



Closing the Loop in Electronics: A Review on Sustainable Utilization of E-Waste

Junaid Saddiqi¹ · Kasumawati Binti Lias¹ · Malaika Saddiqi²

Received: 25 January 2026 / Accepted: 18 July 2026

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Abstract

Even as global efforts to manage the growing volumes of solid and hazardous waste in an environmentally sound manner, the world is now facing an even more complex challenge, the rapid growth of electronic waste (e-waste). The global e-waste market is projected to reach USD 65.9 billion by 2025, reflecting its increasing environmental and economic significance. E-waste accumulates as a byproduct of technology-driven lifestyles, including households, educational institutions, workplaces, and IT sectors. E-waste poses serious threats to the environment as well as to health conditions due to the toxic elements like heavy metals and flame retardants that can pollute the ecosystem. At the same time, e-waste represents a valuable resource due to the presence of precious and rare-earth metals. However, existing research has largely focused on environmental hazards and management challenges, with comparatively limited emphasis on sustainable and low-cost utilization strategies. This review aims to critically examine current e-waste recycling and utilization technologies, with a focus on identifying practical and sustainable approaches for resource recovery. The study is based on a structured literature survey primarily conducted using the Scopus database, where relevant studies were systematically screened and categorized into key thematic areas, including environmental impacts, material composition, recovery techniques, and emerging utilization strategies. This review summarizes current e-waste recycling and use technologies by combining environmental risk assessment with resource recovery potential. It looks at the chemical makeup of e-waste and its health impacts while examining physical and chemical recovery methods in terms of scalability and practical use. It focuses on challenges in developing countries, such as poor infrastructure and the environmental risks tied to unregulated e-waste imports. To tackle these issues, this study suggests a low-cost and practical method for extracting carbon materials from waste batteries to create conductive inks for sensor applications. This proposed approach represents a novel contribution by demonstrating the potential of converting e-waste into functional materials, supporting circular economy principles, and enabling localized, sustainable resource utilization in resource-limited settings.

Keywords Hazardous Waste · Electronic Waste · IT sectors · Obsolescence · Conductive Ink · Flame Retardants

Extended author information available on the last page of the article

Introduction

E-waste refers to discarded electrical and electronic equipment [1–3], that has reached the end of its useful life or is not wanted by the user. It comprised several devices that operate using electricity [4], batteries [5] and are disposed of due to damage, technological upgrades [6] or obsolescence [7]. Modern products demonstrate markedly improved performance [8], over earlier generations in many respects; however, despite these advantages, they also accelerate obsolescence [9]. Consequently, e-waste has emerged as a paradox in both everyday life [10] and industrial practice. Different international organizations view e-waste differently. In 2024, the United Nations Institute of Training and Research identified it as one of the fastest-growing and most complex waste streams, posing risks to human health and the environment while causing the loss of valuable raw materials [11]. In 2025, the European Commission reported that WEEE is one of the fastest-growing waste streams globally and in the EU, containing complex and hazardous materials that pose serious environmental and health risks if not properly managed [12]. In 2025, the Basel Convention noted that while electronics have transformed communication, work, education, and entertainment, their rapid growth has significantly increased end-of-life devices, driving the global rise in e-waste [13].

To further contextualize the global rise of e-waste concerns, it is essential to examine the scale and distribution of e-waste generation [14]. Recent statistical evidence highlights the scale of global e-waste. In 2022, the International Telecommunication Union reported a record 62 billion kg generated worldwide (7.8 kg per capita), with only 22.3% formally collected and recycled using environmentally sound practices [15]. This indicates that nearly 77.7% of global e-waste remains uncollected or is processed through informal or environmentally unsafe methods. Europe was the region that generated the most e-waste (17.6 kg per capita) [16], Accounting for a significant share of global generation, with a recycling rate of 7.5 kg per capita) [15]. Asia generates the least e-waste (6.4 kg per capita) [17] representing a substantial proportion of total global e-waste due to its large population, but the recycling rate is also lower (0.76 kg per capita) [15] equivalent to a very small percentage of formally processed waste. Oceania generates e-waste close to Europe about 16.1 kg per capita) [18]. The recycling rate is (6.66 kg per capita). Similarly, America is also at the top (14.1 kg per capita) with a recycling rate of 4.2 kg per capita. African countries had the lowest rate, with less than 1 per cent of e-waste being documented as formally collected and recycled [15]. Despite these statistics, a major concern arises for countries that import e-waste [19], [20], which do not have adequate frameworks or infrastructure for the disposal of electronic waste [21]. Unregulated importation of waste can cause pollution of the soil, water, and atmosphere due to the presence of harmful chemicals [22]. The Global e-Waste Monitor 2024 reported a record 62 million tonnes of e-waste in 2022, an 82% increase since 2010, and projects it to reach 82 million tonnes by 2030 [23]. These trends not only highlight the scale of the problem but also directly influence the selection of appropriate utilization strategies. For instance, regions with high e-waste generation but low recycling rates present opportunities for decentralized and low-cost recovery technologies, whereas regions with established infrastructure can adopt advanced and high-efficiency recycling systems.

Building on these statistics and growth projections, it becomes equally important to identify the major sources contributing to the rising amount of e-waste [24]. E-waste mostly arises from technology-based devices [25], which are categorized into household appliances

like refrigerators [26], washing machines [27], microwaves [28]; consumer electronics like smartphones [29], laptops [30], televisions [31], tablets [32], information and communication technology (ICT) devices [33] like servers, routers, printers, etc, as well as new smart and medical devices [34]. These technology based devices are composed of complex mixture containing valuable and toxic substances [35] like metals [36], plastic [37], glass [38]. The major risks associated with e-waste stem from the presence of hazardous substances such as heavy metals (e.g., mercury, cadmium, lead), flame retardants (e.g., pentabromophenol, polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA)), and other potentially toxic compounds that contaminate soil [39], water [40], and air [41]. Despite these negative impacts and environmental issues faced by e-waste [42], it contains several essential components and valuable elements that make it a critical resource for sustainable material management. Some of the valuable elements found in e-waste include precious metals like gold [43], silver [44], and platinum [45], as well as base metals like copper [46], aluminum, and nickel [47], and other strategic metals like palladium [48], cobalt [49], and rare earth metals which are being used in the manufacture of electronic components. Most research on e-waste has focused primarily on its hazardous nature and management challenges, with relatively little attention given to efficient utilization strategies [50]. Fig. 1 shows Scopus-based bibliometric analysis indicates a relatively sharp increase in publications primarily addressing e-waste generation and environmental impacts, whereas research focused on the utilization and value recovery of e-waste remains comparatively limited. The bibliometric analysis in the proposed study primarily focuses only on the Scopus database due to its broad coverage, standardized indexing, and suitability for citation and trend analysis. While Web of Science and Google Scholar also provide valuable data, they were excluded to ensure consistency and avoid duplication. Most recent studies highlight problems and risks, but few propose practical solutions for material reuse or sustainable applications. This evident imbalance highlights a significant gap in research and directly limits progress toward circular economy objectives, as insufficient focus on utilization and value recovery hinders the development of sustainable, closed-loop systems where e-waste is effectively transformed into secondary resources rather than being treated solely as a disposal problem.

During the previous five years, studies on the use of e-waste have begun to concentrate on the conversion of discarded electronics to precious materials using various approaches [51], [52] such as the recovery of precious metals, such as gold [53], silver [54], palladium [55], and platinum [56] from printed circuit boards by using techniques such as hydrometallurgy [57], bio-leaching processes [58], and the use of eco-friendly solvents; the separation of rare earth elements in magnets [59] and other electronic components using selective separation techniques; the recovery of materials such as lithium, cobalt, nickel, and manganese in spent lithium-ion batteries [60], [61]; and the processing of metal fractions to produce functional nanocatalysts and nanosensors [62] for sensing, energy, and other applications related to the environment. On the other hand, polymeric materials in cables and plastic cases are being reused to make composite materials [63], [64], while the material rich in carbon in e-waste is preferably used in the production of graphene-based materials and conductive materials for energy storage components [65], [66]. In the context of economic viability, the majority of the methods used to deal with e-waste have limitations in relation to the high processing costs, as well as the inability to be scaled up. Countries with a developed economy are in a better position to adopt technology to utilize e-waste. But the environmental and

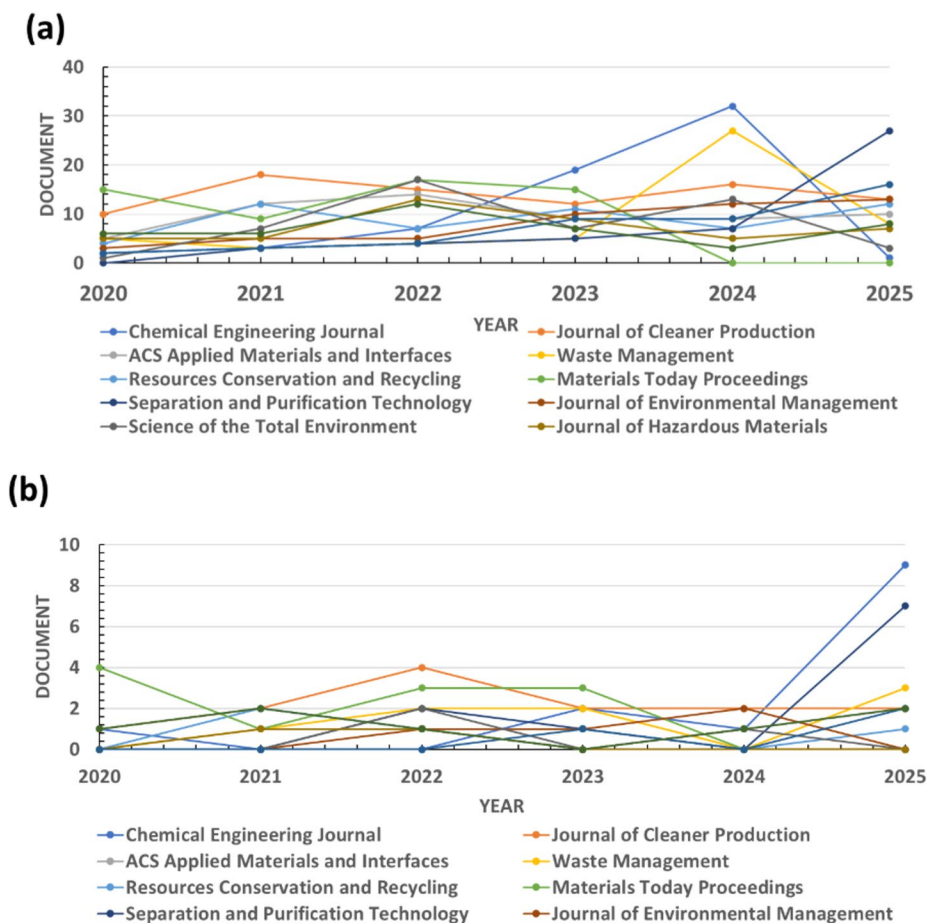


Fig. 1 Scopus-based publication trend (2020–2025) showing extensive research on e-waste impacts compared to the limited focus on e-waste utilization and value recovery across major journals

health problems of processing are increasingly being transferred to developing countries with less strict regulations and limited capabilities to manage the problem themselves [67], [68]. According to Scopus Statistics, there is an imbalance in e-waste utilization research, with China leading (5 publications) while developing and emerging economies contribute minimally, underscoring the gap between technological capacity and global e-waste responsibility as shown in fig. 2. The increasing volume and changing composition of e-waste not only present environmental challenges but also create significant opportunities for resource recovery and sustainable material utilization. For instance, the growing proportion of discarded electronic devices rich in metals and carbon-based materials provides a viable feedstock for developing low-cost recovery technologies and functional materials. However, the variability in waste composition and the lack of standardized collection systems impose constraints on the efficiency and scalability of these approaches. Therefore, understanding global e-waste trends is essential for designing targeted and practical utilization strategies.

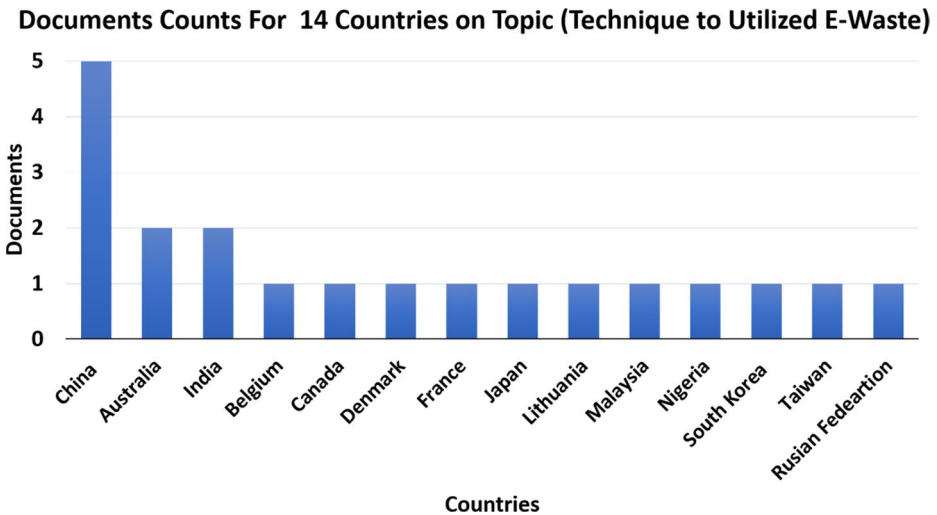


Fig. 2 The Scopus-based analysis of documents by country (2020–2025) reveals a significant imbalance in research on e-waste utilization techniques across 14 listed countries

To ensure a systematic and structured analysis, this review is based on a comprehensive literature survey primarily conducted using the Scopus database, selected for its wide coverage and standardized indexing. Relevant studies published in recent years were screened using keywords related to e-waste generation, recycling technologies, resource recovery, and sustainable utilization. The selected literature was further categorized into thematic areas, including environmental impacts, material composition, recovery techniques, and emerging low-cost utilization strategies. This approach enables both descriptive synthesis and critical comparison of existing methods, allowing the identification of key research gaps, technological limitations, and opportunities for sustainable innovation. The review also emphasizes novel, low-cost, and environmentally sound options, such as the utilization of battery waste carbon to generate conductive ink, emphasizing the application of the concept of the circular economy, and developing standardized sustainable processes that can make e-waste, an environmental issue, an asset.

Global Status of E-Waste

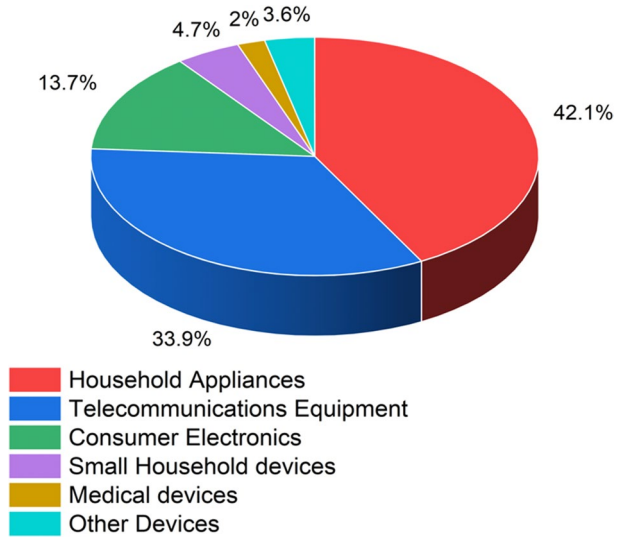
The global production of e-waste has now attained alarming proportions. According to estimates by UNEP, in collaboration with ITU and the Global E-waste Statistics Partnership, over 60 million tons of e-waste are generated globally each year [69]. However, less than 25% is properly collected and recycled, with most e-waste either mismanaged or improperly processed, often involving hazardous materials such as heavy metals [70], flame retardants [71], and organic pollutants [72]. These global trends highlight a critical imbalance between e-waste generation and formal recycling capacity, particularly in developing regions. This gap presents both a challenge and an opportunity: while inadequate infrastructure limits the adoption of advanced recycling technologies, it simultaneously encourages the development of low-cost, decentralized, and scalable utilization strategies that can operate under

resource constraints. Several international bodies like the Basel Convention secretariat, World Health Organization (WHO), European Commission, U.S. Environmental Protection Agency (EPA), and a host of other non-governmental bodies like Greenpeace and ISWA are working towards these issues through proper plans, strategies, and procedures. The role, types, and detailed contributions given by these bodies from the perspective of global management of wastes are given in Table S1, which also reflects their contributions towards successful global digital recycling procedures and preservation of global health. While global data clearly indicate the rapid growth of e-waste, existing reports often lack consistency in data collection methodologies across regions, making direct comparisons challenging and highlighting the need for standardized reporting frameworks.

Sources and Types of E-Waste

E-waste can be classified based on the source and function of electronic devices [89]. E-waste is produced as a result of household appliances, industrial, medical, and public sectors. The household appliances are categorized as large household appliances, such as fridges [90], freezers [91], washing machines [92], cookers, air conditioners [93], and microwaves [94]. Smaller household appliances, such as toasters, irons, clocks, vacuum cleaners, electric kettles, and blenders, are other sources. Computers and telecommunication, the IT sector, generate e-waste in the form of computers [95], laptops [96], desktops [97], phones [98], telecommunication gadgets such as scanners [99], network cables, and other telecommunication devices [100]. Consumer electronics such as televisions [101], radios [102], music devices [103], camcorders, digital cameras [104], and audio players [105] are other sources of e-waste. Lighting apparatus including fluorescent [106], halogen lamps [107]. High-intensity discharge lamps are disposed of regularly. Other sources include electrical and electronic tools such as lawn mowers, drills, sewing machines, and electric saws [89]. Another source includes e-toys and leisure/sporting equipment, including consoles, electric trains, and racing cars [108]. Medical devices [109] such as dialyzers [110], medical fridges, ultrasound machines, cardiology machines, and ventilators [111]. E-waste also includes monitoring and control devices (e.g., sensors, valves, smoke detectors, thermostats) and automatic dispensers. Its diverse sources demand specialized recycling methods. Large household appliances dominate (42.1%), followed by IT and telecom equipment (33.9%), consumer electronics (13.7%), and small devices (4.7%) [112]. Other categories contribute much less, with medical devices, lighting, and electrical/electronic tools each under 2%, and automatic dispensers, toys, sports, and monitoring and control devices and other 3%. As shown in fig. 3, the diversity of e-waste sources and device types directly determines the feasibility and efficiency of recovery processes. Metal-rich components such as printed circuit boards are suitable for high-value metal extraction, while polymeric and carbon-rich fractions offer potential for conversion into functional materials such as composites and conductive inks. This highlights the need for material-specific and application-driven utilization strategies

Fig. 3 Distribution of E-Waste by Type in the European Union (Data from EUR-Lex, Directive 2012/19/EU)



Composition and Effects of Hazardous Substances in E-Waste

E-wastes contain a number of hazardous substances [113] which are embedded in metals, plastics, and electronic components [114]. The major risks posed by these components include neurotoxicity [115], damage to vital body organs, and congenital disorders [116]. Flame retardants, polychlorinated biphenyls (PCBs) [117]. Some organic compounds, which are embedded in plastics and capacitors, account for endocrine disruption. Other potential dangers posed by metals like nickel, copper, and chromium, which are used in connectors and electronic components, may contaminate soils and water, leading to effects on plant life and microbial populations [118]. The heterogeneous composition of e-waste presents both challenges and opportunities for sustainable utilization. While the presence of hazardous substances complicates processing and requires careful handling, the coexistence of valuable metals and functional materials provides strong potential for resource recovery and value-added applications. Therefore, effective utilization strategies must balance environmental safety with economic feasibility. Improper disposal or recycling releases these substances into the air, soil, and water, worsening environmental pollution. The composition, sources, and effects of these chemicals are presented below in Table 1.

The data in Table 1 reveal that many hazardous substances in e-waste, such as lead, mercury, and cadmium, are toxic and very persistent in the environment, creating big challenges for safe processing. At the same time, the presence of toxic and valuable materials within the same waste stream complicates recovery processes. This requires solutions that effectively balance material extraction efficiency with environmental safety. This situation highlights the need for developing selective and environmentally sound usage strategies.

Table 1 Major chemical contents in E-waste, their common sources, and their effects on human health, soil, and air

Chemical	Common Source in E-Waste	Effect on Human Health	Environmental Impact (Soil & Air)	Key References
Lead (Pb)	Cathode ray tubes (CRTs), batteries, solder, PVC cables	Loss of appetite, Abdominal pain, Renal dysfunction, Fatigue, Sleeplessness, Headache, Hypertension, Neurotoxicity, anemia	Contaminates soil, bioaccumulates in plants; can leach into groundwater; airborne lead dust can affect nearby areas	[119], [120], [121], [122], [123]
Mercury (Hg)	Fluorescent lamps, switches, batteries, and thermometers	Inorganic mercury salts can irritate the gastrointestinal tract and lead to kidney damage. In contrast, organic mercury compounds, due to their fat-soluble nature, can cross the blood–brain barrier and result in neurological and behavioral disorders.	Pollutes soil and may volatilize and get released into the atmosphere, to settle elsewhere; very toxic to aquatic organisms.	[123], [124], [125], [126], [127]
Cadmium (Cd)	Batteries (Ni-Cd), semiconductors, pigments, plastics	Kidney damage, lung damage, bone fragility, carcinogenic	Easily migrates through soil and could affect the groundwater; persists in the environment; toxic to plants and microorganisms	[128], [129], [130], [131], [132]
Chromium (Cr, especially Cr VI)	Stainless steel components, metal plating, circuit boards	The toxicity of chromium depends on its oxidation state, with trivalent [Cr(III)] and hexavalent [Cr(VI)] being the most common. Cr(VI) is significantly more toxic due to its strong oxidizing nature and is readily absorbed through the lungs and gastrointestinal tract, whereas Cr(III) is poorly absorbed and less harmful.	May leach into soil and water, bioaccumulate, and prove toxic to microorganisms	[133], [123], [134]
Brominated Flame Retardants (BFRs)	Plastic casings, printed circuit boards	Endocrine disruption, thyroid dysfunction, developmental issues	Residues in soil and water volatilizes and accumulates in the atmosphere, and is known to bioaccumulate in the ecosystem, targeting wildlife.	[135], [136], [137]
Polychlorinated Biphenyls (PCBs)	Capacitors, transformers, and old electronic devices	Cancer risk, liver damage, immune and reproductive system effects	Highly persistent, can contaminate soils and sediment, volatilize from these materials to become airborne, and bioaccumulate in living tissue.	[138], [139], [140], [141]
Arsenic (As)	Semiconductors, LEDs, glass	Skin lesions, cancer, cardiovascular, and neurological effects	Pollutes soil and water; toxic to both plants and animals; also leaches into the groundwater	[142], [143], [144]

Table 1 (continued)

Chemical	Common Source in E-Waste	Effect on Human Health	Environmental Impact (Soil & Air)	Key References
Nickel (Ni)	Batteries, circuit boards, and electroplating	Contact of Ni to the skin causes skin irritation, and oral exposure may lead to erythema, eczema, lung fibrosis, and carcinogenic properties that increase the cancer risk	Elevated nickel concentrations in soil can inhibit plant growth. Nickel toxicity in plants manifests as chlorosis, necrosis, and wilting, and it disrupts the activity of antioxidant enzymes such as superoxide dismutase and catalase, leading to increased oxidative stress.	[123], [145], [146]
Copper (Cu)	Wires, printed circuit boards, and connectors	Cu is an essential trace element required in both plants and animals for several enzymatic reactions as a catalyst and cofactor. However, an excess of Cu can result in copper toxicity, but excessive exposure can cause liver/kidney issues	Accumulates in soil; can be toxic to plants and aquatic life at high concentrations	[123]
Zinc (Zn)	Galvanized metals, batteries, circuit boards	High doses can cause nausea, vomiting, and anemia	Accumulates in soil; can be toxic to plants and microorganisms	[147]
Tin (Sn, including organotin compounds)	Solder, coatings	Elevated tin levels can accumulate in the liver, bones, lymph nodes, and kidneys. Prolonged exposure to tin is associated with liver toxicity, immune system disorders, depression, and neurological damage.	Persists in soil and water; toxic to aquatic organisms, especially Microorganism	[147], [148]
Platinum Group Metals (PGMs: Pt, Pd, Rh)	Catalytic converters, hard drives	Low human toxicity, but Pd primarily targets mitochondria by increasing reactive oxygen species (ROS) production and impairing the mitochondrial respiratory system, which can ultimately trigger apoptosis.	Can accumulate in soil; minimal air dispersion; bio-accumulation potential	[149], [150], [151]
Beryllium (Be)	Electrical connectors, PCBs, aerospace electronics	Lung disease (chronic beryllium disease), carcinogenic	In plants, beryllium disrupts multiple physiological and morphological processes, leading to reduced growth. It notably impairs seed germination, biomass production, and root development.	[151], [152]

Precious and Rare Metals in E-Waste

E-waste comprises various hazardous materials and elements, such as lead, mercury, and cadmium [153], and brominated flame retardants, which are extremely harmful to human health and the environment when disposed of incorrectly [154]. Despite the dangers associated with the risks of e-waste, it also contains rare and precious resources crucial to modern

electronics and new technology [155]. In the periodic table, certain elements are classified into three categories of endangerment [156], limited availability, increased threats, and serious threats [157], [158] as shown in Fig. 4. Several of these critical and endangered materials, including gold, palladium, rhodium, indium, tantalum, and rare earth materials, neodymium, and dysprosium [159], can also efficiently be extracted from waste electronics [160]. These materials are highly expensive and scarce in natural deposits, making their recycling crucial for both environmental and economic sustainability, especially given the energy-intensive and destructive nature of mining. Table S2 underscores their importance by detailing their sources, periodic classification, cost, and criticality level. The increasing demand and limited natural availability of these critical metals make e-waste an important secondary resource. This creates strong economic incentives for developing efficient recovery technologies, particularly in regions where primary resource extraction is not feasible. However, fluctuations in metal content and market value can influence the economic viability of different utilization pathways.

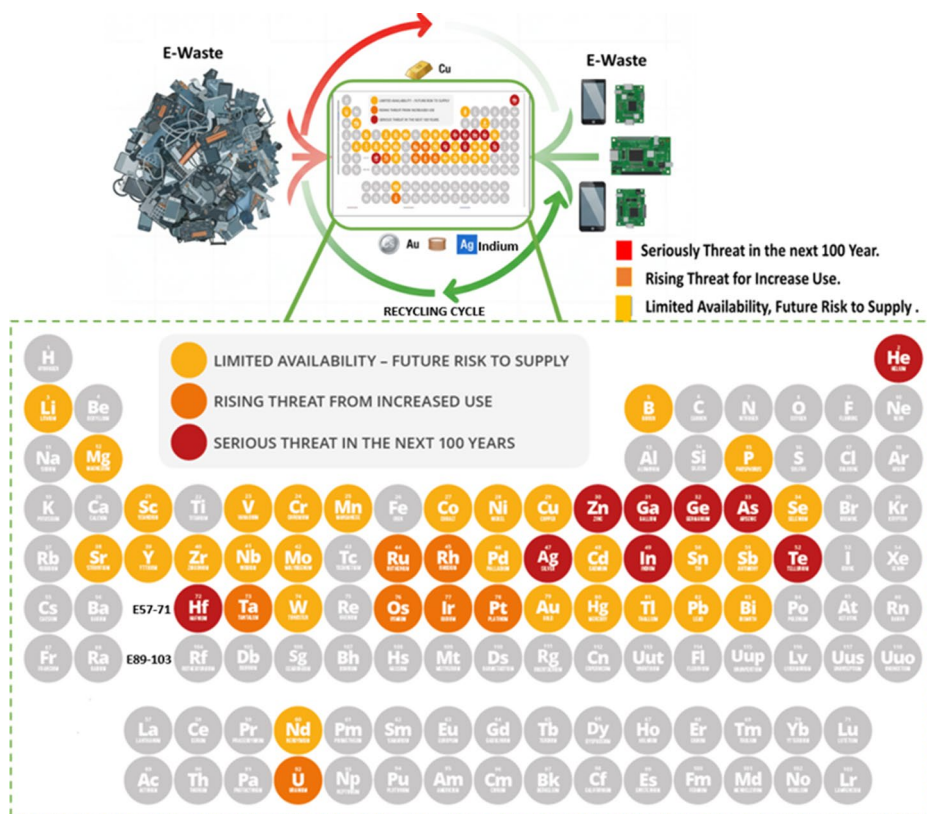


Fig. 4 Illustration of Endangered Elements and their representation in Periodic table

Utilization Strategies of Precious and Rare Metals from E-Waste

Electronic waste consists of a wide array of precious and rare metals. Recycling requires the convergence of more than one processing or analytical method [190]. The current processing methods for electronic waste include physical pretreatment processes [191] combined with thermal [192], chemical [193], electrochemical [194], or biological methods [195]. Depending on the type of electronic material to be processed, as shown in fig. 5, physical or mechanical methods for initial purification allow for the liberation or beneficiation of metal-containing materials found on PCBs, connectors, integrated circuits, batteries, or cable assemblies. Enriched or purified material is then subjected to pyrometallurgical [196] or hydrometallurgical processing [197] to separate or selectively dissolve metals through either phase or selective dissolution. Separated metals can be further purified using solvent extraction, ion exchange, or electrochemical deposition. Advanced analytical instruments enable monitoring of composition and recovery during recycling. Together, these methods provide an integrated approach for recovering high-purity metals such as gold, silver, platinum, palladium, copper, and rare earth elements from e-waste. The processing methods described under Table 2 can thus provide an integrated approach to the recovery or recycling of high-purity metals like gold, silver, platinum, palladium, copper, or other rare earth metals within the integrated framework of electronic wastes. Although significant progress has been made in metal recovery technologies, most approaches remain energy-intensive and economically demanding [42], limiting their practical implementation, particularly in developing countries. Furthermore, limited attention has been given to decentralized and low-cost alternatives, indicating a gap between laboratory-scale innovation and real-world application.

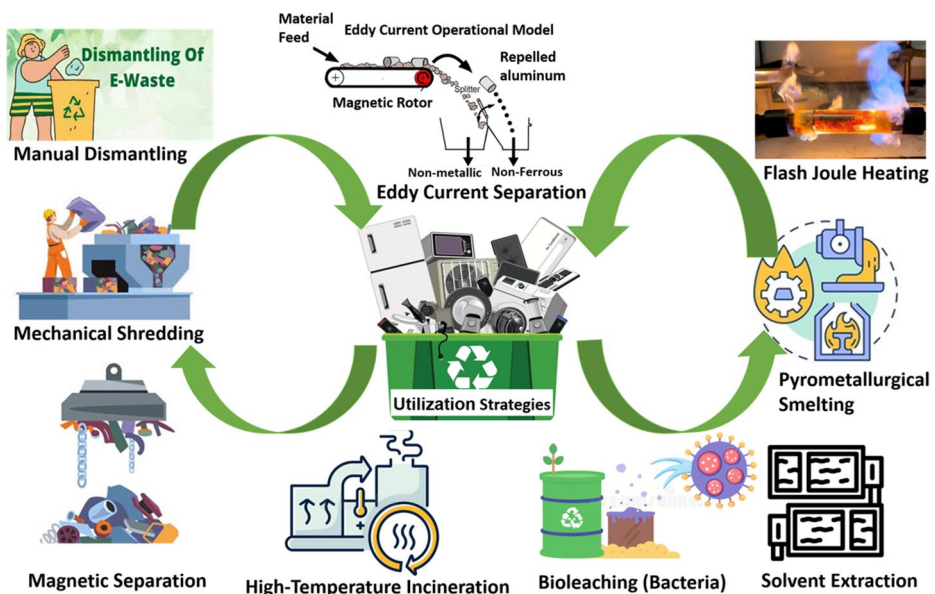


Fig. 5 Overview of e-waste recycling and utilization strategies, illustrating the sequential processes from manual dismantling, mechanical shredding, magnetic and eddy current separation, and thermal treatments, to chemical and biological methods

Table 2 Major e-waste utilization methods, their principles, characterization techniques, and required materials or instruments

Recycling Method	Recovery Efficiency (%)	Key Features/Principle	Characterization Techniques Used	Energy Demand	Chemicals Used	Instruments/Equipment	Metals Extracted	Environmental Impact	Key References
Manual Dismantling	60–80	Physical separation of components before processing	Visual inspection, weight analysis	Low	None	Screwdrivers, cutters, pliers	Au, Ag, Cu	Very Low	[198], [199]
Mechanical Shredding & Crushing	50–70	Size reduction to liberate metal fractions	Spectra Analysis	Moderate	None	Shredders, crushers, mills	Cu, Al, Fe, Au	Low (dust/noise)	[200], [201]
Magnetic Separation	70–90 (ferrous metals)	Magnetic force-based segregation	XRD, elemental analysis	Low	None	Magnetic separators	Fe, Ni	Low	[202], [203]
Eddy Current Separation	65–85 (non-ferrous metals)	Electromagnetic induction to separate non-ferrous metals	Conductivity analysis	Moderate	None	Eddy current separators	Al, Cu	Low	[204]
Density/Gravity Separation	60–80	Separation based on density differences	Particle density testing	Low–Moderate	Water or heavy liquids	Shaking tables, hydrocyclones	Cu, Sn, Pb	Moderate (water usage)	[205]
Pyrometallurgical Smelting	90–98	High-temperature melting to separate metal phases	XRF, ICP-MS, SEM-EDS	Very High	Fluxes (SiO ₂ , CaO), coke	Furnaces, smelters	Au, Ag, Pt, Pd, Cu	High (emissions, slag)	[206], [207]
High-Temperature Incineration	70–85	Thermal decomposition of organics to enrich metal residue	XRF, ash analysis	Very High	Controlled oxygen	Rotary kilns, incinerators	Concentrated metal ash	High (toxic emissions)	[207]
Hydrometallurgical Acid Leaching	85–95	Dissolution of metals into the liquid phase	UV-Vis, ICP-OES, AAS	Moderate	HCl, H ₂ SO ₄ , HNO ₃ , Aqua regia	Reactors, stirrers	Au, Al, Zn, FeAg, Cu, Pd	Moderate–High (chemical waste)	[208]
Selective Leaching	80–95	Target-specific dissolution	XRD, pH analysis, ICP-MS	Moderate	Thiourea, thiosulfate, glycine	Leaching tanks	Au	Moderate	[209]

Table 2 (continued)

Recycling Method	Recovery Efficiency (%)	Key Features/Principle	Characterization Techniques Used	Energy Demand	Chemicals Used	Instruments/Equipment	Metals Extracted	Environmental Impact	Key References
Solvent Extraction	85–98	Phase transfer using organic extractants	FTIR, ICP-OES	Moderate	Cyanex 272 (bis(2,4,4-trimethylpentyl) phosphinic acid), D2EHPA (Di-(2-ethylhexyl) phosphoric acid), TBP (Tri-n-butyl phosphate)	Mixer-settlers	Au, Pd, Pt	Moderate (organic solvents)	[210]
Ion Exchange	80–95	Metal adsorption on functionalized resins	Breakthrough curve analysis	Low–Moderate	Chelating resins	Columns, pumps	Rare earth elements (REEs)	Low–Moderate	[211]
Electrowinning	85–98	Electrochemical deposition of metals	Electrochemical impedance spectroscopy	Moderate–High	Electrolytes	Power supplies, electrodes	Cu, Au, Ag	Low (controlled system)	[212]
Electrorefining	90–99	Purification of impure metals	Purity analysis (ICP)	High	Acidic electrolytes	Electrolytic cells	High-purity Cu, Ag	Low–Moderate	[213]
Bioleaching (Bacteria)	60–90	Microbial oxidation of metal compounds	Microbial analysis, ICP-MS	Low	Acidithiobacillus spp.	Bioreactors	Cu, Au, Ce, Cl, Cr	Low (eco-friendly)	[214]
Bioleaching (Fungi)	55–85	Organic acid secretion for metal solubilization	FTIR, SEM	Low	Aspergillus, Penicillium	Fermenters	REEs, Cu	Low	[215]
Flash Joule Heating	70–90	Ultra-fast resistive heating for metal vaporization	XPS, SEM-EDS	High	Conductive carbon matrix	High-voltage pulse systems	Au, Ag, Pd	Moderate (energy-intensive, but rapid)	[216], [217]
Thermal Plasma Processing	90–99	Plasma arc for metal separation	Optical emission spectroscopy	Extremely High	Argon plasma	Plasma reactors	Au, Precious metals, REEs	Moderate–High (controlled emissions)	[218]

Table 2 (continued)

Recycling Method	Recovery Efficiency (%)	Key Features/Principle	Characterization Techniques Used	Energy Demand	Chemicals Used	Instruments/Equipment	Metals Extracted	Environmental Impact	Key References
Urban Mining/Landfill Mining	50–80	Recovery from accumulated waste deposits	Bulk compositional analysis	Moderate	Chemical reagents	Excavators, processing plants	Mixed precious & rare metals	Moderate (site-dependent)	[219]

The comparison of recovery techniques in Table 2 shows clear trade-offs between efficiency, cost, and environmental impact. High-efficiency methods like pyrometallurgical and hydrometallurgical processes achieve better metal recovery rates but come with high energy use and environmental issues. In contrast, physical and mechanical methods are more environmentally friendly and cheaper, but they often lead to lower recovery efficiency. These trade-offs highlight the need for hybrid and scalable solutions, especially in developing countries where economic and infrastructure limitations make it hard to adopt new technologies.

Limitations of Current Utilization Strategies for E-Waste

In spite of the rising trend in the use of approaches applicable to the utilization of e-waste, some challenges are still evident. Mechanical and physical separation techniques are often ineffective in metal recovery that is embedded within complex parts. Pyrometallurgical methods are often not environmentally friendly since they often result in the release of harmful gases. Additionally, the hydrometallurgical and solvent extraction methods are often characterized by the use of high amounts of chemicals. Furthermore, these methods pose serious challenges to the environment since effluent discharge is often harmful. Biologically driven methods are often hampered by the slow rates of the process. In addition, changes in the composition of the effluent often pose challenges to the effectiveness of the recovery processes; all the possible limitations are discussed under Table 3.

Environmental Consequences of Cross-Border E-Waste Trade

Building on the previous discussion of e-waste generation, composition, and recovery technologies, it is equally important to consider the global movement of e-waste and its environmental implications. The transboundary flow of e-waste, particularly from developed to developing countries, not only exacerbates environmental and health risks but also directly influences the feasibility and implementation of sustainable utilization strategies. In many e-waste importing countries, such as Pakistan [254], India [255], Indonesia [256], Vietnam [257] *e.t.c.*, the transboundary electronic waste is generally treated as a source of easily retrievable and commercially valuable materials rather than a toxic waste stream requiring proper management. In the informal or semi-formal recycling communities, there is selective recovery of high-value materials such as copper wires, aluminum carcasses, steel components, reusable chips, and circuit boards laden with precious metals through cheap manual disassembly, burning, and low-cost chemical processing. Conversely, the non-recoverable or low-value fractions, which include brominated plastic packaging, lead-filled glasses, mercury-filled components, cadmium, acid sludge, and fine metal-polluted dust, are often casually disposed of in unseaworthy open landfills, water bodies, or simply burned in uncontrolled environments. Thus, directly or indirectly linked to the broader challenges of e-waste utilization discussed earlier, improper handling and informal recycling practices limit the recovery of valuable materials and reduce the efficiency of the resource utilization pathway, and also contaminate the environment. This pattern of selective recovery allows the countries with imported e-waste to meet their material and economic needs for the time

Table 3 Key Limitation of current Utilization Strategies for E-Waste

Method	Key Limitation Factors
Manual Dismantling	In manual dismantling, components are separated manually[220]. Although it is an inexpensive process, it is quite costly because it is time-consuming and relies on manual expertise[221]. Notably, it exposes people to hazardous metals, flame retardants, and dust, which might pose health hazards.[222] The process is inefficient, especially when it comes to dismantling smaller components like microchips, resulting in the loss of valuable metals.
Mechanical Shredding & Crushing	Mechanical processes employ the use of rotors, hammering, and crushers.[223] Even though the method of fragmentation is efficient, there are environmental challenges in terms of microplastics, metallic dust, and aerosols, which contribute to soil and air pollution.[224] Metals with close densities are difficult to separate, hence some materials are lost. High consumption of energy is another environmental concern[225]
Magnetic Separation	Magnetic separation focuses on ferrous metals through magnetic forces[226]. The key disadvantage lies in its inability to separate non-ferrous metals such as copper, gold, and silver[227]. Small particles and metal fragments in plastic waste are most likely to evade separation, thereby lowering recovery rates. It lacks direct emission by-products but is inefficient on its own for metal recovery.
Eddy Current Separation	This process depends on induced currents to repel non-ferrous metals. It is very effective for aluminum and copper[228], although it finds difficulties with small particles and complex streams, because the process can lose materials. Besides, it requires a high-velocity machine, which increases energy consumption[229].
Density/Gravity Separation	Density-based separation segregates metals and plastics by density using water or heavy liquids[230]. Its drawbacks are problems in separating metals of very similar densities, large quantities of water involved, and the generation of contaminated wastewater[231] that may contain dissolved metals or chemicals, harmful to aquatic life if untreated[232].
Pyrometallurgical Smelting	Smelting represents a process of recovering metals by melting the materials at very high temperatures[233]. Its disadvantages are huge: high energy consumption, loss of certain metals due to volatilization (such as gold, silver, indium), and toxic gases, dioxins, and heavy metals fumes are emitted, causing serious health problems for the people and the local ecosystem[234]. Plastics are destroyed, and the recovery of non-metallic fractions isn't possible.
High-Temperature Incineration	This is the burning of e-waste at temperatures above 1000 °C, thereby reducing the mass of waste[235] but releasing dangerous substances such as dioxins, furans, CO, and NOx. This may result in metals being oxidized or lost in ash[236]. This practice has bad biological effects on human and animal life due to air pollution. It is also inefficient on its own for material recovery.
Hydrometallurgical Acid Leaching	Acid Leaching involves the use of strong acids such as HCl, H ₂ SO ₄ , or HNO ₃ [237]. However, the process has its disadvantages: it involves the use of chemical reagents that can be harmful, as well as toxic chemicals in the wastewater[238]. Sometimes the process does not result in the total removal of the metals, requiring the wastewater to be neutralized.
Selective Leaching	Selective leaching is targeted at specific metals through the use of complexing agents or pH control[239]. This method increases selectivity; however, it requires close monitoring, is a slow process, and generates metal-rich residue. The leachates may also be harmful to living organisms such as aquatic life and microbes in the soil[240].
Solvent Extraction	Solvent extraction is a process that extracts metals from ore using organic solvents[241]. The disadvantages include the use of toxic and inflammable chemicals of solvents, which are a burden during disposal[242]. Cross-contamination may reduce the selectivity index of solvent extraction.
Ion Exchange	Ion exchange is a process where metal ions are trapped by resin beads[243]. Its limitations include that when the resin is saturated, it is a slow process, and the presence of impurities in the solution disrupts the process. Used resins with high metal concentration also pose hazards in the environment when discarded[244].

Table 3 (continued)

Method	Key Limitation Factors
Electrowinning	Electrowinning involves removing metals using an electric current[245]. Disadvantages include high electricity consumption and inefficiency in weak solutions. Other disadvantages are the fouling of electrodes, which increases costs. It is vital to take caution while disposing of electrolyte solutions to prevent environmental pollution.
Electrorefining	Electrorefining involves the use of electrochemical reactions to refine metals[246]. This technique produces highly purified metals, but its limitation is the same as seen in electrowinning: higher energy costs, the use of pretreated solutions, and the possibility of toxic sludge formation.
Bioleaching (Bacteria)	Bacteria such as <i>Acidithiobacillus</i> [247] have metals that can be extracted via biological methods[248]. The limitations include slow reaction rate, pH and temperature sensitivity[249], and toxicity to metals such as Hg. There is no emission, and it is hard to scale up to an industry.
Bioleaching (Fungi)	Fungal bioleaching leverages organic acid secretion to mobilize metals. Drawbacks include slow process rate, variable metal dissolution[249], contamination possibilities, and release of volatile organic compounds from certain fungi. Even large-scale industrial applications have been less common.
Flash Joule Heating	Flash Joule heating strikes e-waste with a sudden, extreme pulse that sends metals to vaporize[250]. But it's energy-hungry, it gives us limited control over which metals we recover[251], and the process releases metal-rich vapors that must be captured safely[251]. Air pollution is a real concern in this method.
Thermal Plasma Processing	Plasma processing forces e-waste up to extreme temperatures of over 2000 °C-to melt it[252]. The drawbacks are huge energy consumption, high initial costs, and the requirement for complex gas treatment systems. Toxic gases produced must be handled with great care; while metals are handled quite effectively[253], most non-metallic residues tend to get destroyed in the process.

being, while also dumping the potential detrimental implications associated with the hazardous waste in more developed countries. Although various organizations have established legal frameworks and regulations governing the importation of e-waste, these instruments largely remain on paper, with limited enforcement or implementation. A summary of these organizational regulations and their provisions is presented in .Table 4

Emerging Trend and Future Direction

Current trends in e-waste studies suggest a recognition that, despite the significant utilization and recovery methods available for e-waste, their requirements for complex infrastructure development, heavy machinery usage, and well-equipped laboratory settings limit their usability in many parts of the world, which limits their implementation, especially in developing countries. To overcome these challenges, countries with limited resources need to find alternative solutions. As part of the global community, each of us can contribute according to our means. So it needs to find an e-waste utilization method that will not only work in developing technological settings around the world but will also be environmentally friendly. In this regard, used dry-cell batteries are one such promising yet unexploited alternative for e-waste utilization. Batteries are comparatively smaller e-waste components, yet are available universally in every corner of the world, often disposed of carelessly in garbage. Besides this, dry-cell battery components often have carbon compounds that can easily be extracted using environmentally friendly processes. The carbon rod in dry-cell batteries can easily be converted into conductive ink using several processes as shown in Fig.

Table 4 Major Regulations and Initiatives Governing E-Waste Import and Management

Regulation/Initiative	Year	Region/Organization	Key Provision Related to E-Waste	Key References
Pakistan Environmental Protection Act (PEPA)	1997	Pakistan	Section 13 prohibits the importation of hazardous waste, whereas Sect. 14 limits the handling of hazardous substances.	[258]
Trade Policy 2006–07	2006	Government of Pakistan	Prohibits the import of dangerous waste as defined in the Basel Convention.	[259]
Basel Convention	1989 (in force 1992)	UNEP (Global)	Regulates cross-border transfers of hazardous waste through Prior Informed Consent (PIC); 172 signature countries	[260]
Bamako Convention	1998	African Nations	It completely forbids the importation and transfer of hazardous waste across Africa	[261]
Export and Import of Hazardous Waste and Hazardous Recyclable Material Regulations (EIHWRMR)	2005	Canada	Prohibits or strictly regulates the import, export, and transit of hazardous waste	[262]
EU Waste Shipment Regulation (WSR)	2006	EU	Facilitates the export/import of used electronics and some categories of electronics waste for the purpose of repair and recycling, among others, in accordance with certain documentation and classification criteria.	[263]

6, which are not only cost-effective but also environmentally friendly. This conductive ink drawn from used dry-cell battery components is environment-friendly as well as utilized as a sustainable alternative to graphene-based conductive ink. Later, this e-waste-based conductive ink can be used to make flexible Interdigital capacitive sensors (IDC).

Conclusion

This review highlight the current methods for handling e-waste, along with their limitations. It also examines the risks and profit-making potential associated with e-waste. An overview of the various harmful chemical compounds found in e-waste and their effects on human health and the environment is included. The possibility of extracting metals from e-waste using physical and chemical processes is explored, comparing these methods and focusing on their scalability. The review highlights the challenges faced by developing countries in implementing these costly techniques. Additionally, it emphasizes new, low-cost, and eco-friendly options, such as using battery waste carbon to create conductive ink and developing functional materials from polymers. These alternatives have significant potential for transformation. This study fills an important gap in the existing research, where most studies focus on environmental dangers and management issues. There has been little attention

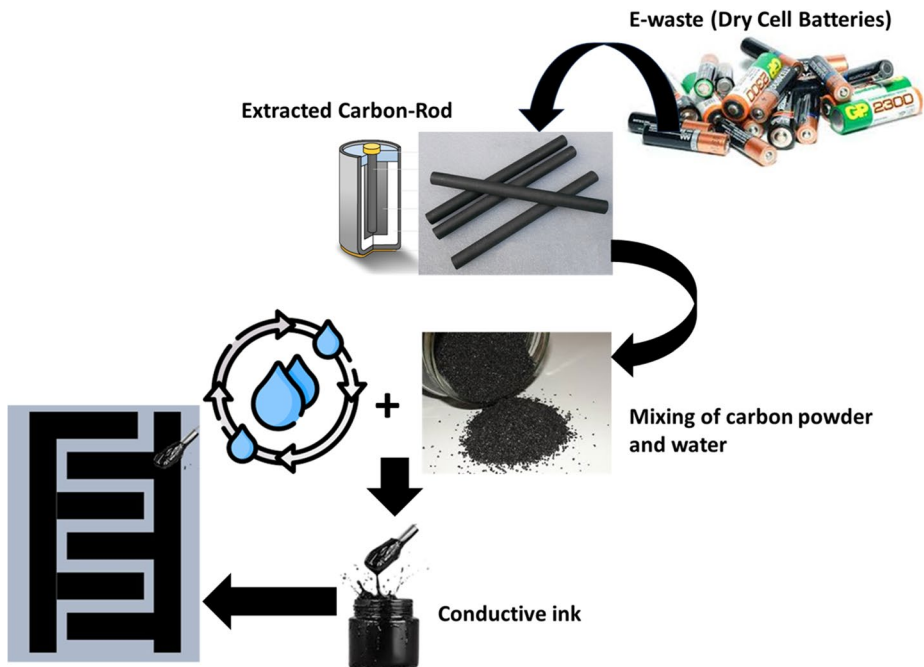


Fig. 6 Schematic illustration of e-waste-based conductive ink development: discarded dry-cell batteries are disassembled to extract carbon rods, which are processed into carbon powder and subsequently formulated into conductive ink for printing flexible electronic electrodes

on practical, low-cost, and scalable strategies for using e-waste, especially in settings with limited resources. By highlighting alternative methods like carbon extraction for conductive ink, this review aims to bridge that gap and encourage solution-focused research. However, this work has certain limitations. The analysis is primarily based on secondary data and published literature. The bibliometric analysis is also restricted to the Scopus database, which may not fully capture all global research contributions. Future research should focus on developing low-cost and scalable e-waste recycling technologies that can be used in areas with limited resources. Special attention should go to decentralized processing systems that cut down on costly infrastructure while ensuring safety and efficient recovery. Additionally, combining technological innovation with supportive policies is vital for encouraging sustainable e-waste management practices, particularly in developing countries where informal recycling is common. Strengthening partnerships between universities, businesses, and policymakers will be key to promoting circular economy goals. Moreover, upcoming studies should work on improving recovery methods for specific materials and creating standardized processes that increase economic viability and support widespread adoption of sustainable e-waste recycling strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s43615-026-01084-x>.

Acknowledgements The authors would like to acknowledge the support provided by Supervisor, Universiti Malaysia Sarawak.

Declarations

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

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Authors and Affiliations

Junaid Saddiqi¹  · Kasumawati Binti Lias¹ · Malaika Saddiqi²

✉ Junaid Saddiqi
25020243@siswa.unimas.my

✉ Kasumawati Binti Lias
lkasumawati@unimas.my

¹ Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan 94300, Malaysia

² Department of Zoology, Punjab University, Lahore, Pakistan