Environmental Science & Technology LETTERS

pubs.acs.org/journal/estlcu

Review

Recovery of Metals from E-waste: Facts, Methods, Challenges, Case Studies, and Sustainable Solutions

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Cite This: *Environ. Sci. Technol. Lett.* 2025, 12, 8−24

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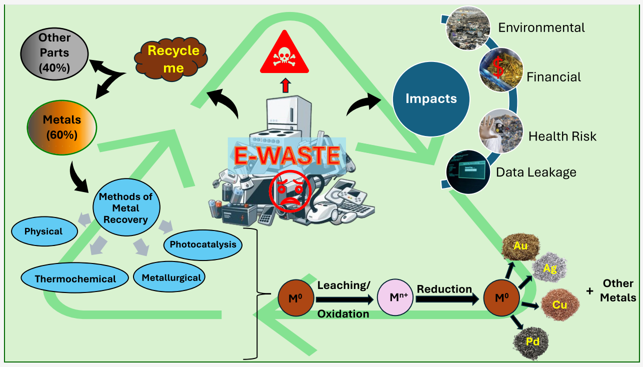
ABSTRACT: The growing issue of electronic waste (E-waste), driven by the exponential growth in electronic device usage, presents significant environmental and economic challenges. E-waste production has surged, increasing by ∼2 million metric tonnes (Mt) annually, reaching 60 Mt in 2023, with projections suggesting it will exceed 70 Mt by 2030. Despite China, the United States, and India being the top E-waste producers, their recycling rates remain critically low at 16%, 15%, and 1%, respectively. E-waste contains valuable metals, such as gold (Au), silver (Ag), and copper (Cu), which comprise ∼60% of its composition. However, only 17.4% of the global E-waste was appropriately recycled in 2023. This Review discusses the latest data on E-waste, evaluates current metal recovery methods, and emphasizes the urgency of sustainable solutions to mitigate environmental hazards and promote a circular economy. The paper also covers case studies highlighting challenges and potential strategies for enhancing metal recovery efficiency, contributing significantly to global sustainability efforts and waste management.



KEYWORDS: *E-waste, metals, recycling, recovery, sustainability, waste management*

1. INTRODUCTION

Electronic waste (E-waste) possesses hidden treasures in the heart, and it has a bright future to restore through recovery from metal resources.[1] Advancements in technologies, communication, and daily life have led to the explosion of electronic devices in modern society.[2] However, modernization and rapid digitalization led to the rapid growth of electronic devices, which surged E-waste generation and created significant environmental and economic challenges.[3] E-waste is a term for discarded electrical and electronic equipment. It represents a growing global concern due to its exponential growth, resource value, and environmental hazards.[4] The improper management and disposal of E-waste affect the environment and human health, and urgent sustainable solutions are being demanded to recover and mitigate its adverse effects.[5]

E-waste is a mixture of abandoned electrical and electronic equipment with numerous materials and components such as precious and base metals, glass, plastics, and other valuable and hazardous constituents.[6] Precious metals, including platinum (Pt), Au, Ag, rare earth metals, and base metals, are of vital interest owing to their economic value, recyclability, and crucial role in advanced technologies.[7−11] E-waste contains a considerable amount of precious base metals, making it a worthy resource for recovery via recycling.[12,13] It is the most critical aspect of E-waste recycling, as it addresses both environmental issues and the shortage of significant metals.[14]

The present review introduces innovative metal recovery techniques from E-waste, focusing on underexplored sustainable methods like photocatalysis and biohydrometallurgy, highlighting their environmental sustainability and efficiency compared to traditional methods. It presents a new process that combines milling, screening, and gravity concentration, achieving over 98% Au recovery a significant advancement in E-waste recycling. The review addresses sustainability challenges, incorporates recent case studies, and provides a detailed evaluation of current practices, identifying gaps in efficiency, environmental impact, and scalability. It emphasizes the critical issue of low recycling rates in major E-waste-producing countries such as China, the USA, and India, offering strategies to improve metal recovery efficiency and promote a circular economy. By offering a targeted analysis of these advanced recovery strategies, the manuscript provides valuable insights for

Received: August 19, 2024
Revised: December 5, 2024
Accepted: December 6, 2024
Published: December 10, 2024

researchers and policymakers to enhance the sustainability and economic viability of E-waste management. Table 1 summarizes recent literature on metal recovery, requiring a concise review for further discussion.

Table 1. Recent Literature on the Recovery of Metals from E-waste

	year	recovered metal(s)	foci	ref
1	2023	Cu, Zn	cementataion and electrowinning using methanesulfonic acid	15
2	2023	Au	precipitation using a quaternary ammonium salt	16
3	2023	Au	life cycle assessment	17
4	2023	Au	covalent organic framework and membrane separation techniques	18
5	2023	Au, Pt, Ag	studies in Vietnam and southeast Asia	19
6	2023	all metals	neural network-based optical recognition	1
7	2024	Au	photocatalysis	20
8	2024	Au, Ag, Pd	physicochemical reactions	21
9	2024	Cu	data-driven approach	22
10	2024	Au, Pd	tridentate thioether extractants	23
11	2024	Au	imidazolium-based poly(ionic liquid)s	24
12	2024	Au, Pt, Pd	sunlight-boosted tannin-grafted mesoporous silica	25
13	2024	Ag, Au	electrodeposition using a MoS_2 cathode	26
14	2025	Au, Pd, Pt	coral-like adsorbents	27
15	2025	Au	adsorption by a self-assembled thiourea-cross-linked reduced graphene oxide framework ball	28
16	2025	Au	porous activated carbon-coated electrode	29
17	2025	Au, Pt	porous organic polymer	30
18	2025	all metals	facts, methods, challenges, case studies, and sustainable solutions	this paper

2. E-WASTE GENERATION, COLLECTION, AND RECYCLING

The Global E-waste Monitor 2024 was unveiled on March 20th, 2024. The statistics say that over 40 Mt (Million Metric Tonnes) of E-waste was produced in 2014. At that time, it was predicted to grow by an average of 2 Mt per year, with over 60 Mt by the end of 2023.[31] In 2022, the world saw a historic milestone with a staggering 62 billion kg of E-waste produced globally, averaging around 7.8 kg per capita annually, and that 62 billion kg of E-waste in 1.55 million trucks wrapped around the Earth's Equator, Figure 1(a). Of this amount, 22.3% of the E-waste was officially collected and recycled using environmentally responsible methods. This 62 billion kg included small and large equipment, temperature exchange equipment, screen/monitors, photovoltaics, etc., Figure 1 (b). In 2023, the total unrecycled E-waste on earth is 347 Mt, of which only 17.4% is predicted to be recycled appropriately.[32] However, not all E-waste produced has been documented. Up to now, barely 78 countries have any form of law for dealing with E-waste.

The highest E-waste-producing regions are Asia, the Americas, and Europe, Figure 2 (a). Global E-waste is projected to reach nearly 70 Mt by 2030, which will be a massive threat to the ecosystem if not recycled, Figure 2 (b). The most productive E-waste per capita by region is Europeans (16.2 kg), Oceania (16.1 kg), and Americas (13.3 kg), Figure 2 (c). This E-waste contains various materials, of which 60% are metals, 15% plastics, 12% CRT and LCD, 5% metal plastic mixtures, 2% printed circuit boards, 3% pollutants, 2% cables, and 1% others Figure 2 (d).[33,34]

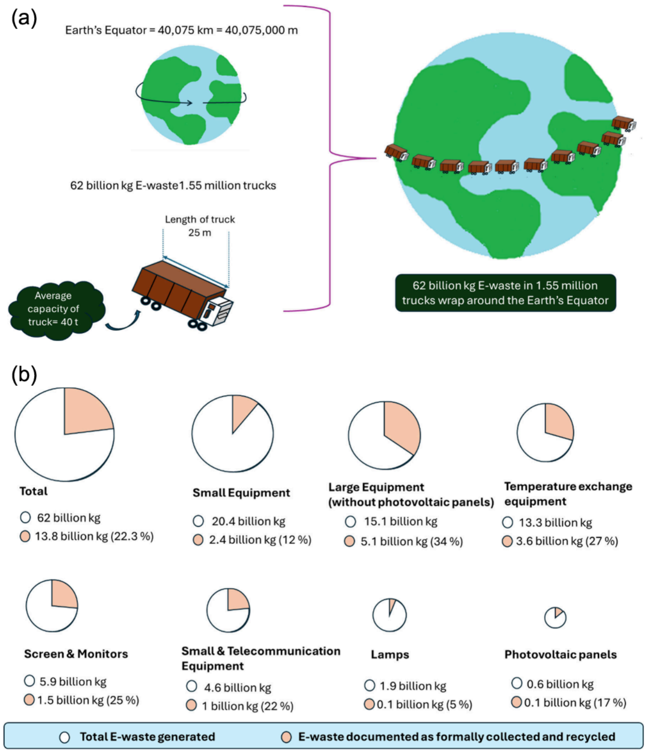


Figure 1. (a) Data showing that 1.55 million trucks with a 40 t capacity and a 25 m length revolving around the Earth's equator produced 62 billion kg of E-waste (b) from 62 billion kg, total generated and the total collected or recycled E-waste, including various types of equipment.

The highest E-waste-producing countries are China, the United States, and India, Table 2.[35] Several factors may be involved, including population, as India and China are the two most populous countries in the world, with over a billion people each.[36] Larger the population, higher the demand for electronic devices, leading to a substantial increase in E-waste. The United States has a large population, though smaller than China and India. However, its E-waste output per capita is higher than India's due to greater access to electronic devices and frequent upgrades. Some other regions for high E-waste production in these countries are robust economic growth, rapid urbanization, and high levels of consumption and production of electronic goods. China is also a global manufacturing hub for electronics, producing massive quantities of devices for domestic and export use. With this high production level, there is also high consumption, particularly as incomes rise in urban areas.[37]

The highest recycling percentage of E-waste is in Europe (Poland, Austria, and Finland), Table 2. Solid political policies, vital infrastructure, and high public awareness are why Europe is the leader in E-waste recycling. These countries have invested in creating a system that encourages recycling and holds producers accountable for their products throughout their lifecycles. In contrast, other countries, especially developing regions, face significant challenges such as weak legislation, underdeveloped infrastructure, and reliance on informal recycling sectors. These disparities highlight the global need for stronger international cooperation, policy alignment, and investments to improve E-waste management worldwide.[38]

https://doi.org/10.1021/acs.estlett.4c00696
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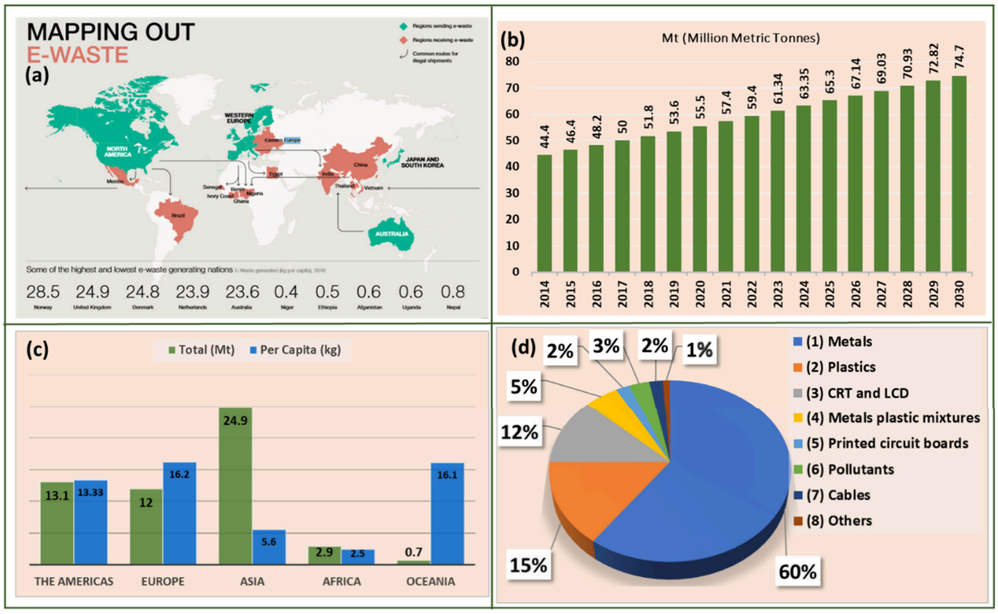

Figure 2. Data for E-waste generation and future predictions. (a) Mapping of E-waste by region. (b) E-waste monitoring up to year 2030 (global E-waste statistics). (c) E-waste generation by the area in total (metric tons) and per capita (kilograms). (d) Metals and other materials found in E-waste.[31−34]

Table 2. Most E-waste-Producing Countries, According to E-waste Produced, and Most E-waste-Recycling Countries, According to Recycling Percentage (data based on Global E-waste Statistics Partnership)[38]

Most E-waste-Producing Countries					
rank	country	continent	e-waste produced (kt)	e-waste recycled (kt)	recycling rate (%)
1	China	Asia	12 066	1952	16
2	United States	Americas	7188	4054	56
3	India	Asia	4137	60	1
4	Japan	Asia	2638	613	23
5	Brazil	Americas	2443	79	3
6	Russia	Asia	1910	121	6
7	Indonesia	Asia	1886	0	0
8	Germany	Europe	1767	957	54
9	United Kingdom	Europe	1652	502	30
10	France	Europe	1445	861	60
Most E-waste-Recycling Countries					
rank	country	continent	e-waste produced (kt)	e-waste recycled (kt)	recycling rate (%)
1	Poland	Europe	517	418	81
2	Austria	Europe	175	133	76
3	Finland	Europe	118	90	76
4	Norway	Europe	145	107	74
5	Sweden	Europe	221	151	69
6	Estonia	Europe	19	12	65
7	Iceland	Europe	8	5	65
8	Ireland	Europe	103	67	65
9	Belgium	Europe	252	163	65
10	Switzerland	Europe	204	129	63

3. COMPOSITION OF METALS IN E-WASTE

This discussion has been done in supplimentory information S1 section.

4. IMPLICATIONS AND CHALLENGES WITH E-WASTE

A large group of metals in E-waste emphasizes the significance of effective methods for metal recovery due to their critical importance in fabricating new devices, minimizing environmental issues, diminishing resource depletion, and improper disposal. Ineffective metal recovery causes substantial health and environmental hazards.[39] Additionally, some metals present in E-waste, such as Mercury (Hg) and Pb, increase the risk of the above hazards, raising the alarm for the proper recycling, recovery, and waste management practices in society.[40] Here are some consequences and challenges associated with E-waste.

4.1. Economic Impact of E-waste Recycling. The economic aspects of metal recovery through e-waste recycling are significant, driven by the high value of Au, Ag, Cu Pd, and rare earth elements found in discarded electronics. Recovering these metals can be more cost-effective than mining new ores, particularly for precious metals, which exist in higher concentrations in E-waste than natural deposits. However, the profitability of this process depends on the efficiency of extraction technologies and the fluctuating market prices of these metals. The capital and operational costs of advanced recycling methods, such as hydrometallurgical and pyrometallurgical processes, must also be considered. In addition, policies promoting circular economies and extended producer responsibility can create economic incentives for companies to invest in sustainable recovery technologies. As global demand for metals grows, E-waste recycling offers a promising economic opportunity to reduce raw material extraction costs, mitigate supply chain risks, and address environmental concerns.[41,42]

4.2. Environmental Impact. Environmental impact is the utmost concern. It includes toxic components and hazardous materials in E-waste, including Cd, Hg, Pb, and brominated flame retardants.[43] Poor recycling and inadequate disposal enhance the possibility of releasing these into the environment, resulting in water, air, and soil contamination.[44] Conversely, electronic devices in E-waste contain precious materials, including Au, Ag, Ni, Pd, Cu, and rare earth metals.

https://doi.org/10.1021/acs.estlett.4c00696
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Inappropriate disposal leads to the loss of those precious resources and worsens the situation by creating extra demand for mining and extraction.[20]

4.3. Waste Management Challenges. Waste management faces numerous challenges that include environmental, economic, social, and technological aspects in which lack of recycling infrastructure for E-waste is utmost as several regions have a shortage of proper facilities for E-waste recycling as well as incapable of handling the ground scale E-waste, resulting in improper disposal either incineration or in landfills.[45] In contrast, some sectors use informal recycling processes to destroy this E-waste, which includes hazardous chemicals, and burn the E-waste in open areas to extract valuable materials, leading to significant health damage and environmental problems.[46]

4.4. Increasing Health Risks. Developing countries use unsafe and informal E-waste recycling, resulting in workers being exposed to harmful chemicals in the industries, which can cause skin, respiratory, carcinogenic, and many other issues with prolonged exposure to these conditions.[47] Alternatively, improper disposal of E-waste can cause hazardous problems by contaminating water resources and food supplies and threatening the health of communities.[48]

4.5. Access to Technology and Data Leakage. In recent years, especially during COVID-19, there has been a rapid increase in technological advancements and strategies to attract consumers to upgrade their electronic devices. This has led to increased E-waste, resulting in improper disposal due to increased volume.[49] The COVID-19 pandemic led to a surge in demand for electronic devices as people adapted to remote work, online learning, and virtual communication. This increased purchase of new electronics is expected to result in a significant rise in e-waste in recent years as these devices end their valuable lives. The rapid speed of technological advancements and frequent upgrades further contribute to the expected E-waste growth.[50] Junior et al. have comprehensively reviewed the increase of E-waste during the COVID-19 pandemic.[51]

Urbanization and population growth have significantly contributed to the rise in E-waste generation, overcoming existing waste management systems and infrastructures in many regions.[52] In response to these pressures, developed countries often export E-waste to developing nations, which, while economically beneficial in the short term, leads to serious environmental and health consequences for the receiving countries. The negative impact of E-waste on the environment and health cannot be overstated, and it is crucial to address this issue urgently.[53] These nations typically need stricter regulations and strong waste management policies, which worsens the risks of improper disposal and recycling of E-waste. Additionally, this unregulated export of E-waste can result in unethical access to sensitive personal or organizational data, increasing risks to security and privacy.[54]

To solve this problem, more strict international regulations regulating the trade of E-waste must be established. The Basel Convention, which regulates the transboundary movement of hazardous waste, provides a framework. However, stricter implementation is needed to prevent the illegal export of E-waste to countries with insufficient infrastructure. Developed countries should also take greater responsibility by enhancing their domestic recycling capabilities and supporting sustainable E-waste management programs in developing nations.[55]

The UN Sustainable Development Goals (SDGs) also emphasize responsible consumption and production, mainly through promoting sustainable E-waste management practices. By encouraging recycling, reducing waste generation, and adopting global partnerships, the SDGs aim to minimize E-waste's environmental and health impacts.[56]

Moreover, executing Extended Producer Responsibility (EPR) policies would require manufacturers to ensure that their electronic products are disposed of or recycled responsibly, regardless of where the waste ends up. By investing in recycling technologies and creating take-back programs, companies could help minimize E-waste's environmental and health impacts. Moreover, educational initiatives in developing countries to build local capacity for safe E-waste recycling and handling would reduce exposure to toxic materials while fostering economic opportunities.[57]

Addressing the security risks associated with E-waste export requires more stringent data protection measures before shipping electronics. Data demolition protocols must be enforced to ensure that sensitive information is wiped clean before devices leave the country. In doing so, environmental and security concerns surrounding E-waste export can be mitigated.[42]

The above challenges encourage improved recycling technologies, good waste management practices, sustainable product designs, strict regulations and policies, and recovering valuable metals from E-waste to overcome these problems and improve the circular economy.

5. SUSTAINABLE PRACTICES IN THE RECOVERY OF METAL FROM E-WASTE

5.1. Need for Sustainability. E-waste consists of valuable metals as well as several hazardous elements. A vast quantity of hazardous metals (Cd, Hg, Pb, and Cr) present in electronic trash can potentially elevate the toxicity levels within the ecosystem.[58] The prolonged presence of E-waste in the environment can heighten potential exposure to dangerous substances. These hazardous elements could be linked to significant groundwater contamination and risks to human health.[59] The soil-crop-food chain is an essential means by which harmful compounds from E-waste enter the human body. The presence of toxicity, adverse environmental consequences, and the requirement for financial compensation due to E-waste have made it imperative to recover metals within it.[60]

The concentration, on-site location, and duration of exposure to harmful chemicals in E-waste can affect potential detrimental health impacts.[61] Technological devices are becoming increasingly common in everyday life with the increasing population. The rise in electronic product use will lead to a corresponding increase in the output of electronic trash. If E-waste is not disposed of or recovered correctly, it can lead to significant environmental damage and potentially endanger human health.[62] Several persistent metals can persist in the soil for thousands of years due to E-waste, presenting various health hazards to higher organisms.[63] Some metals hinder plant growth, disrupt ground cover, and harm soil.[64] It is widely recognized that these metals cannot be chemically broken down but need to be physically removed or converted into nontoxic substances to prevent their presence in the global environment.[65,66] Due to dangerous compounds, including the discussed metals and other chemicals, the management and processing of E-waste can pose a significant risk to the environment and human health.[67] An investigation unveiled that lead could impact the liver, kidneys, and neurological system and interfere with cognitive development.[68] Cr(VI) can

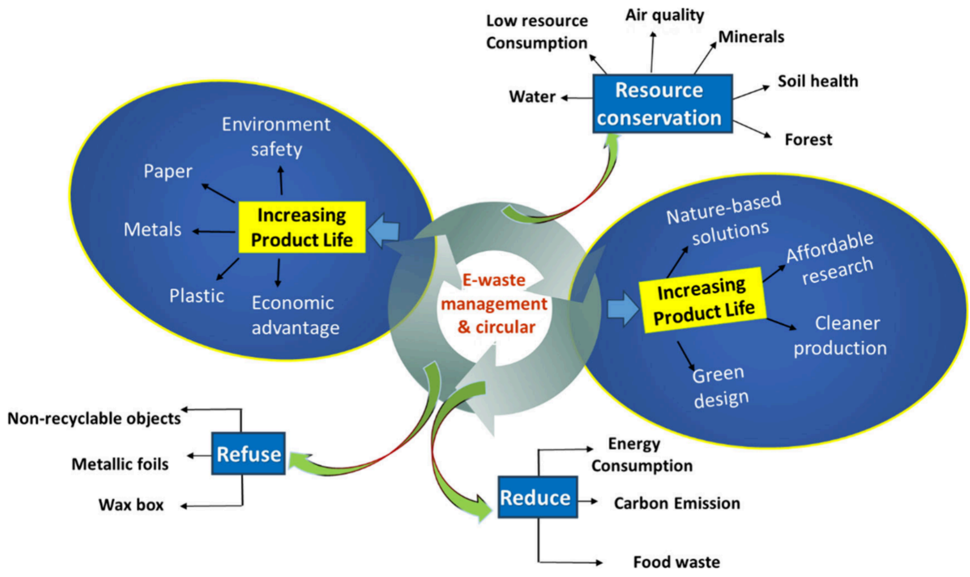

Figure 3. Circular economy for E-waste management.

lead to the development of cancer in the nasal passages, sinuses, or lungs, as well as respiratory and kidney damage and impaired immune systems.[69] Ni can potentially induce asthma and dermatitis.[70] Additionally, exposure to Mercury can lead to memory impairment, compromised immunological function, and muscular weakness.[71] During embryonic development in animal health, both Cr(III) and Cr(VI) compounds have been found to induce neural tube abnormalities, deformities, and even mortality in mice.[72] Furthermore, the Cr(VI) compounds are considered environmental pollutants and occupational carcinogens for humans.[73] Environmental consequences are typically assessed using a life cycle analysis, which evaluates the input energy, material resources, and output streams such as metals, glass, plastic, oil, and gas. Table S2 illustrates the environmental effects of several technologies used in MREW.

5.2. Path toward Sustainability. An in-depth assessment of sustainability for any process necessitates thoroughly examining the three key sustainability factors: environmental, economic, and social. Ensuring sustainability is crucial when recovering metals from E-waste.[74] Excessive consumption of fossil fuels significantly affects environmental sustainability, leading to increased carbon dioxide (CO_2) emissions. Additionally, wastewater formation contributes to eutrophication, acidification, marine and freshwater ecotoxicity, human toxicity, and water depletion.[75]

5.2.1. Sustainable Practices to Reduce Emissions. Recycling processes for metals from E-waste, including pyrometallurgy, hydrometallurgy, and biohydrometallurgy, have varying impacts on CO_2 emissions and energy consumption. Sustainable practices to reduce emissions require focusing on these processes, their efficiency, and their environmental consequences.

Pyrometallurgy, used to recover metals from E-waste, is highly energy-intensive, consuming up to 2000−2500 kWh per ton of material and emitting 3 to 5 tons of CO_2 per ton processed. Its significant carbon footprint makes it one of the least sustainable recycling methods. Instead, hydrometallurgy works at lower temperatures (∼100 °C) and is more energy-efficient, requiring 500−800 kWh per ton of material and emitting only 0.3 to 0.5 tons of CO_2 per ton processed. However, hydrometallurgy generates hazardous liquid waste, which presents environmental challenges. Biohydrometallurgy, utilizing microorganisms, offers a greener alternative with minimal energy demands (100−300 kWh per ton) and near-zero CO_2 emissions. Additionally, it produces little hazardous waste, though it operates slower. Ongoing research is focused on improving the efficiency of biohydrometallurgy without compromising its environmental benefits, making it a promising solution for sustainable E-waste recycling.[76−81]

More recently, photocatalysis, an emerging technology for MREW, offers another sustainable alternative by utilizing light to drive chemical reactions that extract valuable metals. This process typically operates at ambient temperatures and uses simple photocatalysts such as titanium dioxide (TiO_2) to leach Au ions in solution.[20] The dissolution took nearly 12 h, further reducing the leachate yields Au metal with purity up to 99.0%. The energy requirement for photocatalytic recovery is significantly lower than that of pyrometallurgy and hydrometallurgy, as it mainly relies on solar or artificial light, reducing dependency on external energy sources. Additionally, CO_2 emissions are minimal, making photocatalysis a highly eco-friendly option.[82] It also avoids producing hazardous chemical waste, positioning it as a clean and efficient approach for future E-waste recycling. However, the scalability and efficiency of photocatalysis still need refinement for large-scale applications.

5.2.2. Promoting the Circular Economy. Integrating circular economy principles and sustainable development goals has recently emerged as a critical outline for organizations and institutions. Researchers encourage prioritizing material recycling and optimizing resource recovery from waste streams to control future environmental degradation.[83] Maximizing material utilization is imperative to decrease waste production. This results in adopting eco-friendly technologies, formulating green policies, and nurturing innovative corporate mindsets. Figure 3 illustrates how the principles of a circular economy can be applied to managing E-waste by emphasizing the comprehensive strategy that balances environmental and economic priorities in E-waste management, promoting sustainable resource use, and extending the lifecycle of products. It focuses on expanding product life and conserving resources. Increasing the lifespan of materials such as metals, paper, and plastics can enhance environmental safety and create economic benefits. On one side,

https://doi.org/10.1021/acs.estlett.4c00696
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strategies like reducing and refusing waste contribute to these goals by minimizing the need for new materials. In contrast, resource conservation is promoted through green design, cleaner production, and nature-based solutions, which help achieve sustainable E-waste management.[84]

5.2.3. E-waste Microrecycling. Unlocking the commercial potential of recovering metals from E-waste presents an enticing opportunity for private enterprises. However, the logistical challenge of transporting large volumes of such waste entails significant expenses.[85] Microrecycling units offer a solution by being deployable in compact spaces, typically around 50 m^2, at a comparatively low cost. This microrecycling approach involves gathering and sorting E-waste materials from nearby communities at small-scale facilities, thereby reducing transportation costs, minimizing the use of raw materials, conserving fossil fuels, and benefiting the environment.[86] Furthermore, it facilitates the production of recycled materials with added value for future applications.[87]

These microfactories employ techniques, including micro recycling units, to extract materials from E-waste through fractional heating and separating different metals, polymers, and ceramics.[88] Moreover, selective thermal transformation makes it possible to trigger multiple reactions that carefully segregate crucial metals and alloys. Recent research has revealed that innovative methods can yield valuable materials such as metals, metal nanoparticles, alloys, and nanoceramics from E-waste.[89,90] The primary goal of this approach is to manage and recycle E-waste on a smaller scale, thereby generating value-added materials that neighboring industries can utilize efficiently, securely, and sustainably.[91]

5.2.4. Providing Expert Training to Waste Management Employees. Waste management is a complex process with several functions: processing, utilizing tools, implementing safety measures, monitoring, and supervision. Therefore, waste management authorities can significantly benefit from having well-trained personnel who can play essential roles in waste management.[92] Various stakeholders, including academic institutions, research organizations, ministries, municipalities, local public, and technical experts, can participate in waste management training to ensure its success.[93,94] A similar structure can be implemented for efficient management of electronic trash, surrounding regulatory entities, governmental institutions at both local and national levels, nongovernmental groups, the corporate sector, and society at large.[91]

5.2.5. Social Sustainability Extended Producer Responsibility Framework and Other Regulations. Social sustainability involves ensuring that society can meet the long-term needs of its members while promoting well-being, justice, and equity. Achieving social sustainability in E-waste management is complex, as it is shaped by various factors such as geography, culture, and religion.[95] Predicting the social sustainability of emerging recycling technologies is particularly challenging. One of the most effective tools for understanding social impacts is the Social Life Cycle Assessment (S-LCA). However, studies on the S-LCA of E-waste recycling processes still need to be available.[96] Umair and colleagues provided valuable insights into the social impacts of informal E-waste recycling sectors, but further research is required to broaden the understanding.[97] Society can benefit from using recycled materials, green technologies, and cleaner fuels, contributing to a more sustainable future. As technological advancements continue, the acceptance of eco-friendly products is likely to grow, further supporting social sustainability. Nevertheless, conducting an S-LCA is essential for a more comprehensive analysis of social impacts.[85]

Figure S1 shows the legislation and regulations for handling E-waste in several nations.[98,99] Developed countries implement various measures, such as EPR, to address the issue of E-waste previously discussed in section 4.4.[100] EPR is a concept introduced in 2000 that mandates manufacturers assume responsibility for the eventual disposal of their products. The primary goal of EPR is to minimize waste and promote sustainable use of natural resources.[101]

Deposit-refund schemes, such as the advance recycling fee (ARF) and advance disposal fee (ADF), should be implemented to enhance E-waste management. ARF typically taxes the sale of E-waste to finance recycling expenses. Instead, ADF refers to the revenues explicitly created to cover the costs of disposing of E-waste.[102] The assessment of ARF can be calculated based on the product's weight sold per unit.[103] A technology package for managing E-waste, which includes the treatment and recovery of essential metals, is necessary. The treatment of E-waste involves three primary steps. During the initial stage, E-waste generates raw materials for the subsequent steps through refining, disassembling, and separation. All separation methods are implemented in the second phase following the physical separation of electronic trash. During the third phase, recycling and recovery protocols are implemented to extract valuable metals from E-waste.[104,105] Following the laws and regulations of a developed country is the most effective approach to achieving optimal outcomes in E-waste management.[106]

5.2.6. Implementing Effective E-waste Regulations. Success in various fields has consistently hinged on the implementation of strong policies. Despite being a significant electronics manufacturer, India's E-waste management remained promising due to insufficient policies. Recognizing this gap, the Indian Ministry of Environment, Forest, and Climate Change (MoEFCC) has formulated guidelines for E-waste management.[107,108] Over the years, Indian policymakers have introduced several waste management recommendations from 1989 to 2016.[109] Initial E-waste handling guidelines were drafted in 2009, followed by their incorporation alongside plastic waste rules in 2011. However, India's current E-waste management policies require substantial refinement to safeguard the environment and public health.[110] Addressing this issue necessitates comprehensive adjustments.[111]

Similarly, while China boasts various waste management policies, the majority focus on municipal solid waste.[112] In contrast, the European Union (EU) was pivotal in developing E-waste management criteria in the early 2000s following debates initiated by the 1989 Basel Convention. The 2002 Directive marked a significant milestone by establishing targets for recycling, recovering, and treating WEEE.[113] Subsequently, this European directive served as a blueprint for formulating laws in subsequent years. Nations like Canada, the US, Japan, and Australia incorporated similar principles into national legislation.[114−117]

5.2.7. Implementing Substantial Penalties for Those Who Violate the Rules. Those who disregard waste management regulations may face significant fines. Regulatory bodies should clearly outline the consequences for all parties involved, ensuring transparency and accountability. It is imperative to delineate the responsibilities of individuals, institutions, and industries to ensure effective and ethical implementation. Moreover, stringent measures should be applied, especially for

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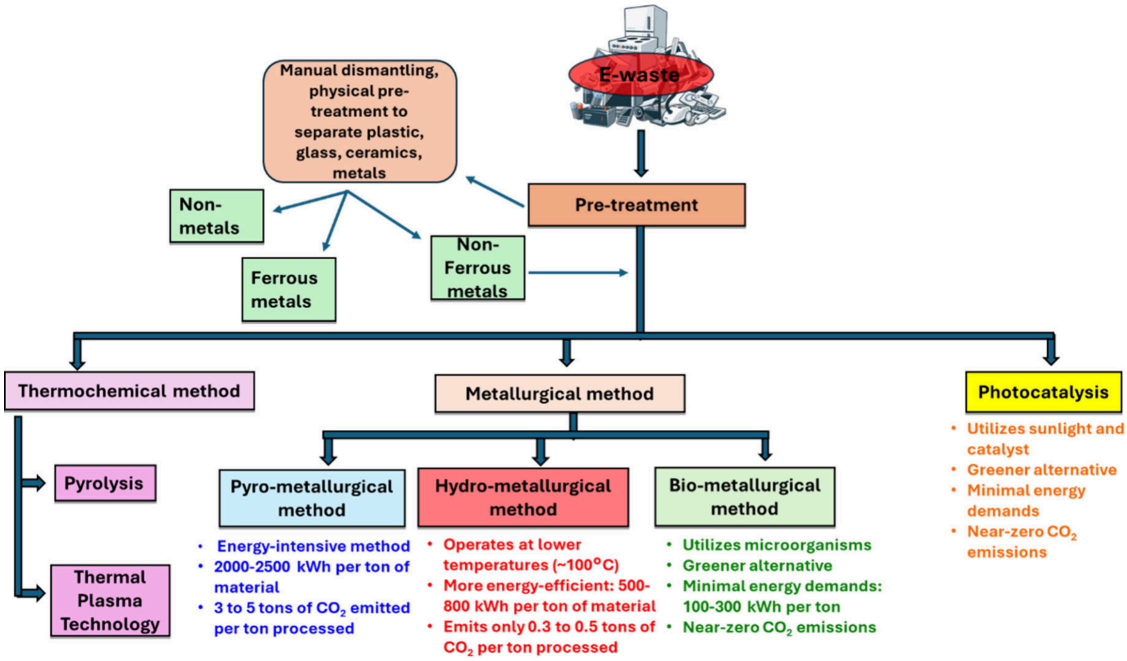

Figure 4. Different types of methods involved in the recovery of metal from E-waste.

those who ignore E-waste disposal protocols due to the potential hazards.[118,119]

5.2.8. Incentivizing Top Performers. In addition to penalties, regulatory bodies should offer incentives to recognize and reward outstanding performance in waste management. As evidenced by annual audits, enterprises, communities, institutions, or industries excelling in waste management should receive beneficial rewards. This approach encourages a positive outlook among stakeholders involved in waste generation and its management.[90] As highlighted by Cucchiella and co-workers, incentivizing NGOs and manufacturers to participate in E-waste management activities, including collection, storage, and recycling, across various administrative levels is crucial for promoting effective waste management practices.[120]

6. METHODS AND MATERIALS

Several methods are utilized to extract metals from E-waste, each presenting its own set of pros and cons.[121] This MREW method holds promise for medium—and small-scale enterprises, drawing interest due to its economic viability. As highlighted in studies by Ashiq et al., both conventional and contemporary approaches exist for this purpose.[122] E-waste undergoes dismantling as a preliminary step before metal extraction. Figure 4 illustrates the diverse array of techniques employed in metal recovery.

6.1. Pretreatment/Physical Recovery. Physical recycling methods are crucial in recovering metals and nonmetals from E-waste. According to the literature, physical recycling is the predominant and widely adopted technology for managing E-waste globally.[123,124] It serves as a fundamental pretreatment step preceding further processing.

Before metal recovery can occur, E-waste requires dismantling as a necessary pretreatment measure. This process involves using tools such as screwdrivers, hammers, and conveyor beds to disassemble components into distinct parts suitable for recycling.[125] Subsequently, material shredding becomes imperative. E-waste undergoes grinding and crushing in specialized equipment, followed by processing through magnetic and density separators to eliminate nonmetallic constituents.[126]

Additional studies outlined in the literature cover techniques such as milling, froth flotation, and electrostatic separation utilizing corona discharge to differentiate between nonmetallic and metallic components.[127] The corona discharge method emerges as an environmentally sound and effective pretreatment solution for PCBs, with a proven track record in mineral processing. This method exploits variances in electrical conductivity and density between nonmetallic and metallic E-waste.[128]

Froth flotation, another method highlighted in recent research, capitalizes on the principle of hydrophobicity.[129] The nonmetallic portion of E-waste exhibits hydrophobic characteristics, while the metallic part is hydrophilic, so separation can be achieved based on this property. The high surface energy of metallic components contributes to their increased hydrophilicity, facilitating their segregation.[130]

The milling technique, as elucidated by Blumbergs et al.[131] revolves around crushing E-waste particles to sizes below 200 mm. This size reduction, executed under controlled temperatures, is an efficient pretreatment procedure. Following pretreatment, E-waste proceeds to the metal recovery stage. The diverse methods discussed herein underscore the multi-faceted approach to E-waste management. The literature includes several methods to recover metals from E-waste, such as physical, chemical, bioleaching, and hybrid methods, such as the electrochemical and plasma arc processes. However, the some demand methods are thermochemical method, pyrometallurgy, hydrometallurgy, bioleaching, and photocatalysis, which are discussed here:

6.2. Thermochemical Method. The thermochemical method is further classified into pyrolysis and thermal plasma technology

6.2.1. Pyrolysis. Pyrolysis is classified under thermochemical processes and involves the thermal decomposition of targeted materials without oxygen. Extensive research is underway to explore the feasibility of recovering metals from E-waste utilizing

https://doi.org/10.1021/acs.estlett.4c00696
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thermochemical methods.[132,133] Various pyrolysis techniques have been employed for metal extraction, including microwave-induced pyrolysis, vacuum pyrolysis, and catalytic pyrolysis.[134]

6.2.1.1. Microwave-Induced Pyrolysis. represents a cutting-edge approach that utilizes radiation as a heating source.[135] The uniform heat distribution throughout the sample obviates the need for crushing, a requirement in conventional pyrolysis methodologies.[136]

6.2.1.2. Vacuum Pyrolysis. conducted under vacuum conditions, necessitates the utilization of a vacuum pump and a sealed system to regulate pressure. This technique operates in an oxygen-free environment, inhibiting the generation of hazardous chemicals and preventing metal oxidation, resulting in the direct recovery of metals in their metallic state. Numerous successful studies have demonstrated the efficacy of vacuum pyrolysis in recovering metals from printed circuit boards, integrated circuits, light-emitting diodes, and lithium-ion batteries.[137]

6.2.1.3. Catalytic Pyrolysis. is particularly effective at lower temperatures, allowing for the degradation of waste materials even in the presence of catalysts. Al_2O_3 and zeolite emerge as two pivotal catalysts in this process, facilitating the decomposition of E-waste constituents.[138]

6.2.2. Thermal Plasma Technology. While current thermochemical methods effectively recover metals from E-waste, researchers and technologists actively pursue more environmentally sustainable approaches for future advancements.[10] Thermal plasma technology has emerged as a promising path for MREW. This eco-friendly and sustainable technology is particularly significant for extracting metals from biomedical and municipal solid waste.[139]

Various plasma methods, including DC nontransferred arc plasma torch, plasma arc melting technology, DC extended transferred arc plasma reactor, plasma arc furnace, argon, and argon hydrogen plasma jets, enable the recovery of metals from metal-containing waste such as PCBs, galvanic sludge, aluminum dross, red mud, copper-clad laminate, and incinerated ash.[140] Among these techniques, plasma arc melting technology is a superior purification method, significantly reducing waste volume. This process involves a graphite-based electrode plasma, a direct-fire incinerator, and a high-efficiency air filter, as illustrated in Figure S2.

Despite its efficiency, plasma technology's commercial viability in various industrial applications remains challenging. The high electrical energy requirements pose a significant obstacle to its widespread adoption and feasibility.[141] Nonetheless, ongoing research aims to address these challenges and bridge the gap, making thermal plasma technology a more economically viable option for MREW.

The literature explains that the plasma system is categorized into low and high temperatures. High-temperature plasma systems operate within the range of 10^6 to 10^7 °C. The plasma becomes fully ionized within this temperature range, causing atoms to deviate from their original orbits. Conversely, low-temperature plasma systems function within the 101 to 105 °C temperature range.[139] In low-temperature plasma methods, only partial ionization of the plasma occurs.

Despite its potential, further literature on thermal plasma technology for metal recovery is affirmed as it has yet to achieve full commercialization and continues to be explored.[140] Continued research efforts are essential for elucidating this innovative technology's full potential and practical application in MREW.

6.3. Metallurgical Method. Various metallurgical technologies, such as pyro-metallurgical, hydrometallurgical, and biometallurgical processes, have proven effective in treating E-waste. However, pyro-metallurgical and hydrometallurgical methods pose significant environmental challenges, primarily due to the generation of substantial amounts of toxic byproducts.[142]

6.3.1. Pyrometallurgical Method. Pyro-metallurgical technology incorporates combustion, smelting, incineration, and pyrolysis processes within a blast furnace.[143] Operating at around 950 °C, this method transforms E-waste into approximately 70% metal-based residue, 23−25% oil, and the remaining portion as gases.[144] The procedure involves several stages, including smelting, incineration, electrochemical refining, and combustion. Initially, crushed E-waste materials undergo furnace treatment to eliminate plastics, followed by smelting and electrochemical refining. Recovered metals accumulate in a molten metal bath and are subsequently segregated based on metallurgical and chemical properties. An advantage of this technique lies in its ability to utilize various E-waste scraps as raw materials for metal recovery, demonstrating successful metal retrieval from copper-based scrap.[145]

However, pyro-metallurgical processes have drawbacks such as high energy consumption, costliness, and the formation of toxic compounds like furans and dioxins.[146] Therefore, ensuring proper installation to minimize emissions of toxic substances is imperative for mitigating environmental pollution.[147]

6.3.2. Hydrometallurgical Method. Hydrometallurgical processes utilize chemical reagents to extract metals, with acids primarily leaching base metals. This method employs a range of chemicals, including, cyanide, thiosulfate, hydrochloric acid, sulfuric acid, and nitric acid, among others.[148] Figure S3 illustrates the various types of leaching methods employed in this technique.

While hydrometallurgical processes effectively leach metals from E-waste, they also generate a substantial amount of waste.[149] The extensive use of chemicals in these processes produces large quantities of waste.[150] highlighting the need for greater environmental sustainability in this technique.

Cyanidation is widely employed for recovering metals such as Ag and Au due to its efficiency and simplicity.[151,152] Table S3 combines the diverse leaching agents utilized in hydrometallurgical methods and their advantages, limitations, and toxicity.

6.3.3. Biohydrometallurgical Methods. The biohydrometallurgical method has garnered considerable industry interest as it represents one of the most sustainable and promising techniques for metal recovery.[153] Often referred to as the "green recovery" method, it is recognized for its environmental safety and sustainability. This approach boasts several advantages, including low cost, minimal chemical requirements, low energy consumption, and straightforward management.[154] However, its time-intensive nature has hindered full industrialization. Biohydrometallurgical processes primarily encompass biosorption and bioleaching methodologies.[155]

Adsorbents, synthesized from waste biomass, serve as platforms for the adsorption of metals onto their surfaces. Previous studies have successfully utilized fungi, algae, bacteria, and eggshell membranes for metal biosorption.[156] Notably, certain fungi species, such as Aspergillus spp., have effectively recovered Au,[157] while biomass from Aspergillus carbonarius has successfully been shown to extract Cu from E-waste.[158] The efficiency of the biosorption method hinges on factors such as

https://doi.org/10.1021/acs.estlett.4c00696
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the type of biosorbent, various biological ligands, characteristics of the target metals, and the pH of the solution.[159] As described in prior research, bioleaching involves the mobilization of metal ions from insoluble materials through complexation processes and biological oxidation.[160] Various microorganisms, including heterotrophic bacteria, autotrophic bacteria, and heterotrophic fungi (e.g., Aspergillus sp., Penicillium sp.), play critical roles in bioleaching processes.[161]

Bioleaching occurs in three steps:

i. Acidolysis,
ii. Complexolysis
iii. Redoxolysis and

Researchers have extensively investigated bioleaching to recover Al, Au, Ni, Cu, Pb, and Zn from E-waste.[162] The mechanism of bioleaching is illustrated in Figure S4.

In the bioleaching process of E-waste, adding iron [Fe^{2+}] and a sulfur or pyrite source is crucial, as these substrates are typically absent in the E-waste itself.[163] Acidophilic bacteria facilitate the oxidation of Fe^{2+} to Fe^{3+} and sulfur, producing protons essential for converting insoluble metals such as Cu^0, Ni^0, and Zn^0 into their soluble forms Cu^{2+}, Ni^{2+}, and Zn^{2+}, respectively. This transformation is depicted in eqs 1 to 6.[164]

$$4Fe^{2+} + O_2 \rightarrow 4Fe^{3+} + H_2O;\ \Delta G = 39.7\ \text{kJ mol}^{-1} \quad (1)$$

$$2Fe^{3+} + Cu^0 \rightarrow 2Fe^{2+} + Cu^{2+};\ \Delta G = -347.1\ \text{kJ mol}^{-1} \quad (2)$$

$$2Fe^{3+} + Zn^0 \rightarrow 2Fe^{2+} + Zn^{2+};\ \Delta G = -1235.9\ \text{kJ mol}^{-1} \quad (3)$$

$$2Fe^{3+} + Ni^0 \rightarrow 2Fe^{2+} + Ni^{2+};\ \Delta G = -822.6\ \text{kJ mol}^{-1} \quad (4)$$

$$S^0 + 105O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+;\ \Delta G = -822.5\ \text{kJ mol}^{-1} \quad (5)$$

$$2Cu^0 + 2H^+ \rightarrow Cu^{2+} + 2H_2O;\ \Delta G = -774.5\ \text{kJ mol}^{-1} \quad (6)$$

These conversions occur within an acidic medium at ambient temperature. Table 3 summarizes the green recovery method and the microorganisms utilized.

6.4. Photocatalysis. Photocatalysis is an emerging and environmentally friendly method for recovering metals from E-waste. This process uses light energy, typically from UV or visible light, to activate a photocatalyst, which drives chemical reactions that can recover metals from E-waste components. For this, the redox potential of metal/metal ions (M^0/M^{n+}) should lie within the band gap of the photocatalyst to leach the M^{n+} from M^0, followed by a reduction of M^{n+} to M^0.[171] For reduction of M^{n+} to M^0, the reduction potential of photocatalyst in the CB should be less than the reduction potential of M^{n+} which are E_o = −0.45, −0.28, −0.26, −0.13, + 0.34, + 0.80, + 0.987, + 1.18, + 1.50 V for Fe^{2+}/Fe^0, Co^{2+}/Co^0, Ni^{2+}/Ni^0, Pb^{2+}/Pb^0, Cu^{2+}/Cu^0, Ag^+/Ag^0, Pd^{2+}/Pd^0, Pt^{2+}/Pt^0, and Au^{3+}/Au^0, respectively, and vise versa for leaching of M^0 to M^n.[172]

Recently, Shang et al. used this approach, enabling the selective, efficient, and scalable extraction of Au from various types of E-waste. The dissolution phase was completed within 12 h, and subsequent reduction of the leachate resulted in Au metal with a purity of up to 99.0%. In large-scale operations, the system can process 10 kg of E-waste per batch, yielding 8.82 g of Au.[20] The other researchers recovered Ag, Au, Pd, Pt, Rh, Ru, and Ir from waste circuit boards using TiO_2 as a photoatalyst.[173] In contrast, Au and Pd were recovered by using different halogen aqueous solutions and light as the energy source for the leaching of metal ions, followed by a step reduction process.[174] Interestingly, these much fewer studies have been performed using photocatalysis, and all included TiO_2 as photocatalysts.

Unfortunately, work has been scarce in the photocatalytic recovery of metals until now. Researchers used high temperatures and furnaces to study the photoreduction process after the leaching of metal ions. Therefore, there is no need to work on a photoreduction process to complete the photocatalytic recovery of metals from E-waste. More smart materials need to be designed considering the band gap of materials and their band edge potentials. Type-II and S-scheme heterojunctions are better choices to stop the recombination of electrons and holes, along with the absorbance of materials to be shifted in the visible regions for better use of complete solar radiance.

Table 3. Green Recovery Method, Along with Types of Metal Recovered and Microorganisms

type of microorganisms used	methodology used	name of metal recovered	concentration of metal recovered	ref
Ferrooxidans, *Acidithiobacillus thiooxidans*, *Ferrooxidans*, and *Leptospirillum*	bioleaching	Cu	95%	165
Leptospirillum ferriphilum	bioleaching	Fe	8000 g/L	166
Pseudomonas fluorescens	bioleaching	Au	54%	167
Aspergillus niger consortium	bioleaching	Ni, Au, Cu	74%, 87%, 82%	168
Lactobacillus acidophilus	coupling of biosorption and bioleaching	Au	85%	169
Aspergillus carbonarius	biosorption	Cr	92%	170

7. EFFICIENCIES AND LIMITATIONS OF METAL RECOVERY TECHNIQUES

The conventional methods of E-waste disposal in landfills, particularly in underdeveloped nations, are becoming increasingly obsolete and contributing to soil and water pollution in surrounding areas. Cd, Hg, and Pb emerge as the most toxic elements found in leachates.[175] Hg leaches during the disposal of electronic devices such as circuit breakers, while Pb is known to leach from Pb-containing glasses.[176] Recognizing the environmental and health risks, researchers and stakeholders are actively seeking alternative technologies to repurpose E-waste and mitigate its harmful impacts on human life and ecosystems.[84]

Various methods, including thermochemical, pyrometallurgy, hydrometallurgy, and biohydrometallurgy, are being employed and evaluated to recover different metals from E-waste.[177] The efficiency of these techniques has been subject to review, with ongoing research focusing on the advantages and limitations of each methodology used for metal extraction from E-waste.[178] Environmental sustainability stands out as a critical consideration when selecting a method for metal recovery.[179] Nearly every technique utilized for metal recovery exhibits a unique set of advantages and limitations.[180]

Pyrometallurgy is widely known for its efficiency, as it can process a large volume of E-waste while generating energy. However, this method presents significant environmental challenges, releasing hazardous carcinogens such as dioxins and furans into the atmosphere.[181] Although it is excellent at

https://doi.org/10.1021/acs.estlett.4c00696
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effectively recovering metals like Cu, Au, and Ni, the ecological cost of pyrometallurgy is a significant limitation, leading researchers to seek greener alternatives.

Hydrometallurgy, on the other hand, offers high recovery rates and is less time-consuming than other methods. It is often more selective for specific metals and utilizes fewer harmful gases than pyrometallurgy. However, it generates substantial amounts of hazardous effluent, which presents an environmental concern. Despite this drawback, hydrometallurgy's versatility in processing various metal types has made it a popular technique, especially for precious metal recovery.[182]

Biohydrometallurgy is an eco-friendly alternative that employs microorganisms to leach metals from E-waste. While environmentally sustainable, this method is generally slower than thermochemical or hydrometallurgical approaches. Despite its time-intensive nature, biohydrometallurgy's reduced environmental impact and adaptability make it an attractive option for sustainable E-waste management. Its potential scalability further enhances its appeal in the context of a circular economy.[183]

In addition to these traditional methods, new approaches like the green synthesis of metal-based nanoparticles from E-waste are gaining attention.[184] This innovative process uses biological agents such as plants, microorganisms, and animal derivatives to synthesize nanoparticles, offering numerous advantages over conventional recovery techniques.[185] Green synthesis's versatility reduced environmental footprint, and potential for high-value applications position it as a promising area of research in E-waste valorization. Table S4 comprehensively compares these methods and their respective advantages and limitations.

This review, while extensive in its coverage of emerging metal recovery technologies from E-waste, faces some inherent limitations. First, the scope of the review is limited by the availability of peer-reviewed studies and access to data from different regions, particularly those with less developed E-waste recycling infrastructures. As a result, certain geographic or regional insights may be diminished. Additionally, the review focuses on technological methods but does not delve deeply into the economic feasibility or commercial scalability of many proposed techniques. Many of the novel approaches, such as photocatalysis and biohydrometallurgy, are still in experimental stages, and their real-world applications are either limited or unproven at large industrial scales. This gap limits the practical recommendations that can be derived for immediate application in global E-waste recycling.

8. CASE STUDIES AND BEST PRACTICES

8.1. Case Study A. E-waste recycling facility in Karnataka, India

Location: Karnataka, India

Capacity: Full 10 tons/day recycling capability, handling 6 tons/day

Land Area: 1.5 acres with 25,000 sq. ft. closed and 60,000 sq. ft. open

Total Employees: 100 (50 males, 50 women)

Five-Year Profit Trend: High

8.1.1. Overview. This E-waste recycling plant in Karnataka, India, is one of the oldest and most successful in the country. Focusing on transforming E-waste into valuable materials using cost-effective, indigenous, and eco-friendly technology suitable for Indian conditions, the facility offers a comprehensive range of services, including collecting, processing, and recycling various forms of E-waste. The company has developed a specialized CRT (Cathode Ray Tube) recycling process, highlighting its commitment to innovation and sustainability.

8.1.2. Process Overview. 8.1.2.1. E-waste Collection and Logistics. The company handles logistics for collecting E-waste through e-auctions or direct purchase, ensuring proper documentation of weight, source, and other relevant details.

8.1.3. Screening and Preprocessing. All collected E-waste undergoes screening for radioactive elements before entering the disassembly facility. Streams are separated at the first level for efficient processing.

8.1.4. Manual Dismantling. Staff are equipped with safety gear and essential tools to manually dismantle E-waste at individual work tables equipped with air suction ducts to reduce emissions. Deconstructed parts are separated into distinct streams.

8.1.5. Resource Recovery and Recycling. The resulting streams, including metal-rich pieces, printed circuit boards, plastics, cables, and CRTs, undergo mechanical size reduction and density separation to recover resources. Sister firms and third-party industries are contracted for metal recovery and component recycling.

8.1.6. Specialized CRT Recycling Technique. The company has developed its own CRT recycling technique, which involves separating and selling panel and funnel glass from discarded CRTs to manufacturers for improved recyclability. Electric wire heating is used to split CRTs into two parts, with the separation process aiding in eliminating harmful components.

8.1.7. Wire Stripping and Separation. Native stripping equipment removes metal from polymer-coated wires, while cables are manually fed into inlet holes, cut lengthwise, and routed to an eddy current separator to separate metals from nonmetals.

8.1.8. Conclusion. This case study exemplifies best practices in E-waste recycling, demonstrating the successful implementation of innovative technologies and processes to transform waste into valuable resources while prioritizing environmental sustainability and worker safety.[126]

8.2. Case Study B. Organization B's case study: Electronic waste recycling facility in Beijing, China

Location: Beijing, China

Capacity: 10,000 tons per year

Land Area: 1.5 acres with a closed area of 25,000 square feet and an open area of 60,000 square feet

Profitability Trend: Strong over the past five years

8.2.1. Overview. Organization B operates as a leading E-waste recycling facility in Beijing, China, specializing in the dismantling, recycling, and disassembling E-waste. With a dedicated management team possessing professional expertise in the industry, the company is committed to maintaining high standards of quality, integrity, and value in E-waste recycling.

8.2.2. Best Practice. One of Organization B's best practices is implementing a degassing unit to remove coolants from refrigerators safely. This innovative approach ensures the safe handling and disposal of hazardous materials, contributing to environmental protection and worker safety.

8.2.2.1. Processing Methods. The E-waste recycling factory employs a combination of manual and semiautomatic sorting and dismantling processes. Preprocessed materials are then forwarded to the processing stage for further treatment.

8.2.2.2. Specialized Equipment. A distinct queue is designated for refrigerators, with a degassing device available to extract coolants safely. This equipment ensures compliance

https://doi.org/10.1021/acs.estlett.4c00696
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with environmental regulations and minimizes potential hazards associated with coolant disposal.

8.2.2.3. Material Recovery. Recovered materials undergo reprocessing as necessary, with shredded materials crushed and subjected to magnetic separation and eddy current separation to separate metal from nonmetal components. Television sets are processed individually to remove CRTs, with a meticulous approach to ensure the safe handling and disposal of hazardous materials.

8.2.2.4. Glass Recycling. In the case of television sets, the vacuum tube is initially removed, followed by the detachment of the glass panel and funnel. Before glass shatters, harmful substances are eliminated to mitigate environmental impact and ensure safe recycling practices.

8.2.2.5. Conclusion. Organization B's case study highlights the importance of innovative technologies and sustainable practices in electronic waste recycling. By implementing specialized equipment and adhering to high-quality standards, the facility contributes to environmental protection and resource conservation while maintaining strong profitability.[126]

8.3. Case Study C. Organization B's Case Study: Innovative methodologies for electronic waste recycling

8.3.1. Background. With the global proliferation of electronic equipment such as computers, mobile phones, and automation components, E-waste production has a corresponding surge. Organization B, in collaboration with E-waste recyclers, has pioneered methodologies for extracting precious metals like Au, generating metal concentrates that fetch lucrative prices from refiners. Moreover, this process yields an ecologically sound waste stream devoid of hazardous chemicals, aligning with sustainability goals.

8.3.2. Challenges.

1. Malleable metals like Au and Cu tend to smear, complicating direct grinding and gravity concentration methods.
2. Chemical leaching, though effective, is costly and presents challenges in separating dissolved metals.
3. Circuit board flame retardants can produce hazardous compounds during thermal treatment.
4. E-waste commonly sold to smelters does not fetch its total market worth, necessitating advanced gas scrubbing machinery.

8.3.3. Best Practices. Organization B devised a novel approach to address these challenges, incorporating a short milling step, screening, and two stages of gravity concentration. This technique, characterized by its simplicity, cost-effectiveness, and remarkable efficiency, enables effective material separation.

8.3.4. Results. The implemented process yields a coarse Cu concentrate from foils between circuit boards and a fine metal concentrate. Au recovery rates exceed 98%, demonstrating the effectiveness of Organization B's innovative methodologies in maximizing metal extraction from E-waste while minimizing environmental impact.[186]

8.4. Case Study D. Case Study: Environmental and economic analysis of E-waste management in Pakistan

8.4.1. Background. The escalating rate of E-waste generation, increasing by 3 to 5% annually in developing countries, poses significant environmental and economic challenges. To address this issue, a study assessed the ecological sustainability and financial benefits of E-waste management in Pakistan. The study focused on the end-of-life processing of laptop computers and liquid crystal display (LCD) desktop computers, employing the LCA method and the cumulative exergy extraction from the natural environment (CEENE) method for impact analysis.

8.4.2. Methods and Materials. The LCA method was utilized to analyze the environmental impacts of E-waste management, including climate change potential, stratospheric ozone depletion, ecotoxicity potential, human noncarcinogenic potential, and mineral resource depletion. The CEENE method was also deployed to assess resource consumption in E-waste recycling versus landfilling scenarios.

8.4.3. Results. The determined impact scores revealed significant environmental burdens associated with E-waste management, including emissions of CO_2 equivalents and depletion of natural resources. However, the CEENE analysis demonstrated that efficient E-waste recycling could reduce approximately 80% of the impact on natural resources compared to landfilling.

Furthermore, the study evaluated the economic benefits of increasing material weight recovery (MWR) indicators for laptop and LCD computers. By increasing the MWR indicator by 33.8% for laptops and 27.2% for LCD computers, Pakistan could achieve an annual economic benefit of US $191.56 million. These findings underscore the importance of transitioning toward E-waste revalorization to promote sustainable resource consumption and economic growth .[187]

8.5. Conclusion. Innovative improvement measures in waste collection, treatment, and recycling practices present valuable opportunities for developing countries like Pakistan to address E-waste management challenges. By adopting economically feasible, energy-efficient, and environmentally friendly practices, Pakistan can mitigate environmental impacts, conserve natural resources, and realize significant economic benefits from E-waste recycling. This study emphasizes the importance of sustainable E-waste management strategies in achieving long-term environmental and financial objectives.[187]

9. CHALLENGES IN RECOVERY OF METAL FROM E-WASTE

This section discusses various challenges that occurred with MREW. As discussed above, the MREW is a fundamental aspect of managing E-waste seeking to recover/extract precious, base, and rare earth metals from discarded electronic devices.[125] This recovery process faces several significant challenges, which are as follows:

9.1. Complexity in the Composition of E-waste. E-waste contains a complex mixture of metals, plastics, CRT and LCD, metal-plastic mixtures, printed circuit boards, pollutants, ceramics, cables, etc. Consequently, several compounds, materials, and elements in different concentrations complicate the extraction and recovery, especially for extracting specific metals, which can be tricky and challenging. In addition, E-waste contains alloys with metals, even in small quantities.[188,189] Hence, there is always a need to separate and be accurate in the process, which makes recycling difficult.

9.2. Miniaturization and Design of Devices. Urbanization is forcing the world to make compact and miniature designs, which require disassembling devices to recover metals, which is quite a complex process. Recovering metals from these densely packed, small components requires advanced disassembly techniques to avoid damaging materials and ensure efficient recovery. This complexity is exacerbated by the need for specialized techniques to handle miniaturized components without compromising their integrity.[190]

https://doi.org/10.1021/acs.estlett.4c00696
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9.3. Efficient Separation Techniques. Efficient separation techniques are a challenging need for quantitatively extracting metals from E-waste.[191] During the MREW, each metal must be separated or isolated from the complex mixture, which is problematic. This process requires efficient and cost-effective separation techniques to maximize the metal recovery rate.[85]

9.4. High Energy Requirements. Metal recovery from E-waste is an energy-intensive process, posing challenges in balancing sustainability with minimizing carbon footprints. The recovery process's high energy demands make it challenging to maintain environmental sustainability, creating a significant obstacle in pursuing more efficient metal recovery methods.[192]

9.5. Heterogeneous E-waste Composition. The highly heterogeneous nature of E-waste makes applying general treatment approaches to metal recycling challenging. Each type of E-waste may require a different processing method, necessitating a deep understanding of process dynamics and interactions to achieve the highest recovery potential.[21]

9.6. Global Regulatory and Economic Issues. The lack of uniform guidelines across countries complicates E-waste recycling, which is often transported across different regions. This gap in regulations hinders the successful implementation of recycling practices on a global scale. Additionally, the economic viability of recycling is influenced by fluctuating market demand, metal prices, and competition with primary metal production, creating further challenges in the metal recovery process.[42,193]

9.7. Operational and Environmental Concerns. The extended duration of metal recovery operations and the adverse effects on microorganisms involved in bioleaching processes are growing concerns. These factors complicate the scaling up of metal recovery processes for commercial use. Additionally, older and outdated electronic devices often contain fewer common metals and alloys, which may not be compatible with modern recovery processes due to variations in material composition.[191]

9.8. Public Awareness and Infrastructure. Effective E-waste collection, transportation, and handling are essential for successful metal recovery. However, public awareness and proper E-waste disposal practices often need to be improved, making collecting and recycling E-waste efficiently difficult. Improved public education and the development of better supply chains are necessary to enhance the recycling process and ensure that e-waste reaches recycling facilities in a condition suitable for metal recovery.[194]

10. CONCLUSION AND FUTURE PERSPECTIVES

Effective metal recovery from E-waste is crucial for mitigating environmental impacts and ensuring a sustainable future. Recycling E-waste is vital for waste management and recovering valuable resources, such as metals, which contribute significantly to the global economy. Addressing the challenges associated with metal recovery and adopting efficient, sustainable methods are essential steps toward establishing a circular economy and reducing the burden of E-waste on our planet.

To achieve this, it is imperative to recover valuable and critical metals, including rare earth elements, in an economically viable manner. Metal profiling in E-waste is essential for ensuring that each collection is appropriately managed, maximizing the recovery potential while maintaining a balanced approach to recycling. An integrated waste management system based on the principles of reduction, reuse, and recycling, collectively known as the 3R policy, emerges as the preferred strategy for long-term sustainability. This approach minimizes waste generation and ensures that materials are reused and recycled in an environmentally friendly and economically feasible manner.

Adopting new and emerging technologies is essential to overcoming the technical limitations in the metal recovery process. Innovations such as robotics, artificial intelligence, and advanced separation techniques could revolutionize the E-waste recycling industry. For example, recovered glass fibers outperform commercial absorbing materials and hold enormous promise as insulating materials. The concentration of precious metals in the metallic fraction of E-waste facilitates easier recovery and refinement, with noble metal separation offering significant economic potential for sustainable development.

However, current approaches are hindered by several technical challenges, including the need for an understanding of process thermodynamics, complexities in elucidating reaction mechanisms, inadequate downstream recovery, and significant metal losses during processing. Addressing these issues requires a concerted effort across various sectors and the integration of zero-waste and product-centric ideologies into E-waste management practices.

This review emphasizes the need for continued research and collaboration to advance metal recovery technologies, promote responsible E-waste management globally, and adopt sustainable practices that are both environmentally friendly and cost-effective. By including these new technological prospects and addressing existing challenges, the E-waste recycling industry can evolve into a more effective, sustainable, and economically viable system. This evolution is essential for reducing E-waste and preserving the planet's resources for future generations.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.4c00696.

Abbreviations, Composition (type and distribution) of metals in E-waste, Tables, figures, and related References (PDF)

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https://doi.org/10.1021/acs.estlett.4c00696
Environ. Sci. Technol. Lett. 2025, 12, 8−24

https://pubs.acs.org/10.1021/acs.estlett.4c00696

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

S. Jadoun is grateful for the support of the National Research and Development Agency of Chile (ANID) for Projects FONDECYT 3200850 and ANID/FONDAP/1523A0006, Solar Energy Research Center (SERC), Chile.

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