studies show that 20–30% of electronic components in discarded devices retain operational functionality.[157] This presents an opportunity to integrate component harvesting into E-waste valorization chains. According to Iqbal[14] pre-processing and testing reusable components such as integrated circuits (ICs), sensors, or capacitors from printed circuit boards (PCBs) can help in reducing carbon emissions from raw material extraction. Component-level reuse also contributes to reducing raw material demand for critical raw materials (CRMs), enhancing supply chain resilience.[11] Modular design facilitates product segmentation into interchangeable, repairable, and upgradeable units. Devices such as smartphones, laptops, and audio equipment now increasingly embrace modular architectures that enable independent module-level recovery, repair, or substitution.[146] As demonstrated by Fairphone, modular smartphones enabled the recovery of up to 43% of valuable materials in the Fairphone 5 model.[155] Modularization directly impacts remanufacturing efficiency and offers dual benefits: economic through reduced production costs and environmental through lower energy input in component recovery.[158] Moreover, modularity introduces strategic decision-making dynamics between original equipment manufacturers (OEMs) and third-party recyclers (TPRs). As stated by Lai[155] product modularity is found to be high, so manufacturers can either cooperate with or compete against TPRs for core recovery and empirical models show that competition recovery strategies result in higher collection quantities,[155] whereas cooperation tends to yield higher supply chain profit. Disassembly-centric design (DfD) enhances end-of-life (EoL) recyclability by simplifying separation processes. Effective DfD practices include screw-based rather than adhesive joints, avoidance of permanent bonding, and minimization of mixed-material assemblies.[154] Huang[159] proposed a novel "peony diagram" modeling method to quantitatively evaluate and visualize disassembly difficulty using hierarchy-based constraint environments. Applied to smartphones, this technique identifies the shortest disassembly path and prioritizes parts based on difficulty coefficients, facilitating efficient recovery of critical components such as batteries and CPUs.[2] Product-level disassembly indices (like DEI or eDiM) quantify the disassembly effort required, serving as early-stage design decision tools. For instance, Apple's "Daisy" disassembly robot can process 29 iPhone models to recover core components with high precision.[155] Similarly, Xerox's toner cartridge programs rely on disassembly-centric modularity to reclaim 90% of component mass.[155] These industrial cases highlight how DfD enhances reuse pathways, reduces labor intensity, and mitigates safety hazards especially for lithium-ion batteries and hazardous materials.[14] Visual modeling tools like the peony diagram[159] and modular recovery frameworks[155] enable predictive analysis of design alternatives. Integration of these design elements enhances consumer engagement such as self-repair programs and supports downstream processes such as robotic disassembly and intelligent sorting. Furthermore, it enables the practical application of policy instruments like the EU's Ecodesign Directive and EN45554 standards for repairability and recyclability, thereby aligning engineering design with sustainability.

These synergistic design principles are collectively illustrated in the integrated circular design model illustrated in Fig. 7, showing how reuse, modularity, and disassembly co-enable closed loop E-waste systems.

6.2. Circular economy metrics and material flow indicators

The integration of circular economy (CE) principles into E-waste upcycling requires a systemic approach to monitor, quantify, and evaluate the material, environmental, and economic outcomes associated with circular interventions.[11] As per Grandhi[1] it is most important to make effort in deploying robust material flow indicators and circularity metrics that allow manufacturers, policymakers, and researchers to assess progress and identify areas for improvement. Material Flow Analysis (MFA) has emerged as a foundational tool for characterizing the physical pathways of resources across product life cycles, encompassing raw material extraction, manufacturing, use, reuse, and end-of-life stages.[160] By capturing the input–output relationships and stock accumulation of materials, MFA enables a detailed understanding of system-level inefficiencies, leakage points, and the potential for resource recirculation.[161] According to Yang[162] dynamic MFA models account for technology evolution and behavioral dynamics, thereby offering temporal resolution that is crucial for long-lived electronics and infrastructure-heavy recovery systems.[162] These indicators help benchmark circular performance against linear baselines and support scenario modeling for design and policy interventions.[163] The Easy Disassembly Metric (eDiM) and Design for Environment Index (DEI) are used to evaluate the effort and impact associated with product disassembly, offering early-stage feedback to designers for optimizing material selection and assembly methods.[159] Other thermodynamic and energy-based indicators, such as Cumulative Exergy Demand (CExD), assess the quality degradation of resources over multiple life cycles, offering insights into long-term resource conservation strategies.[3] Recycling Input Rate (RIR) and Waste-to-Resource Ratio (WRR) are further employed to track the proportion of secondary materials utilized and the efficiency of waste valorization, respectively.[160] These indicators are particularly relevant in the context of E-waste, where the heterogeneity of components and material complexity pose challenges to clean separation and high-value recovery.[161] The increasing focus on product traceability and environmental reporting under frameworks such as the EU Circular Economy Action Plan and ISO 59010 standards has also prompted the development of lifecycle-compatible indicators such as Circular Transition Indicators (CTIs) and Product Environmental Footprint (PEF), both of which integrate well with digital product passports and supply chain disclosure protocols.[164] Digital tools such as

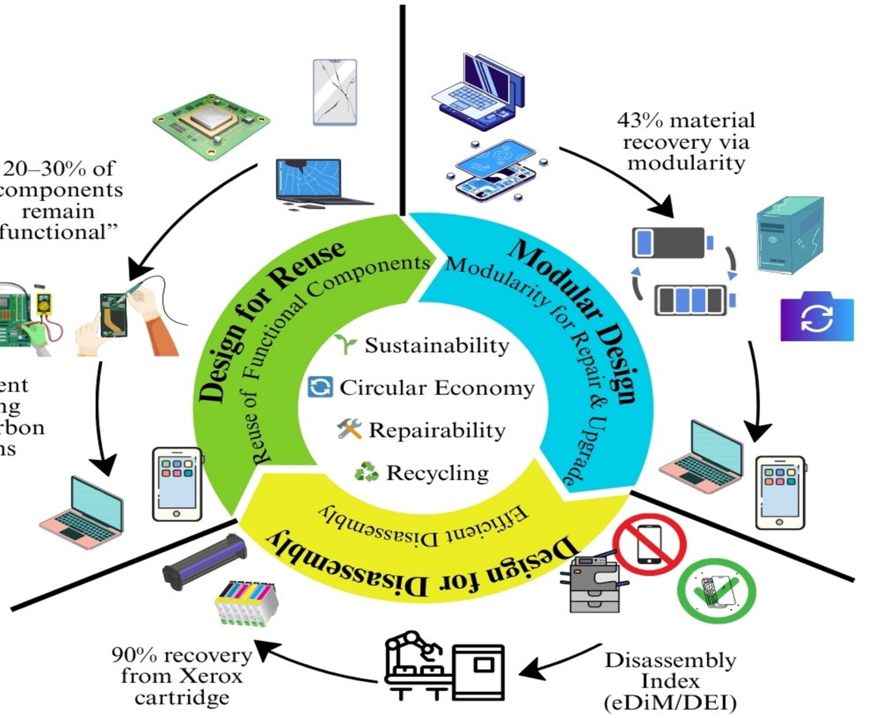


Fig. 7 Integrated circular design model illustrating the interplay between reuse, modularity, and disassembly in sustainable electronics.

Sankey diagrams and peony diagrams are being deployed to visualize material flow networks and circular feedback loops, aiding in the identification of hotspots and intervention leverage points.[159] These visual frameworks not only support transparency and stakeholder engagement but also enhance the interpretability of data for regulatory and industry stakeholders. The convergence of Industry 5.0 paradigms and circular manufacturing practices further introduces advanced digitalization tools such as digital twins and cyber-physical systems, enabling real-time monitoring of circular key performance indicators (KPIs) such as resource efficiency, disassembly success rate, and module reuse frequency.[165]

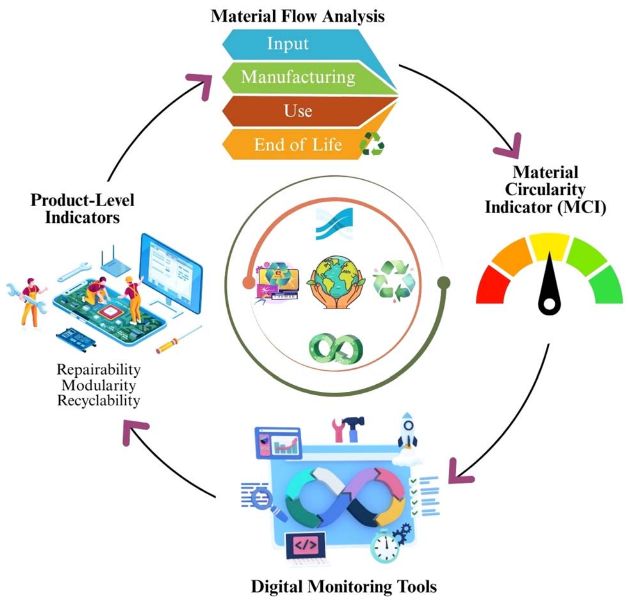


Fig. 8 Multi-layer circular metric framework for E-waste upcycling.

These systems allow predictive modeling of product behavior, facilitating preventive maintenance, optimized end-of-life routing, and extended asset longevity. E-waste upcycling, by implanting such metrics into the decision-making process, ensures that material recovery efforts are not only technologically feasible but also environmentally and economically justified across multiple product life cycles.[13] The integration of MFA and CE indicators is represented through a multi-layer metric framework illustrated in Fig. 8, highlighting synergies between circularity quantification and digital monitoring.

6.3. Alignment with UN SDGs and policy frameworks

The integration of circular E-waste management practices is increasingly shaped by global policy agendas, particularly the United Nations Sustainable Development Goals (SDGs).[1] Effective upcycling, recovery, and reuse of electronic waste align with several SDGs, including SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water).[11,166] A comparative analysis by Lopes dos Santos[166] examined E-waste policies in the UK, Brazil, and Ghana, revealing disparities in SDG alignment in which it was observed that the UK implements extended producer responsibility (EPR) policies that directly support SDGs 3, 6, and 12, whereas Brazil's shared responsibility model incorporates social inclusion and fair labor, aligning with SDGs 8 and 11 and finally with regard to Ghana's challenges with informal recycling, weak regulation, and limited infrastructure it highlights gaps in achieving SDGs 3 and 6. According to Murthy and Ramakrishna,[167] although 71% of the global population is covered by E-waste legislation, gaps remain in enforcement, infrastructure, and public awareness. Informal processing practices such as open burning and acid leaching continue to pose serious threats to human health and the environment, undermining SDGs 3, 6, 14, and 15.[1] Vulnerable populations, particularly children and pregnant women, face disproportionate exposure to toxic substances in informal recycling settings.[11] Policy frameworks such as the EU Circular Economy Action Plan, ISO 59000 series standards, and Basel Convention amendments are promoting SDG-aligned practices by enhancing traceability, regulating transboundary waste movement, and enforcing minimum recyclability and repairability criteria.[168] Instruments like the Ecodesign Directive, Right to Repair laws, and green public procurement further reinforce SDG 12 by supporting sustainable product lifecycles and reduced resource extraction.[169] The use of circularity indicators, such as the Material Circularity Indicator (MCI), Recycling Input Rate (RIR), and Product Environmental Footprint (PEF), helps monitor alignment with the SDGs and provides actionable data for lifecycle policy interventions.[163] In sum, policy-driven alignment between E-waste upcycling and the SDGs requires formalizing informal economies, strengthening metrics and reporting, and harmonizing national frameworks with international sustainability benchmarks.[1] Such integrated approaches will be essential for driving system-wide circularity and long-term resilience. Fig. 9 provides the understanding of the role and application of different SDGs in mitigating E-waste impacts.

7. Industrial translation, challenges, and future perspectives

The industrial translation of E-waste upcycling and recycling technologies is considered important for enabling sustainable resource recovery, which is significantly burdened with the constant technological, economic, regulatory, and infrastructural barriers.[170] While promising laboratory-scale processes have demonstrated high yields of critical metal recovery and polymer reuse, translating these innovations into

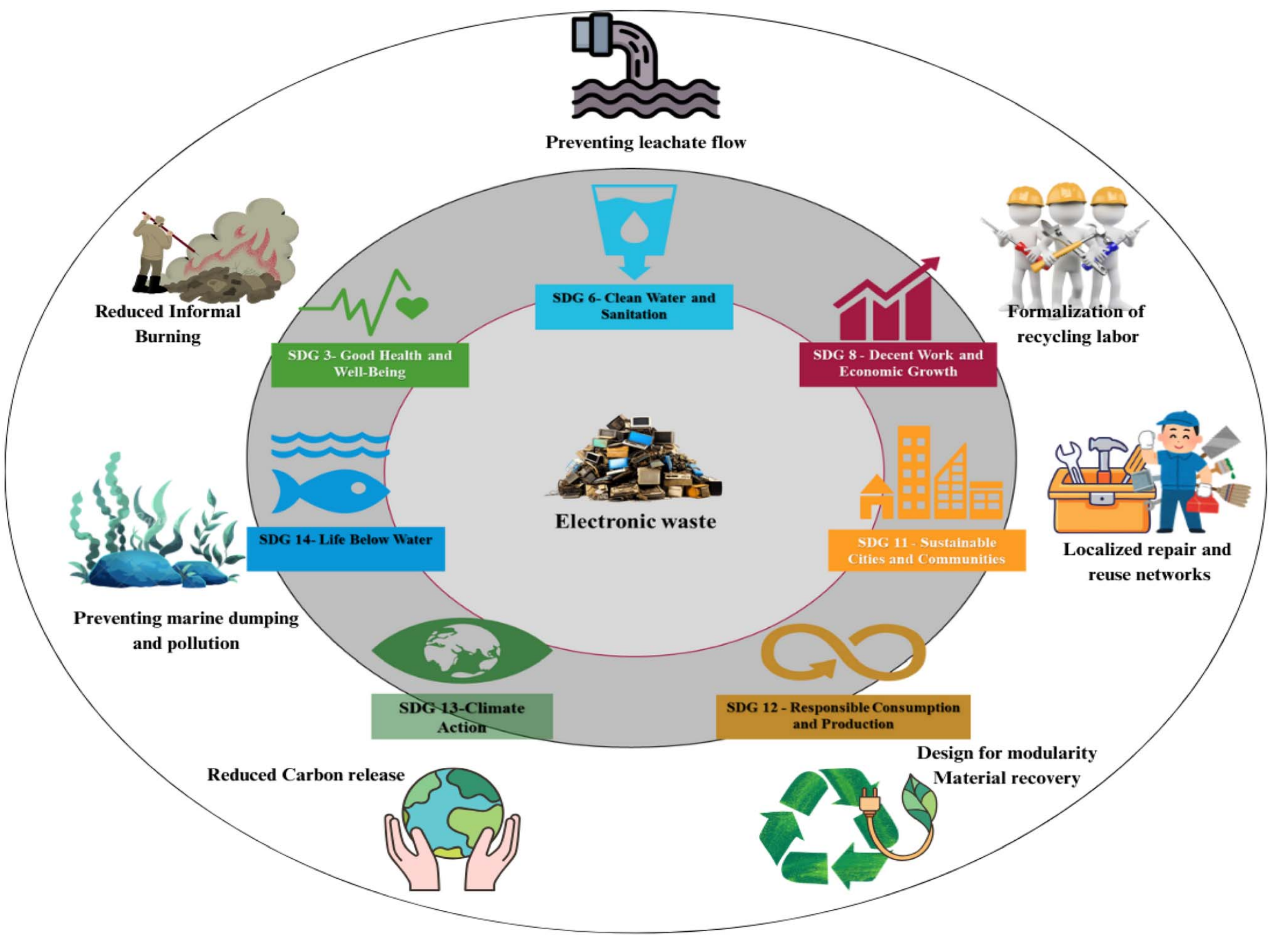


Fig. 9 Role and application of different SDGs in mitigating E-waste impacts.

Table 15 Different aspects of E-waste directives used towards the upcycling of E-waste[1,96,174]

Aspect	European Union	United States	China	India
Core framework	WEEE Directive, RoHS, Ecodesign, and Right-to-Repair (EN45554)	No federal law; state-level e-waste and repair laws	WEEE regulation and circular economy promotion law	E-waste management rules (2011; amended 2016, 2018, and 2022)
Governance	Harmonized and EU-wide	Fragmented and state-driven	Centralized and top-down	Central rules and weak state enforcement
EPR	Binding mandatory targets	Patchy and state-specific	Producer-funded subsidy system	Formal EPR with compliance gaps
Design leverage	Strong (repairability, disassembly, and spare parts)	Minimal	Limited	Limited
System outcome	Highest formal collection and recycling rates	Uneven coverage and lower averages	Rapid formalization and centralized treatment	Dominant informal sector

scalable, economically viable, and environmentally safe industrial operations remains a formidable challenge.[25] E-waste processing technologies can be broadly categorized into pyrometallurgical, hydrometallurgical, and biometallurgical methods.[11] Among these, hydrometallurgical approaches, especially solvent extraction and acid leaching, have shown up to 95% efficiency in metal recovery but pose secondary environmental challenges due to the use of corrosive chemicals.[9] Biometallurgical methods, using microbial bioleaching, offer a 30–50% lower environmental footprint but face issues in reaction kinetics and process stability at the industrial scale.[9,15] Reverse supply chain integration and smart logistics networks are vital for efficient upcycling but are underdeveloped, especially in regions where informal recycling dominates.[1] Designing closed-loop, data-driven systems, potentially using blockchain or IoT technologies, has been proposed to enhance traceability and accountability in E-waste flows.[171,172] Furthermore, selective polymer recovery and non-metallic component reutilization remain technologically immature, requiring advancements in multi-material separation, automation, and modular recycling.[173] Many recovery facilities operate below capacity due to supply chain volatility and inconsistent E-waste streams.[172] Moreover, in developing countries, informal recycling often undercuts formal systems due to lower operational costs and the absence of compliance requirements.[17] Cost–benefit analyses indicate that urban mining from E-waste could be more cost-efficient than virgin mining for several metals such as gold, palladium, and copper, especially when externalities are considered.[15,17] However, initial setup costs and lack of extended producer responsibility (EPR) mechanisms make the market readiness of these technologies variable across regions. Financial incentives, such as green subsidies, tax exemptions, or producer take-back credits, are critical to bridging this economic gap.[171] Innovative business models such as product-service systems (PSSs), buy-back schemes, and leasing electronics are gaining interest for reducing end-of-life discard rates and enabling traceable returns. Policy frameworks play a pivotal role in enabling sustainable industrial translation.[1] The EU WEEE Directive and RoHS Directive serve as global benchmarks, enforcing eco-design, material restrictions, and mandatory take-back schemes.[172] Switzerland and Japan have implemented advanced EPR systems that shift financial and logistical responsibility to producers, encouraging design for disassembly and recycling.[171] Conversely, in low- and middle-income countries, enforcement remains weak. Although over 78 countries have adopted E-waste legislation, only a fraction enforces it effectively.[173] The informal sector still processes most of the E-waste in regions like South Asia, Sub-Saharan Africa, and parts of Latin America, using crude techniques that pose severe health and environmental risks.[15,17] Strengthening international conventions like the Basel Convention and promoting technology transfer, especially through South–South cooperation and UN-driven circular economy platforms, are crucial for harmonizing global E-waste practices.[9] Achieving genuinely circular E-waste upcycling requires alignment between policy instruments, product design, and environmentally optimized processing routes.[1] The European Union combines binding Extended Producer Responsibility (EPR) under the WEEE Directive with RoHS substance restrictions and enforceable eco-design and repairability requirements such as Ecodesign Directive, EN45554.[164] This integration directly links product design to end-of-life outcomes and is reflected in the world's highest formal collection and recycling rates. In contrast, the United States lacks a federal E-waste or eco-design framework, relying instead on fragmented state-level take-back laws with limited design leverage.[174] China operates a centralized WEEE system supported by its Circular Economy Promotion Law, achieving rapid formalization and large-scale recycling capacity, but with weaker transparency and eco-design mandates than the EU.[175] India has adopted EU-style EPR on paper through successive E-Waste Management Rules, yet enforcement remains limited and informal processing still dominates, constraining the impact of circular-design provisions (Table 15).[1,96]

7.1. Future perspectives

Future industrial strategies for E-waste management must evolve toward more integrated, equitable, and scalable solutions. One promising direction involves the development of decentralized micro-recycling hubs equipped with artificial intelligence for real-time diagnostics and operational optimization. These hubs can be tailored to both urban and rural contexts, enhancing accessibility and responsiveness in local E-waste processing.[47] In parallel, hybrid metal recovery technologies that combine hydrometallurgy and bioleaching with circular water and reagent systems present a sustainable pathway to improve material recovery efficiency while reducing environmental footprints.[11] Additionally, the integration of environmental ethics and social justice principles into supply chain design is crucial to ensure the inclusion and fair compensation of informal sector workers, who currently handle a substantial share of E-waste under hazardous conditions.[171] A future-ready system also requires robust cross-disciplinary collaboration among academia, industry, and policy stakeholders to convert laboratory-scale research into scalable, regulatory-compliant, and economically viable industrial technologies.[1] By aligning these technological innovations with supportive regulatory frameworks and market incentives, E-waste upcycling can transition from isolated pilot projects into mainstream sustainable manufacturing practices, firmly embedded within the global circular economy.[14]

8. Conclusion and recommendations

E-waste represents a paradox of modern innovation, a rapidly growing environmental hazard and an untapped reservoir of valuable resources. This review underscores the transformative potential of upcycling as a holistic approach to valorize E-waste beyond conventional recycling. Through a multidisciplinary synthesis of material composition analysis, upcycling pathways, and green processing techniques, the study demonstrates how E-waste can be converted into high-value functional materials such as electrocatalysts, supercapacitor electrodes, and advanced sensors. The integration of bioleaching, deep eutectic solvents, and biomimetic synthesis enables low-impact, decentralized processing suitable for diverse socioeconomic contexts. Importantly, the upcycling paradigm aligns with circular economy principles by reducing toxicity, extending material life cycles, and promoting design for reuse and modularity. Life cycle assessment studies further highlight the environmental and economic benefits of upcycled materials compared to primary mining and informal recycling. However, translating these technologies into industrial-scale solutions requires overcoming critical barriers such as inconsistent feedstock quality, lack of policy harmonization, limited infrastructure, and informal sector exclusion. Future efforts must focus on integrating environmental ethics, policy frameworks, and cross-sector collaboration to scale up innovations and foster inclusive, circular E-waste economies. Ultimately, upcycling offers a pathway to reimagine E-waste not as a burden, but as a cornerstone of sustainable innovation.

Author contributions

Pranav Prashant Dagwar: writing the original draft. Debajyoti Kundu: original draft preparation; supervision; writing: review and editing. Deblina Dutta: conceptualization, original draft preparation, supervision; writing: review and editing.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work presented in this manuscript.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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