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DOI: 10.1039/d5su90050f

rsc.li/rscsus

From waste to wealth: advancing e-waste transformation through chemical sciences

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Introduction

The swift progress of technology and the growing demand for electronic gadgets have resulted in a sharp rise in electronic waste (e-waste), creating substantial environmental and health concerns. E-waste, particularly discarded printed circuit boards (PCBs), contains a complex mixture of valuable metals, such as Au, Ag, Cu, and Pd, alongside hazardous substances like Pb, Hg, and brominated flame retardants.¹ The environmentally unsound disposal of e-waste not only results in the loss of precious resources but also contributes to environmental pollution and public health risks. The metal concentration in PCBs significantly

surpasses that found in natural ores, highlighting their economic viability for extracting valuable metals like Au, Ag, and Pd, as well as base metals such as Cu, Fe, and Al, among others.² PCBs are a significant component of e-waste, consisting of metals (30.0–50.0%), non-metals (50.0–70.0%), and small amounts of ceramics and glass fibres. Although PCBs account for only 3.0–5.0% of e-waste mass, they contribute to more than 90.0% of its total value due to the presence of high-value metals.³ Interestingly, the chemical sciences provide innovative approaches to sustainably convert this waste into valuable resources, aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (responsible consumption and production) and SDG 13 (climate action). The materials recovered from e-waste were valued at around \$57 billion in 2019.⁴

This essay explores how the chemical sciences can play a pivotal role in the sustainable recovery of valuable metals from e-waste, focusing on the latest advancements in green chemistry, hydrometallurgy, and the circular economy. By leveraging cutting-edge technologies such as ionic liquids (ILs), deep eutectic solvents (DESSs), and organic/amino acids, we can develop environmentally friendly methods to extract and recycle metals from e-waste, reducing the environmental footprint and promoting resource efficiency.

The challenge of e-waste

E-waste is among the fastest-growing waste streams worldwide, with approximately 53.6 million metric tonnes produced in 2019. Projections indicate this figure could rise to 74.7 million metric tonnes by 2030.⁵ PCBs,

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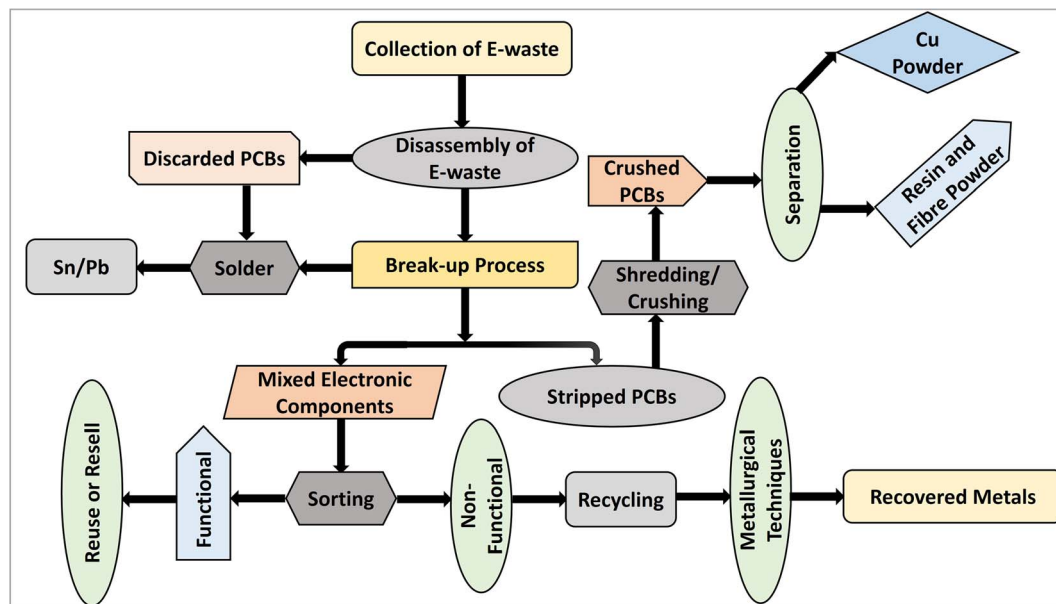


Fig. 1 A generalised flowsheet for recovering metals from PCBs.

a significant component of e-waste, are particularly challenging to recycle due to their complex composition, which includes both valuable metals and hazardous materials. Traditional recycling methods, such as pyrometallurgy and hydrometallurgy, often involve high energy consumption, toxic chemicals, and significant environmental pollution.⁶ These methods are not only unsustainable but also fail to recover all valuable metals efficiently. The general steps for the recovery of metals from PCBs are illustrated in Fig. 1.

Advances in smart disassembly and sorting of e-waste

Efficient sorting and disassembly are critical for maximising metal recovery from e-waste. Smart disassembly techniques, incorporating 3D image recognition and robotic automation, enable the precise removal of valuable electronic components.¹ Machine vision systems have been developed to identify and categorise PCBs, enhancing the efficiency of subsequent recycling processes.⁷

Ionic liquids: a sustainable approach to metal recovery

Green chemistry offers a promising alternative to traditional recycling methods by focusing on the development of environmentally benign processes that minimise waste and reduce the use of hazardous substances. One of the most significant advancements in this field is the use of ionic liquids (ILs) for metal recovery from e-waste. ILs are salts that remain liquid at room temperature and have unique properties, such as low volatility, high thermal stability, and tunable solubility, making them ideal for selective metal extraction.⁸ For instance, the use of 1-butyl-3-methyl-imidazolium hydrogen sulfate has been shown to achieve near-total recovery of Cu from PCBs, with efficiencies exceeding 99.0%.⁹ Similarly, ILs like 1-carboxymethyl-3-methylimidazolium hydrogen sulfate have demonstrated high selectivity for Cu, with leaching efficiencies of up to 98.3% under optimised conditions.¹⁰ These IL-based methods not only offer high recovery efficiencies but also reduce the environmental impact compared to conventional acid-leaching methods. The chemical structures of ILs employed in

the recovery of metals from PCBs are shown in Fig. 2.

Deep eutectic solvents: a green alternative

Another innovative approach in green chemistry is the use of deep eutectic solvents (DESS), which are mixtures of two or more compounds that form a eutectic mixture with a melting point lower than that of the individual components. They are normally synthesised from hydrogen bond acceptors and hydrogen bond donors. The chemical structures of the commonly used DES components employed for metal recovery from PCBs are depicted in Fig. 3. DESs are biodegradable, non-toxic, and cost-effective, making them an attractive alternative to conventional solvents.⁸ For example, choline chloride (ChCl) and ethylene glycol (EG) have been successfully used to recover metals such as Cu, Ni, and Zn from PCBs, with recovery efficiencies exceeding 75.0%.¹¹ DESs can also be tailored to selectively recover specific metals, reducing the need for additional separation steps. For instance, the use of the ChCl : EG DES with I₂ as an oxidant has been shown to achieve high recovery efficiencies for Cu, Ni, and Sn, while minimising the co-extraction of



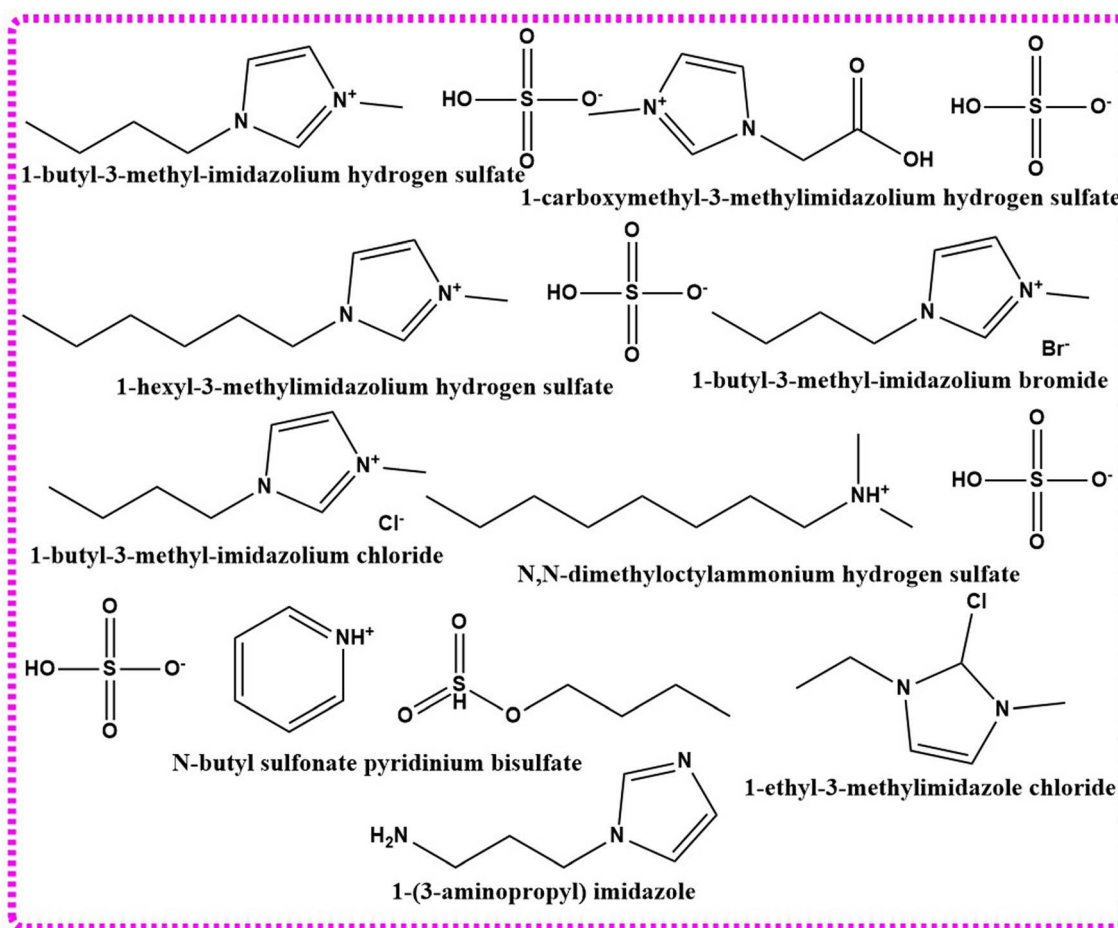


Fig. 2 Chemical structures of ILs commonly used in metal recovery from PCBs.

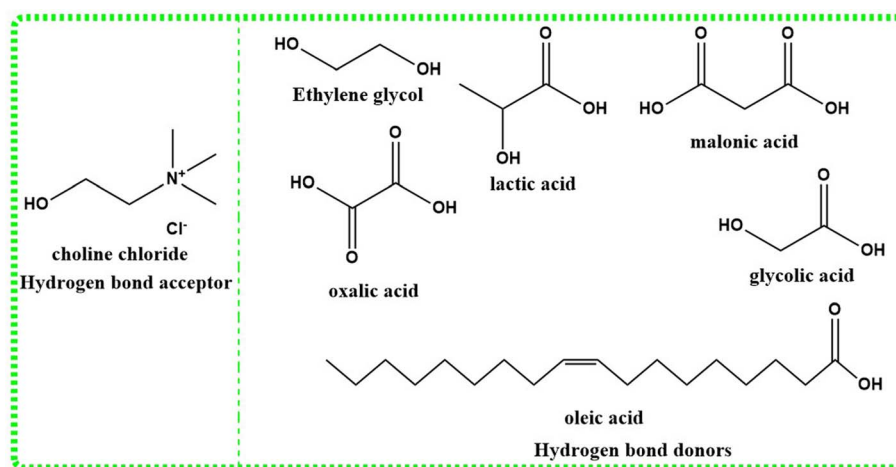


Fig. 3 Chemical structures of the generally employed hydrogen bond acceptors and donors used for the preparation of DESs utilised in metal recovery from PCBs.

other metals. This selective recovery process not only enhances the efficiency of metal extraction but also reduces the environmental impact by minimising the use of hazardous chemicals.

Organic/amino acids: a biodegradable solution

Organic acids, such as citric acid and methanesulfonic acid, have also emerged

as environmentally friendly alternatives for metal recovery from e-waste. These acids are biodegradable, non-toxic, and can be produced through microbial fermentation, making them a sustainable



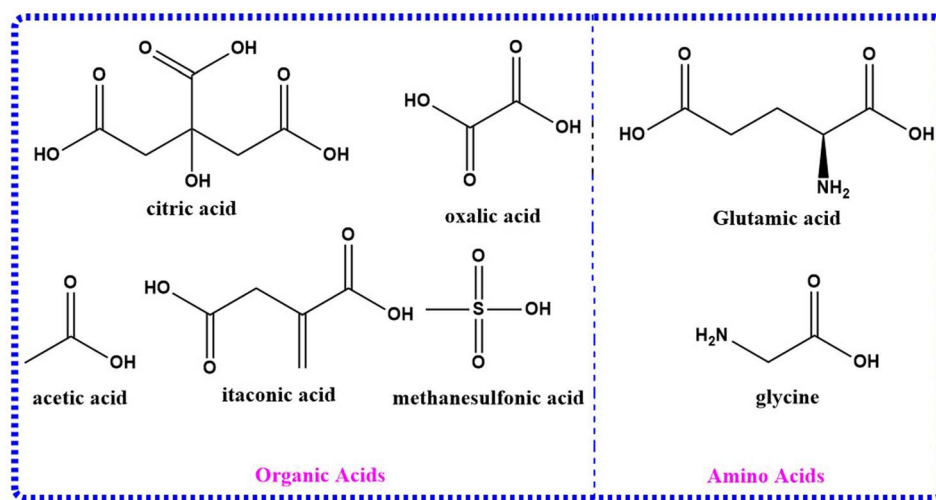


Fig. 4 Chemical structures of organic and amino acids commonly used in metal recovery from PCBs.

option for hydrometallurgical processes.^{12,13} For example, citric acid combined with H_2O_2 has been shown to achieve complete dissolution of metals such as Cu, Sn, Zn, Ni, Al, Au, Ag and Pd from PCBs, with outstanding recovery efficiencies.¹⁴ Moreover, methanesulfonic acid (MSA) has demonstrated high selectivity for solder (Sn–Pb alloy) dissolution, allowing for the efficient separation of metallic and non-metallic components of PCBs.¹⁵ MSA-based leaching processes operate at low temperatures and concentrations, reducing energy consumption and environmental impact. The utilisation of organic acids not only offers a sustainable approach to metal recovery but also supports the principles of the circular economy by encouraging the reuse and recycling of valuable resources.

Amino acids like glycine and glutamic acid are eco-friendly leaching agents due to their metal-chelating properties, which facilitate selective metal recovery. They form stable complexes with metals, improving leaching efficiency. These amino acids operate under mild conditions, requiring lower temperatures and pH levels, which reduces energy costs.⁸ Furthermore, they generate minimal secondary pollution, with no harmful by-products. Studies suggest that adding trace amounts of cyanide to amino acid solutions can enhance leaching kinetics, particularly for Ag. Different amino acid species dominate at varying pH levels,

affecting the overall leaching process.^{16–18} The chemical structures of organic and amino acids frequently used during the recovery of valuable metals from PBCs are displayed in Fig. 4.

The circular economy: closing the loop on e-waste

The circular economy concept stresses the need to design products for reuse, recycling, and resource recovery, thereby reducing waste and fostering sustainability. Within the framework of e-waste management, the circular economy can be achieved through the development of closed-loop recycling systems that recover valuable metals and reintegrate them into the production cycle. By adopting green chemistry principles and innovative technologies, we can transform e-waste from an environmental burden into a valuable resource.¹⁹ For example, the integration of ILs, DESs, organic/amino acids and other green solvents into the recycling process can significantly enhance the recovery of precious and base metals from PCBs, lowering the need for virgin materials and minimising the environmental effect of mining activities.⁸ Furthermore, the development of solvent regeneration techniques can further improve the sustainability of metal recovery processes

by reducing waste and conserving resources.

Policy and societal implications

The effective adoption of sustainable e-waste recycling technologies demands both scientific innovation and supportive policies, alongside active societal participation. Governments and international bodies must take a leading role in encouraging responsible e-waste management, which includes the creation of clear regulations, incentives for recycling, and campaigns to raise public awareness. Additionally, collaboration between researchers, industry stakeholders, and policymakers is crucial to scale up green chemistry technologies and integrate them into the global supply chain.^{1,8}

Future perspectives

The future of e-waste recycling lies in advancing solvent regeneration techniques to improve the recyclability of ILs, DESs, and organic/amino acids, enhancing cost-efficiency. Additionally, the integration of renewable energy sources in recycling plants will help reduce the sector's carbon footprint. To ensure sustainable and standardised practices, global policy harmonisation is essential, establishing unified regulations for effective e-waste management.



Concluding remarks

The chemical sciences offer transformative solutions to the global challenge of e-waste, enabling the sustainable recovery of valuable metals and the reduction of environmental pollution. By leveraging innovative technologies such as ILs, DESs, and organic/amino acids, we can develop environmentally friendly methods to extract and recycle metals from e-waste, promoting resource efficiency and aligning with the principles of the circular economy. However, the successful implementation of these technologies requires a holistic approach that integrates scientific innovation, supportive policies, and societal engagement. As we move towards a more sustainable future, the chemical sciences will continue to play a crucial role in transforming waste into wealth, ensuring the responsible use of resources and the protection of our planet for future generations.

Conflicts of interest

There is no conflict of interest to declare.

Data availability

There is no additional data associated with this article.

Acknowledgements

Deepseek and ChatGPT were used to improve the language and readability of the manuscript; they were not involved in data analysis, interpretation, or scientific content.

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