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Review

Towards resource regeneration: A focus on copper recovery from electronic waste

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ABSTRACT

It is projected that by 2030, the volume of electronic waste will escalate to 74.7 million tons, characterized by intricate compositions and designs, encompassing over 1000 potential toxic substances and heavy metals such as chromium and copper. Amidst the rapid advancements in electrical and electronic equipment, power generation, and transmission sectors, the global demand for refined copper has surged dramatically over the past five decades, nearly doubling in scale. Notably, China has annually imported over 2 million tons of scrap copper from international markets over the past two decades, fostering import dependency and depleting domestic copper resources. This paper conducts a forward-looking analysis of the development trajectory of copper resource recovery from e-waste, delving into the potential value, recovery methods, and environmental implications of this crucial component. From multiple perspectives, including copper's resource distribution, recovery technologies, and environmental and societal impacts, a comprehensive evaluation of the recovery value of copper in e-waste is undertaken. Pyrometallurgy, though initially developed, suffers from low efficiency and purity. In contrast, hydrometallurgy, built upon pyrometallurgy, enhances efficiency, achieving copper leaching rates of over 90%, albeit at the cost of environmental consequences. Furthermore, the emerging bioleaching process continues to progress, offering a promising strategy. Additionally, this paper outlines the prospective directions for future development in this field, aimed at addressing the challenges of e-waste management more effectively and fostering the efficient recovery and reuse of valuable copper metals.

1. Introduction

Electronic waste, colloquially known as "e-waste", refers to discarded electrical or electronic devices that are no longer in use. Currently, there lacks a unified definition for electronic waste on a global scale (Kumar et al., 2017), as these items represent byproducts of technological advancement that have become obsolete and are no longer needed by individuals (Tanskanen, 2013). The Organization for Economic Co-operation and Development (OECD) defines electronic waste as any electrical appliance that has reached the end of its usage lifecycle (Suja et al., 2014), according to the United States Environmental Protection Agency (EPA), electronic waste encompasses large appliances, small appliances, and consumer electronics products (Kahhat et al., 2008), Japan's legislation on electronic waste recycling, such as the "Resource Effective Utilization Promotion Law", encompasses 34 categories of electronic products. These categories span from larger appliances like televisions to smaller devices such as mobile phones (Bø et al., 2010), the definition of electronic waste according to the "Administrative Measures for the Prevention and Control of Pollution from Electronic Waste" in China includes discarded electrical and electronic equipment and their components generated in daily life, as well as products or devices prohibited from production or importation by laws and regulations. Currently, the most widely accepted definition of electronic waste is provided by the European Waste Electrical and Electronic Equipment (WEEE) Directive. It defines electronic waste as discarded electrical and electronic equipment, including all components, sub-assemblies, and consumables that are part of the product at the time of disposal (Shittu et al., 2021).

As the global population continues to grow and demand for a higher quality of life increases, particularly in urban areas, the management of municipal waste faces substantial challenges. It is estimated that approximately 2.01 billion tons of municipal solid waste are generated globally each year (Kaza et al., 2018). The development of the information age and the growing demand for electronic products has led to a

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significant surge in electronic waste, which is expanding at an exceedingly rapid rate. As illustrated in Fig. 1, an estimated 53.6 million metric tons of electronic waste were generated globally in 2019. However, records indicate that only 17.4% of this waste was collected and properly recycled. It is projected that by 2030 (Forti et al., 2020; Vanessa et al., 2020; Kahar et al., 2023), this volume will grow to 74.7 million metric tons. Furthermore, by 2050, the annual production is expected to exceed that of 2020 by 73% (Yang et al., 2023). It is projected that within the next five years, the volume of electronic waste will reach 44.4 million metric tons. By 2026, the global market size for electronic product recycling is expected to reach $658 billion USD (Seif et al., 2023). Due to the complexity of composition and design in electronic waste, it contains over 1000 potential toxic substances, including heavy metals (such as silver, gold, chromium, copper, lead, indium, nickel, lithium, and mercury) and organic pollutants (e.g., polybrominated diphenyl ethers (PBDEs), polybrominated biphenyls (PBBs), and polychlorinated biphenyls (PCBs)) (Pershaanaa et al., 2023; Yin et al., 2021). It harbors up to 60 different types of valuable metals, including copper (Cu), gold (Au), silver (Ag), and nickel (Ni). Improper disposal poses significant threats to the environment and human health (Fig. 2) and leads to considerable resource wastage (Silva et al., 2023; Priya and Hait, 2018).

The transboundary movement of electronic waste is a significant factor contributing to the accumulation of electronic waste in developing countries. This not only poses a threat to environmental sustainability but also has adverse effects on public health. According to statistics, approximately 80% of electronic waste is exported from developed countries to developing ones (Awasthi and Li, 2017; Rasheed et al., 2022). In summary, addressing the escalating global issue of electronic waste and the imperative for the recycling of valuable metals, the pursuit of green and high-value utilization of waste has emerged as a pivotal research objective (Ali et al., 2023). Currently, the primary options for handling electronic waste involve reuse, refurbishment, recycling, as well as incineration and landfilling. Landfilling entails burying electronic waste directly underground. However, electronic waste contains significant quantities of hazardous substances, such as heavy metals and organic compounds (Mtibe et al., 2023), which can lead to severe environmental and soil degradation. Incineration involves burning electronic waste, during which harmful substances, such as dioxins, may be released into the atmosphere, resulting in air pollution and posing significant health risks to humans (Cui and Zhang, 2008). Traditional landfilling and incineration methods are no longer aligned

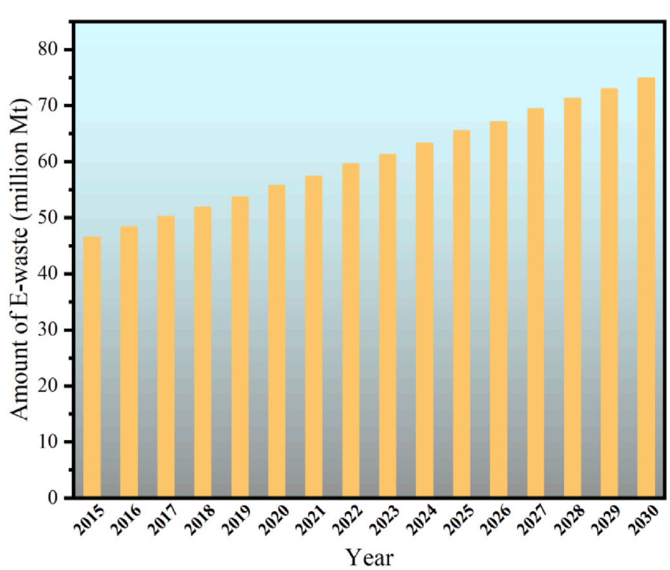

Fig. 1. Global generation of e-waste from 2015 to 2030 (Kahar et al., 2023) Copyright © 2023.

with the requirements for sustainable development. In recent times, the circular economy model has emerged as a new paradigm for economic development, yielding numerous positive impacts on the environment, economy, and society. The concept of a circular economy, which emphasizes waste and pollution elimination through design and the preservation of product and material utility, aims to restore and regenerate natural systems. Material circularity and the recovery of valuable components are principles derived from this circular economy framework (Xavier et al., 2023). By promoting electronic waste recycling and efficient recovery of valuable materials, the associated issues with electronic waste can be effectively addressed (Ding et al., 2019; Wu et al., 2019).

The chemical composition of electronic waste is highly complex, encompassing a diverse range of materials such as steel, iron, plastics, non-ferrous metals, glass, wood, plywood, printed circuit boards (PCBs), concrete, ceramics, and rubber. While these components serve specific purposes within electronic devices, upon disposal, they collectively form electronic waste (Betts, 2008). Specifically, steel and iron account for 50% of the composition, plastics constitute 21%, and non-ferrous metals make up 13%, while other components such as rubber, concrete, and ceramics collectively represent 16% of electronic waste (Burat and Özer, 2018). For instance, within electronic waste, printed circuit boards (PCBs) serve as core components, comprising 3–6% of the total weight of electronic and electrical equipment (Kumari et al., 2024). Typically, from 1 ton of Waste Printed Circuit Board (WPCB), approximately 143 kg of copper, 0.5 kg of gold, 40.8 kg of iron, 29.5 kg of lead, 2.0 kg of tin, 18.1 kg of nickel, and 10.0 kg of antimony can be separated (Kolias et al., 2014). Table 1 presents examples of metal compositions from various electronic waste materials as documented in the literature. With the rapid development of industries such as electrical and electronic products, power generation and transmission, industrial machinery, and construction (Kahar et al., 2023), the global demand for refined copper has surged dramatically over the past 50 years, nearly doubling (Paz-Gómez et al., 2021). Importantly, secondary copper production has reduced energy consumption by 85% and greenhouse gas emissions by 65% compared to primary copper production (Rivera et al., 2021). Copper is a remarkably unique metal, being one of the few materials that can maintain its original chemical and physical properties during the recycling process. This means that copper can be recycled repeatedly without compromising its quality. Its excellent electrical, thermal, formability, and corrosion resistance properties make it a popular choice in a wide range of applications requiring high thermal and electrical conductivity (Gorsse et al., 2023; Yang et al., 2020). Consequently, the proper disposal of electronic waste, reduction of environmental impacts, and recovery of the valuable metal copper have remained focal points of research.

2. Copper in electronic waste and its applications

2.1. The origin and distribution of copper in electronic waste

Copper metal found in electronic waste originates from discarded appliances such as televisions, electrical wiring including those used in construction, and automotive components such as engines (Ji et al., 2023; Liu et al., 2020). Additionally, it is sourced from industrial by-products generated during manufacturing processes, such as copper waste from metallurgical plants. The distribution and presence of copper within electronic waste vary depending on the type and origin of the waste, exhibiting a broad distribution and relatively high concentrations (Baniasadi et al., 2021). For instance, within discarded electrical wiring and cables, copper predominantly resides within the insulation layer and the metallic core of the conductor. In obsolete electronic components, copper is primarily found in printed circuit boards (PCBs) and other electronic elements. Furthermore, in discarded electrical appliances, copper is extensively present in various equipment and components, including but not limited to electric motors, heat sinks, piping,

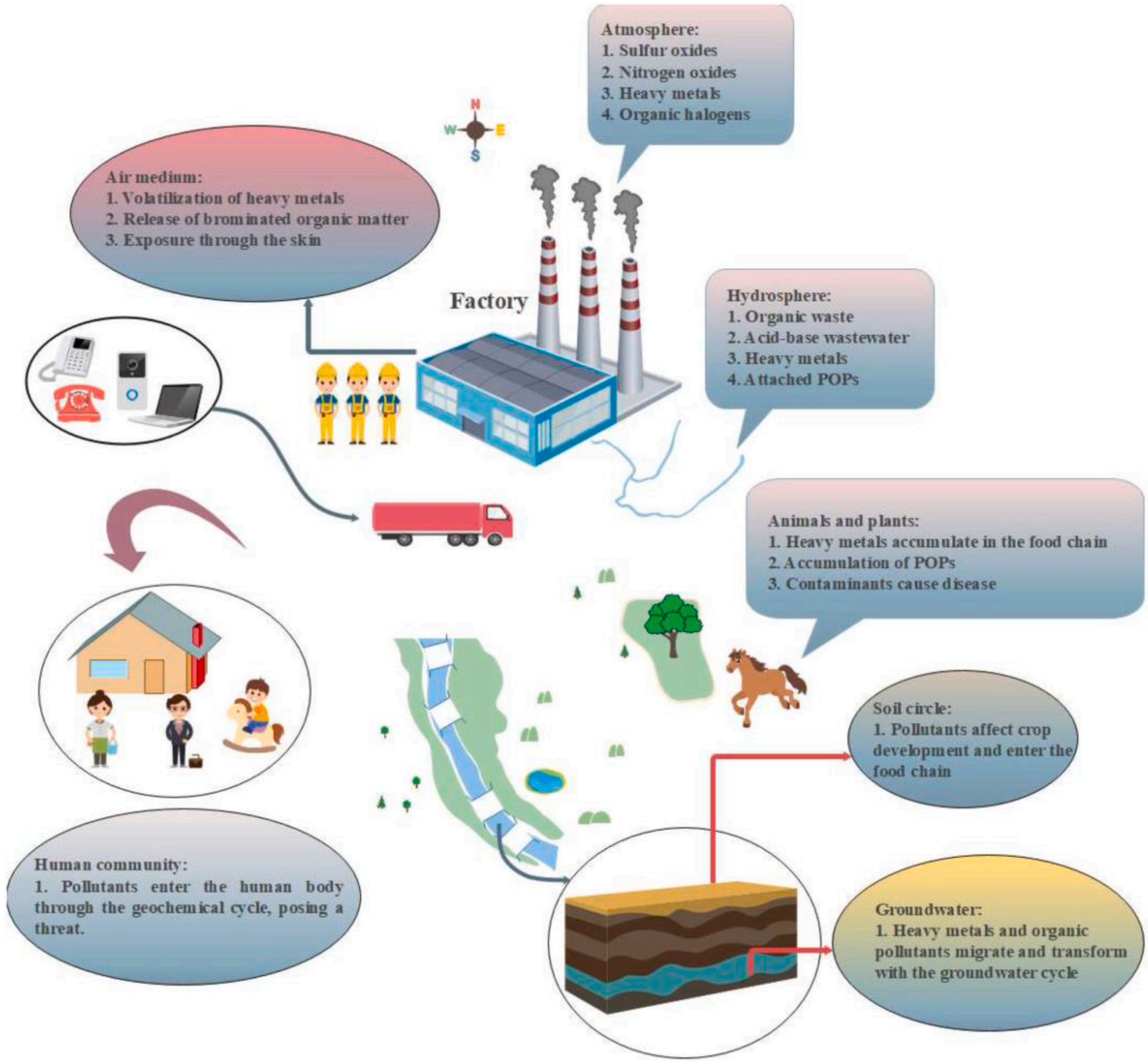

Fig. 2. Schematic of environmental and health impacts of e-waste(Liu et al., 2023a).

Table 1
Composition of different metal contents of e-waste in the literature.

Category	E-waste metal content												Unit	Ref
	Cu	Fe	Al	Pb	Ni	Mg	Zn	Sn	Ca	Co	Li	Mn		
Crushed WPCBs	60.51	0.24	1.15	0.03	0.03	0.06	0.23	0.9	1.94	–	–	–	wt.%	Xie et al. (2024)
Spent Lithium-Ion Batteries	11.56	0.55	17.86	–	27.02	–	–	–	–	162.6	38.3	40.16	g/kg	Cai et al. (2023)
Electroplating sludge	5.52	7.84	3.59	–	6.59	–	–	–	12.44	–	–	–	wt.%	Xiao et al. (2024)
Flue dust	5.0	20.0	7.9	0.7	0.3	0.3	–	–	0.7	–	–	4.4	wt.%	Lee and Mishra (2020)
WPCB	25.4	3.7	4.4	0.1	–	–	–	3.7	7.2	–	–	–	wt.%	Wang et al. (2020)
Mobile phone PCB	21.46	4.67	2.97	–	–	–	0.34	1.49	–	–	–	–	wt.%	Brožová et al. (2021)
Discarded Integrated Circuits	3.04	19.45	–	0.74	8.41	–	–	4.59	–	–	–	–	wt.%	Barnwal and Dhawan (2020)
STPCBs	187.9	32.6	26.1	22.5	4.392	1.504	–	30.5	45.5	0.279	–	–	g/kg	Beiki et al. (2023)
MPCBs	43.19	13.9	2.78	11.8	13.44	–	14.3	–	–	–	–	–	wt.%	Annamalai and Gurumurthy (2020)
WMM	338.45	–	19.22	–	2.95	–	0.31	–	–	–	–	–	mg/kg	Li et al. (2023a)

Note: STPCBs: spent telecommunication printed circuit boards; MPCBs: mobile phone printed circuit boards; WMM: waste memory modules.

and connectors (Gulliani et al., 2023).

According to data released by the International Copper Study Group (ICSG), 32% of the global copper consumption in 2022 originated from recycled copper, underscoring the increasingly significant role of recycled copper in global copper utilization (Paz-Gómez et al., 2021; GROUP, 2023). Moreover, electronic waste harbors a wealth of recyclable elements, with copper content notably substantial, ranging between 10 and 25%. It is particularly noteworthy that in common computers and mobile devices, the copper content in printed circuit boards (PCBs) reaches as high as 20–25%. This proportion even surpasses the copper content found in ores and primary minerals (Fathima et al., 2022; Jadhao et al., 2021). Fig. 3 illustrates the global copper usage (including recycling) from 2005 to 2022 (Paz-Gómez et al., 2021; GROUP, 2023). Copper plays a critical role in numerous sectors, highlighting its significant value and potential for recycling. Therefore, it is imperative to prioritize the recycling of copper from electronic waste and implement scientifically effective methods to enhance both the recovery and reuse rates of copper. This approach aims to achieve the dual objectives of resource circulation and environmental conservation (Barragan et al., 2020).

2.2. The application of copper in electronic products

Copper ranks among the most efficient conductors in terms of electrical and thermal conductivity, boasting a conductivity of up to 5.7×10^7 S/m and a thermal conductivity coefficient of 397 W $m^{-1} \cdot K^{-1}$, significantly surpassing that of other common metals. This characteristic implies that copper effectively reduces resistance during current transmission, thereby minimizing energy losses (Ma et al., 2023; Sun and Ion, 1995). Its ability to fully exploit the excellent properties of various substrates, coupled with its lightweight nature, contributes to reduced production costs. In electrical transmission and distribution systems, copper-core cables are widely adopted due to their high conductivity and stability (Chen et al., 2022a). Copper-based materials play a crucial role in addressing the thermal management challenges of high heat flux electronic components (Duan et al., 2023). Copper tubes and wires are commonly employed in the plumbing and heating systems of buildings, favored for their corrosion resistance and longevity (Ko et al., 2023). Additionally, copper can be crafted into a variety of artistic and decorative pieces, such as the bronze vessels prevalent during the Han Dynasty, which served as luxurious wine vessels of that era (Liu et al., 2023b). Sometimes, it is necessary to emphasize the functionality of copper in specific applications, often in the form of alloys such as Cu-Al alloy (Park et al., 2024). In essence, the utilization of copper in electronic products encompasses various aspects including conductivity, structural materials, heat dissipation, and decoration. These applications provide robust support for the efficiency, stability, and aesthetic appeal of electronic products.

2.3. The value and potential resources of copper in electronic waste

As the world's largest consumer of copper, China heavily relies on external sources for its copper resource supply. To alleviate the shortage of copper materials, China frequently adopts strategies involving the importation of scrap copper. It is astonishing that over the past two decades, China has consistently imported over 2 million tons of scrap copper annually from the international market. Fig. 4 illustrates the main trading countries and routes (countries with import or export volumes exceeding 50,000 tons and trade routes exceeding 60,000 tons) (Liu et al., 2020; Tian et al., 2021; Eheliyagoda et al., 2019). This further underscores the importance of scrap copper recycling to China, which not only contributes to economic gains but also has far-reaching implications for resource security and environmental preservation. Therefore, the rational and efficient utilization and recycling of scrap copper play a pivotal role in driving China's sustainable development.

Copper in electronic waste represents a renewable resource. Through efficient recycling and reuse, it can mitigate reliance on natural resources, mitigate environmental degradation associated with primary copper extraction, thereby promoting resource utilization and sustainable development (Ghosh et al., 2022; Islam et al., 2020). For instance, in electronic products such as smartphones and computers, there exists considerable value in reuse. Utilizing specialized recycling techniques, copper can be extracted from electronic waste and subsequently utilized in the manufacturing of new electronic products or other applications. On the other hand, it is imperative to introduce novel copper processing techniques aimed at reducing overall energy consumption and greenhouse gas emissions, lowering production costs, and managing investment and technological risks. This not only promises significant economic benefits for enterprises but also generates employment opportunities within the community (Kulczycka et al., 2016). Furthermore, governments can incentivize and support the recycling and reuse of copper from electronic waste by enacting relevant policies and regulations. Fig. 5 presents the electronic waste laws, regulations, and legislations followed by various countries for the proper management of electronic waste(Islam et al., 2020). Copper within electronic waste not only holds significant value but also boasts immense potential resources. Through multidimensional exploration and practical endeavors, better realization of this resource's effective utilization can be achieved, thereby fostering resource circulation and sustainable development.

3. Technologies and methods for copper recovery from electronic waste

3.1. Mechanical and physical recycling methods

In the process of electronic waste recycling, mechanical pretreatment

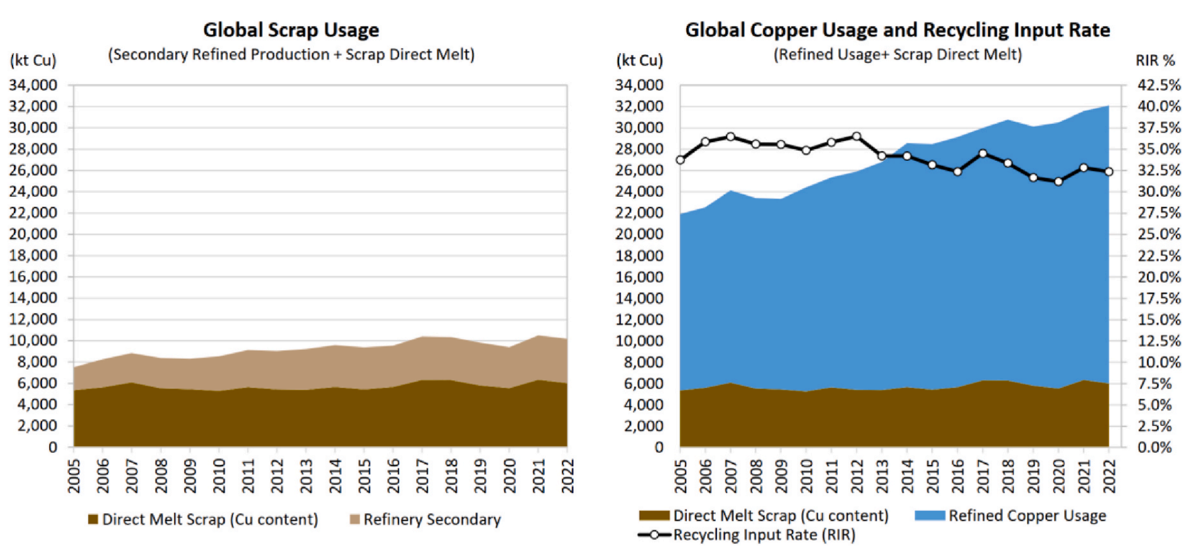

Fig. 3. ICSG global copper usage (Incl. Recycling), 2005–2022 (GROUP, 2023).

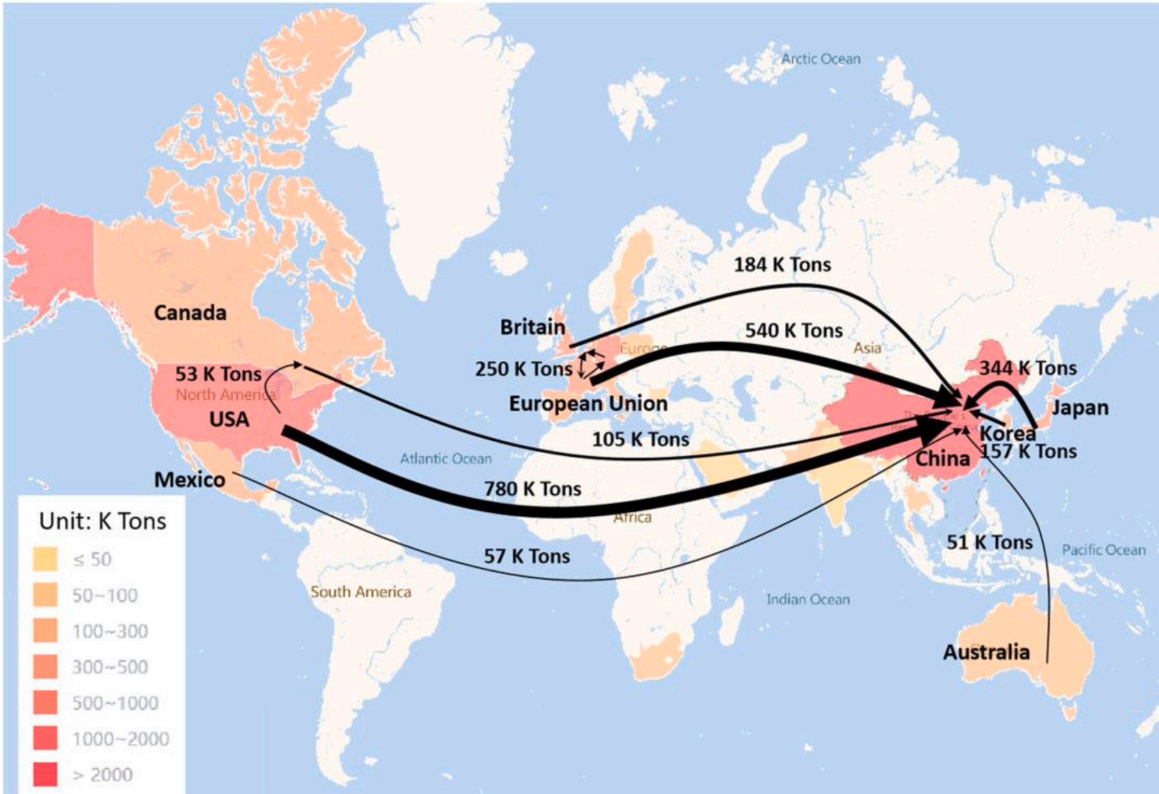

Fig. 4. The main flow routes of international scrap copper(Tian et al., 2021)

is an indispensable preliminary stage, comprising mainly manual dismantling, mechanical crushing, powder processing, hammering, sorting, and component separation steps (Khanna et al., 2020; Liu et al., 2019). The purpose of mechanical pretreatment is to effectively reduce the size of electronic waste so that metals can be fully separated from non-metals, laying a solid foundation for subsequent separation processes. While solid waste exhibits diverse physicochemical properties, crushing and grinding technologies demonstrate wide applicability in handling various types of solid waste. He et al. (2022). comprehensively reviewed the application of crushing and grinding technologies in the treatment of four major categories of solid waste: spent lithium-ion batteries (LIBs), waste printed circuit boards (WPCBs), incineration bottom ash (IBA), and incineration fly ash (IFA). Fig. 6 (A) and (B) depict typical schematic diagrams and main mechanical forces involved in crushing processing, while Fig. 6 (C) and (D) illustrate typical schematic diagrams and main mechanical forces involved in grinding processing (He et al., 2022). Liu et al. (2022). Employed a ball milling and sieving method to recover high-grade copper from waste printed circuit boards (WPCBs). They investigated the influence of milling time on the copper recovery rate during the mechanical processing, and after three rounds of ball milling and sieving, the copper content enriched from the initial 74.22 wt% to 94.72 wt%, achieving a high recovery rate of 86.78%. Verma et al. (2018). Optimized hammer milling parameters for the comminution treatment of printed circuit boards. The results revealed that the copper content in the fraction with a sieve size greater than 100 BSS (British Standard Specification) reached as high as 43 wt%, while the fraction with a sieve size less than 100 BSS exhibited lower copper content. On the other hand, Xian et al. (2021). Employed enhanced gravity separation combined with wet high-gradient magnetic separation to achieve efficient copper recovery through thermal treatment, separation, and enrichment processes, achieving a recovery rate of 74.02%. Gao et al. (2024). Utilized an innovative sulfide roasting-flotation-magnetic separation technology to recover Cu, Ni, Zn, and Fe from electroplating sludge, achieving a copper recovery rate of 83.73%. Meng et al. (2018). Employed a centrifugal gravity separation method to recover Cu from Computer PCBs (CPCBs) (Fig. 7), while also concentrating Ag, Au, and Pd. The total recovery rate of Cu throughout the separation process reached 97.80%. Lee et al.(Lee and Mishra, 2020). Developed a process for recovering metals from flue dust generated during the treatment of electronic waste through magnetic separation and leaching. Through this continuous recovery process, the leaching efficiency of Cu reached 98.0%. Overall, while mechanical processing methods offer a straightforward approach for enriching and recovering copper, their efficiency is comparatively low.

3.2. *Chemical recycling methods*

3.2.1. *Pyrometallurgical techniques for metal copper recovery*

Pyrometallurgy is a metallurgical method wherein metals are separated from impurities at high temperatures, utilizing the heat generated from fuel combustion or certain chemical reactions. It is the most traditional and commonly employed approach for metal separation and recovery, involving processes such as incineration, plasma arc or blast furnace smelting, slag formation, sintering, melting, and high-temperature gas-phase reactions (Hsu et al., 2019). In the processing of WPCBs, pyrometallurgical methods can handle between 1000 and 5000 tons of WPCBs per day, with substantial annual output potential. This process can yield approximately 100,000 tons of copper, 2400 tons of silver, 100 tons of gold, and 50 tons of platinum group metals (Faraji et al., 2022). Fig. 8 illustrates a typical pyrometallurgical process flowchart for WPCB recycling.

Rossini et al.(Rossini and Bernardes, 2006). Adjusted the ratio of electroplating sludge to pyrite and investigated the recovery efficiency of metals Zn, Ni, and Cu at various roasting times and temperatures. The experiments demonstrated that the recovery rate of Cu could reach 50%. Park, H. S. et al.(Park et al., 2019). Reported a three-step method for processing waste mobile phones (WMP) through pyrolysis, physical treatment, and pyrometallurgical treatment (as shown in Fig. 9). The

Fig. 5. Laws and regulations regarding electronic waste management vary among different countries(Islam et al., 2020). © 2019 Elsevier Ltd. All rights reserved.

study extensively examined the smelting process of insoluble residues to simulate the recovery of precious metals (Au and Ag) and key metals (Ni and Sn) in a molten state. The integrated metal recovery system can yield approximately 82.7 kg of Cu from the processing of 1000 kg of WMP. Table 2 outlines the research status regarding pyrometallurgical recovery of metal copper. However, overall, the widespread application of pyrometallurgical methods is limited due to the toxic by-products generated and the additional challenges associated with the complexity of recovering pure metals (Thakur and Kumar, 2020). Furthermore, the efficiency and purity of pyrometallurgical copper recovery are not high, leading to significant energy consumption and high equipment maintenance costs (Zheng et al., 2024a).

3.3. Hydrometallurgical techniques for metal copper recovery

Hydrometallurgy is a technique that utilizes chemical reactions to transfer metals from ores or concentrates into a liquid phase, typically through contact with aqueous solutions, followed by the separation of various metals from the liquid phase to ultimately recover metals or their compounds. Given the limitations of pyrometallurgy in terms of efficiency and purity, hydrometallurgy has emerged as a promising alternative due to its mild reaction conditions, excellent versatility, and high efficiency in comprehensive metal recovery. With the evolving industry landscape and emerging demands, hydrometallurgy is rapidly gaining prominence and experiencing significant development (Zheng et al., 2024b).

Hydrometallurgy can be classified into acid leaching, alkaline leaching, and salt leaching based on the leaching agents employed. Acid leaching involves the use of strong acids and oxidizing agents to strip precious metals into precipitates, while other valuable metals such as copper dissolve in the acid. Following treatment with nitric acid or aqua regia, precious metals can be recovered from the precipitate. The drawback of acid leaching lies in its low selectivity, which necessitates continuous separation methods for enrichment and purification to achieve high selectivity for a particular metal. For instance, Gómez Duran, J. A. et al.(Gómez Duran et al., 2023). Investigated the influence of parameters such as metal maximum effective concentration (MAC), initial sulfuric acid concentration, stirring speed, and oxidizing agent on the recovery of copper, lead, and iron from electronic waste using acid leaching methods. Furthermore, discarded batteries pose a challenging issue within electronic waste, with their most valuable component being the cathode, comprised of various metal oxides. In recent years,

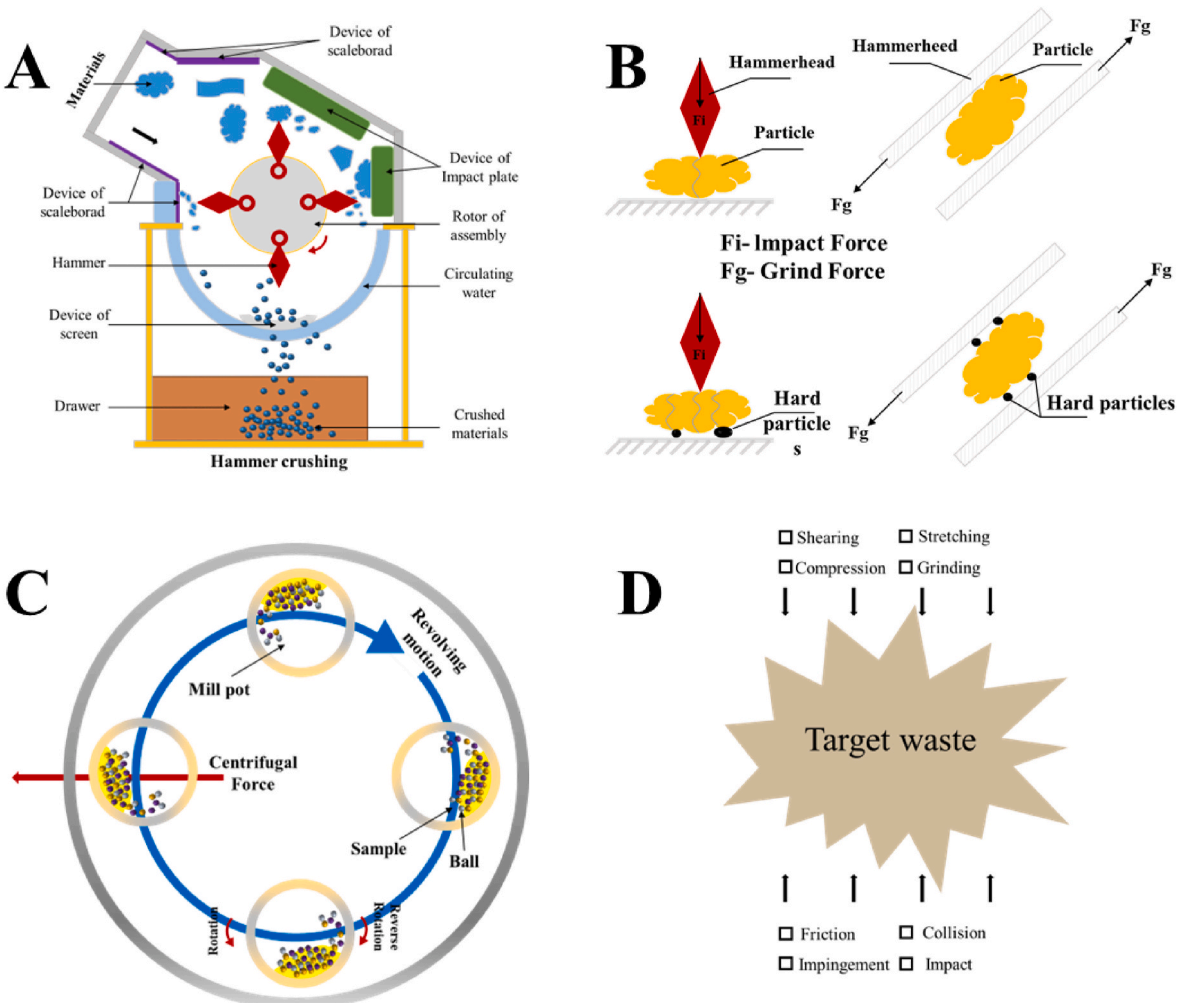

Fig. 6. A and C illustrate typical equipment and schematics for crushing and grinding, respectively. B and D respectively depict the main mechanical forces involved in these two processes(He et al., 2022) © 2022 Elsevier Ltd. All rights reserved.

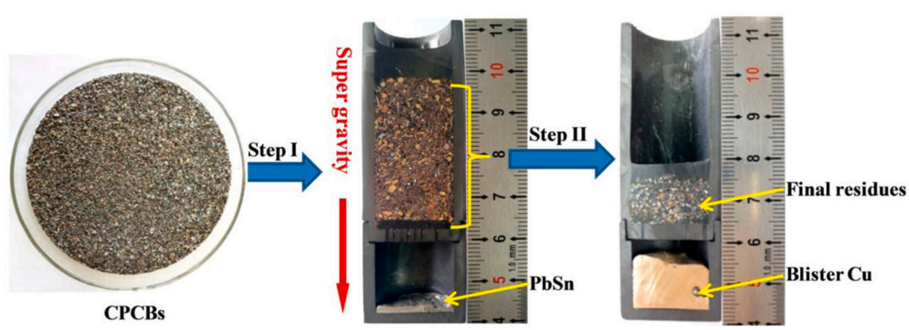

Fig. 7. Centrifugal gravity separation method is utilized to recover Cu from CPCBs(Meng et al., 2018) © 2017 Published by Elsevier B.V.

numerous methods have been reported for recovering metals from cathodes (Ciez et al., 2019; Harper et al., 2019), while there is a clear trend towards implementing green and sustainable recovery approaches (Fan et al., 2021; Jegan et al., 2021; Kim et al., 2021). Table 3 presents additional relevant specific case studies. Generally speaking, the advantages of wet impregnation for metal extraction include high efficiency, strong selectivity (potentially requiring multiple separation steps), and suitability for complex materials. However, disadvantages include extended processing time, challenges in waste liquid treatment, and higher costs.

3.4. Biological recovery method

Bioleaching is an environmentally friendly hydrometallurgical technique that utilizes the activity of microorganisms to effectively recover metals from waste materials. Moreover, these microorganisms can be regenerated for reuse as leaching agents in metal extraction. Currently, research on bioleaching methods is mainly categorized into three major types: single-step, two-step, and waste medium bioleaching methods (as illustrated in Fig. 15). Baniasadi et al. (2019). Provided a comprehensive overview of bioleaching as a sustainable method for metal recovery from electronic waste. Microorganisms with bioleaching

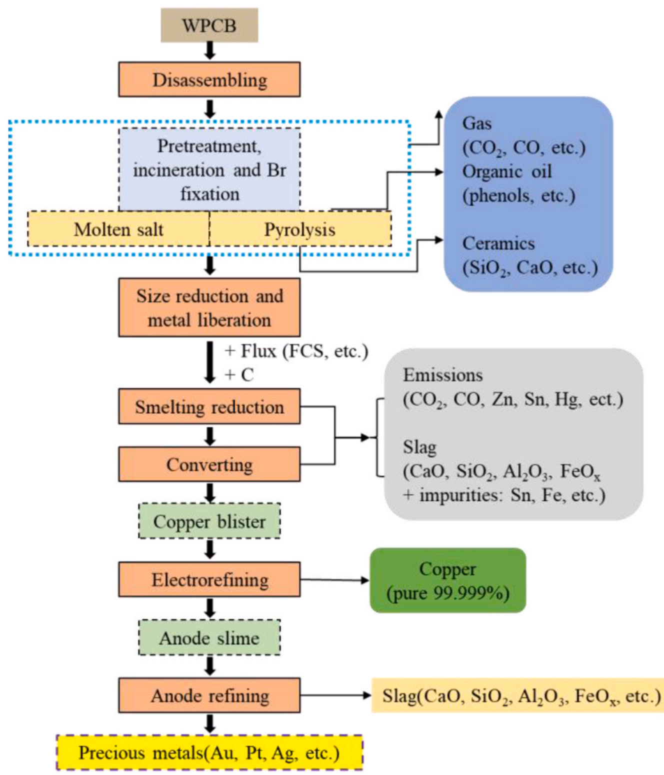

Fig. 8. A typical pyrometallurgical process flowchart for recycling WPCB (Faraji et al., 2022) © 2022 Elsevier Ltd. All rights reserved.

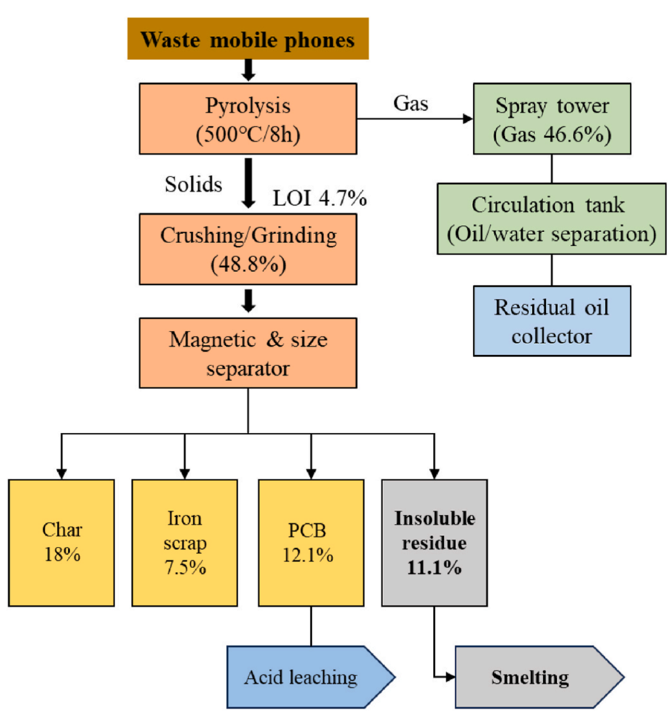

Fig. 9. Flow process based on unit weight of spent mobile phonetreatment: pyrolysis, physical separation, and smelting(Park et al., 2019) Copyright © 2019, American Chemical Society.

capabilities are mainly categorized into three groups: chemolithoautotrophic bacteria (utilizing acidogenesis and redox mechanisms), fungi (employing acidolysis and chelation mechanisms to produce organic acids), and cyanobacteria (decomposing complex

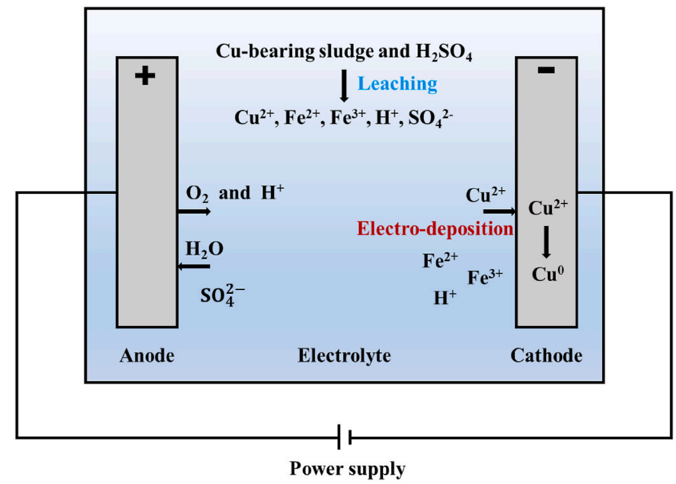

Fig. 10. Chemistry of integrated acid leaching and electrolytic deposition (Trinh et al., 2021).

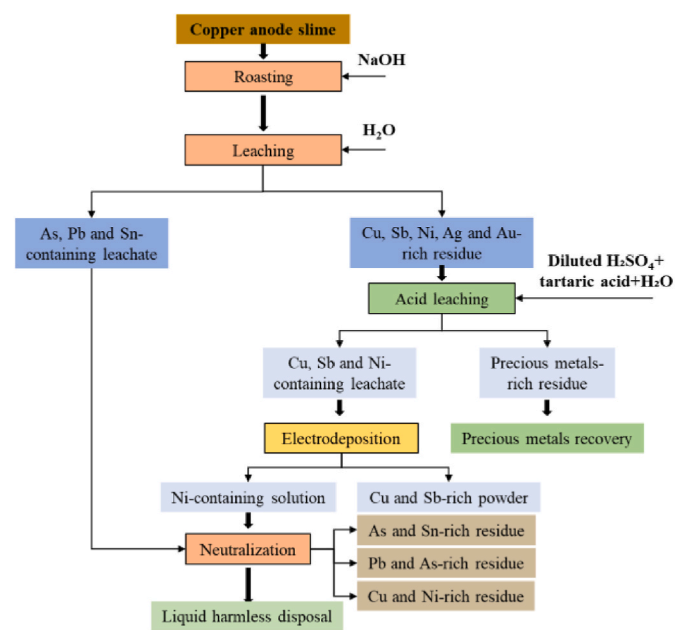

Fig. 11. Developed process for enriching PMs and recovering valuable metals from CAS(Zhu et al., 2022) © 2022 Published by Elsevier B.V.

compounds through chelation). Dong et al. (2023). Extensively explored the prospects of recovering precious metals from WPCBs through the bioleaching approach, and compared the advantages and disadvantages of three recovery technologies: pyrometallurgy, hydrometallurgy, and bioleaching (Table 4). Benzal et al. (2020). Investigated the merits and demerits of bioleaching for copper recovery from PCBs using novel strategies and methods. The new strategy optimized reaction kinetics and overcame leachate transport barriers, resulting in an increase in copper recovery from 50% to 80% within 6 h, significantly reducing the time required to achieve the same recovery rate. Table 5 presents other relevant specific cases.

4. The economic, environmental, and social impacts of copper recovery from electronic waste

4.1. The economic benefits and market potential of copper recovery

In order to improve the processing of waste electrical and electronic

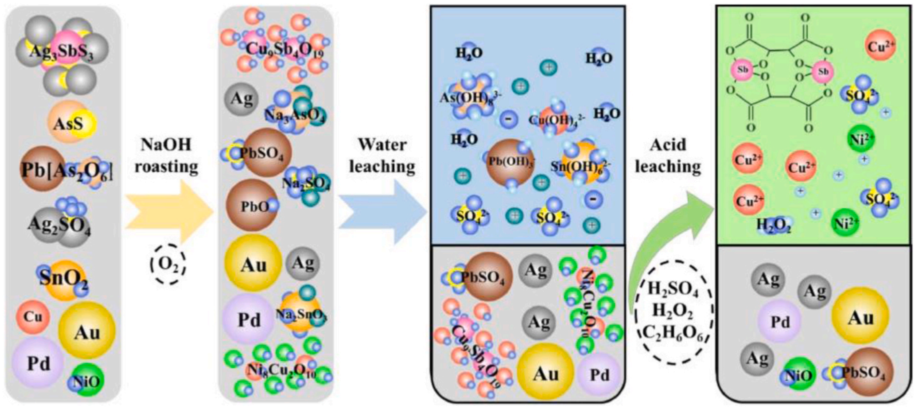

Fig. 12. Proposed mechanism of simultaneous BMs removal and PMs enrichment from CAS(Zhu et al., 2022) © 2022 Published by Elsevier B.V.

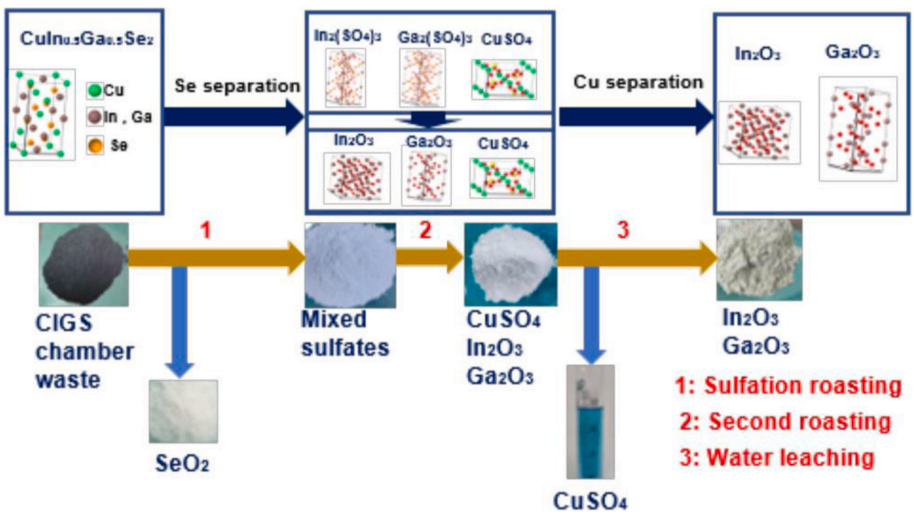

Fig. 13. Two-stage sulfation roasting for controlled phase transformation and selective leaching to separate valuable components(Ma et al., 2020) Copyright © 2020, American Chemical Society.

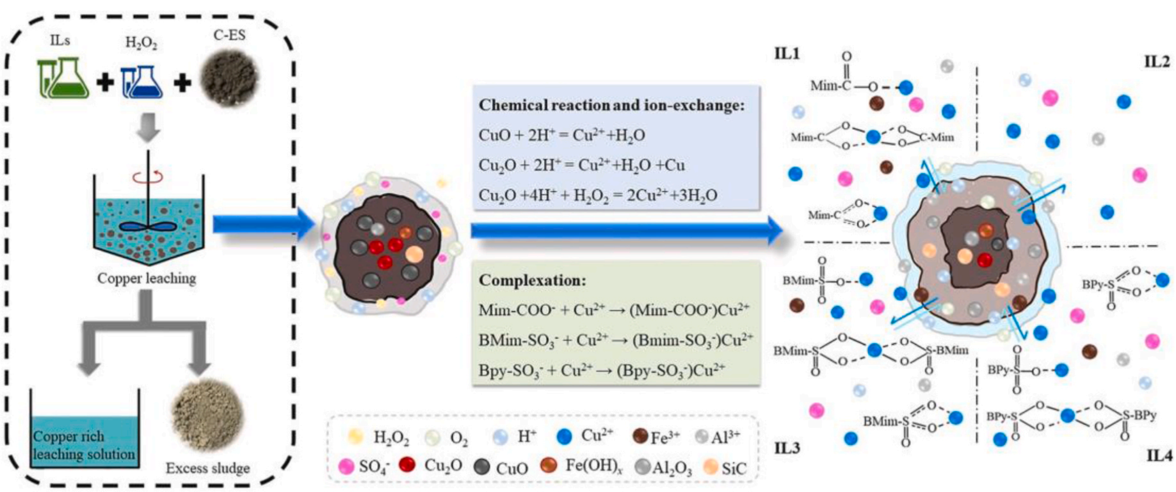

Fig. 14. Four types of green ionic liquids are employed for the leaching of copper from copper-rich electroplating sludge (C-ES) (Li et al., 2023b). © 2023 Elsevier Ltd. All rights reserved. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

products and optimize related subsidy policies, the "Notice on Adjusting the Subsidy Standards for the Treatment Fund of Waste Electrical and Electronic Products" was issued in March 2021 (Table 6), which made adaptive adjustments to the subsidy standards. This policy not only significantly promotes the standardization of the electronic waste treatment industry but also brings new market opportunities and

Table 2
Pyrometallurgical recovery of copper.

Subject of Treatment	Process method	Efficiency of Cu Recovery	References
Electroplating sludge and pyrite	Variations in roasting time, temperature, and ratio	50%。	Rossini and Bernardes (2006)
Waste Mobile Phone (WMP)	Three-step processing involving pyrolysis, physical treatment, and pyrometallurgy.	The processing of 1000 kg of WMP yields a significant amount of 82.7 kg of Cu.	Park et al. (2019)
WPCB	Pyrolysis at 800 °C for 20 min under argon atmosphere.	The residue contains copper with a concentration of 91.7 wt%.	Cayumil et al. (2018)
WPCB	Pyrolysis at 550 °C for 120 min under vacuum conditions.	The residue contains copper with a concentration of 99.5 wt%.	Long et al. (2010)
WPCB	Pyrolysis at 700 °C under a nitrogen atmosphere, followed by the separation of copper, tin, and other metals in the pyrolysis residue through selective crushing, sieving, and other physical methods.	The overall recovery rate of Cu is 95%.	Wang et al. (2020)
WPCB	A cost-effective strategy combining crushing pretreatment with pyrolysis has been developed. With a pretreatment particle size of 4.0 cm and a pyrolysis temperature of 330 °C, lower energy consumption is achieved.	The recovery rate of Cu is 92.38 wt%.	Chen et al. (2021)

economic potential to the industry. The government is striving to reduce direct intervention in the industrial chain and encourages enterprises to reduce reliance on subsidies through independent innovation and optimization and upgrading of the industrial chain. For the electronic waste management industry, true competitiveness lies in the refinement and efficiency of its supply chain. When companies can delve into the processing of electronic waste and extract valuable materials for high value-added utilization, significant economic benefits can be achieved even in the absence of subsidies. With the implementation of new subsidy standards, the electronic waste recycling and processing industry in China may witness a new paradigm shift in market dynamics, harboring substantial economic gains and market potential. Firms should actively adapt to this change by embracing technological innovation and integrating the industrial chain, fully tapping into the "treasures" within electronic waste, thereby injecting new momentum into the industry's sustainable development (Chen, 2021).

Copper, not only an essential strategic resource and industrial material but also a significant driver of economic growth, transformation, and the diversification of reserve assets and investment vehicles. The economic benefits of copper recycling are substantial, facilitating both resource circulation and environmental pollution mitigation. With the escalating costs of copper mining and the gradual depletion of global resources, coupled with the sustained increase in copper prices, the recovery of copper from electronic waste has emerged as an economically viable choice. This recycling approach not only meets a portion of the copper demand but also reduces reliance on primary copper ore, thus slowing the rate of resource depletion. Recovering base metals such as copper and tin from electronic waste not only yields higher economic benefits but also aligns more favorably with sustainable development

Table 3
Hydrometallurgical recovery of copper.

Subject of Treatment	Process method	Efficiency of Cu Recovery	References
The sludge generated from printed circuit boards (PCBs).	The aim is to efficiently extract Cu while inhibiting the dissolution of Fe, using acids such as HCl, HNO_3, and H_2SO_4 for the selective leaching of copper.	Under conditions where the slurry concentration is 4% and the H_2SO_4 concentration is 0.2 M, the leaching rate of Cu reaches up to 95%, while the leaching rate of Fe decreases to less than 5%.	Trinh et al. (2020)
The sludge generated from printed circuit boards (PCBs).	The method combining acid leaching and electrodeposition (as shown in Fig. 10) integrates the dissolution and separation steps into a single stage. Cu can selectively deposit on the cathode under different potential conditions, enabling its reduction on the cathode. This approach identifies optimal conditions for the complete recovery of Cu selectively from the electrolyte.	The resulting Cu product exhibits a purity exceeding 99% and a uniform morphology.	Trinh et al. (2021)
The electroplating sludge containing chromium.	Selective extraction of Ni and Cu through chloride leaching and water immersion method.	Under optimal process conditions, the extraction efficiency of Cu reaches 90.7%.	Huang et al. (2021)
Copper anode slime (CAS).	Utilizing the NaOH roasting-water leaching-synergistic acid leaching green process, employing only low-concentration green reagents, enables efficient removal of base metals and enrichment of precious metals from copper anode slimes simultaneously (as depicted in Figs. 11 and 12).	The final synergistic acid leaching removed 99.68% of Cu.	Zhu et al. (2022)
WPCB	After pretreating WPCB with microwave pyrolysis, metal recovery is achieved through a two-stage acid leaching process using wet metallurgy.	The overall recovery rate of Cu can reach approximately 96%.	Huang et al. (2020)
Ni-Co-Mn ternary (NCM) material.	A comprehensive treatment method combining magnetic separation, alkaline leaching, and ammonia leaching.	Achieves complete removal of Cu impurities.	Wang et al. (2022)
WPCB	Utilizing an ammonia-ammonium sulfate alkaline solution to achieve maximum recovery of Cu and Ni.	Under optimal process conditions, the extraction efficiency of Cu reached 100%.	Jadhao et al. (2021)
CIGS chamber waste (Copper	The two-stage sulfuric acid roasting controls	Under the optimal process conditions,	Ma et al. (2020)

(continued on next page)

Table 3 (*continued*)

Subject of Treatment	Process method	Efficiency of Cu Recovery	References
Indium Gallium Selenide, CIGS, solar cell production process).	phase transformation and selective leaching to separate valuable components (as shown in Fig. 13).	the selective leaching rate of Cu reaches 95.90%.	
Different sources of waste lithium-ion battery cathode materials.	The leaching treatment is conducted using a mixed solution of sulfuric acid and hydrogen peroxide, followed by electrochemical treatment of the resulting solution.	The ICP results after electrochemical treatment indicate nearly complete recovery of Cu (close to 100%).	Rodrigues et al. (2023)
Electronic Waste from Printed Circuit Boards (EWPCB)	The leaching medium consists of a sodium citrate solution, from which base metals are recovered by direct electrodeposition, while the depleted solution is recycled back to the leaching stage. This leaching-electrodeposition cycle is repeated four times.	After four cycles, the leaching efficiency of Cu reached 71%.	Torres et al. (2017)
Electroplating sludge.	Four types of green ionic liquids were employed to leach copper from copper-rich electroplating sludge (C-ES) (Fig. 14).	IL1, IL3, and IL4 all achieved complete leaching of Cu from C-ES, with IL2 exhibiting a high Cu leaching efficiency of 92.11%.	Li et al. (2023b)
WPCB	Under the optimal conditions of 0.5 M glycine, 1% v/v H_2O, 20 g/l slurry density, and ambient temperature, wet leaching of copper metal is performed.	The recovery rate of Cu extraction reaches 99.96%.	Rezaee et al. (2023)

objectives. This practice of "urban mining" not only generates economic value but also alleviates pressure on landfills (Awual and Ismael, 2014; Zhu et al., 2012). The copper content in one ton of PCBs is 10–20 times higher than that in one ton of natural ores, indicating exceptionally high value for recycling purposes (Hossain et al., 2019). Sun et al. (2016). Evaluated various urban waste streams and developed a model to investigate the significance and metal recovery potential of these waste flows. They conducted a case study on eleven local waste streams using resource indices and technological indices. The results indicate significant potential for metal recovery in information and communication technology (ICT) waste as well as end-of-life (EOL) products, particularly in rare earth elements (REEs).

For instance, the recent concept of "urban mining" refers to the recovery of value from various anthropogenic sources through the coordination of materials, information, and services (Xavier et al., 2023). Steuer et al. (2017) proposed an intriguing hierarchical approach to waste management, wherein informal waste management is conducted by waste collectors, waste traders, and intermediaries, with overlapping values of collection and per capita compensation. However, in most cases, the dismantling of electronic waste is performed by untrained and unprotected workers (Scruggs et al., 2016), leading to pollution caused by contaminants such as tin, antimony, chromium, lead, cadmium, and arsenic.

4.2. Environmental impact assessment of copper recycling

4.2.1. Environmental benefits

The extraction process of copper is a resource-intensive activity with significant environmental impacts. Mining of primary copper ores involves substantial land disruption, water resource consumption, and tailings management issues, which not only degrade natural landscapes but also pose environmental concerns such as soil and water pollution (Valderrama et al., 2020; Liu et al., 2021). The recycling of scrap copper products can significantly reduce the generation of pollutants, thus embodying the principles of resource efficiency and environmental sustainability. Through recycling and reuse, copper can circulate continuously within the economy, enhancing resource utilization efficiency and alleviating environmental pressure. Moreover, employing specialized processing techniques enables scrap copper to be re-refined into high-quality copper materials, with emissions of pollutants during this process significantly lower than those from primary mining operations. Yu et al. (2019). Employed a combination of crushing, hydrothermal, and acid leaching processes to treat waste liquid crystal displays (LCDs), aiming to achieve their harmless disposal and resource utilization. They conducted an environmental impact assessment of this technology, indicating that adverse environmental effects during the treatment process are primarily attributed to electricity consumption, followed by the use of hydrogen peroxide and kerosene. Wang et al. (2021). Utilized a Waste Input-Output Impact Assessment (WIO-IA) model to integrate material flows within the scope of the U.S. economy, various recycling indicators, and the impacts of materials production from different sources. The research findings comprehensively depict the quantity and quality flows of copper throughout its entire lifecycle. This assessment method allows for the evaluation of recycling effectiveness based on environmental impact indicators. If all recyclable copper scrap can be fully utilized, energy consumption in the copper production process could be reduced by 15%. An LCA study conducted by Villares et al. (2016) revealed that compared to pyrometallurgical copper recovery, bioleaching for copper recovery significantly resulted in greater environmental impacts across all categories. Similarly, Işildar's LCA and techno-economic analysis, which compared three processes for copper and gold recovery, demonstrated that none of the processes emerged as having the lowest environmental impact across all studied categories (Işildar, 2018). Eric Schwartz et al. (2024) conducted a lifecycle assessment focused on the recovery of copper and gold from waste printed circuit boards (PCBs), evaluating various leaching processes while also considering variations in electricity sources and their differential environmental impacts. The study found that in all cases, the environmental impacts of metal recovery from waste PCBs were lower than those associated with primary metal production.

4.2.2. Reducing the environmental burden of electronic waste

The rapid increase in electronic waste presents challenges due to its valuable components and hazardous environmental substances. Without effective environmental safeguards during the recycling process, there is a risk of exacerbating the release of various pollutants and also the loss of valuable metals such as gold and copper. Electronic waste recycling constitutes a significant component of the economy, with the estimated raw material cost of the 53.6 million metric tons of e-waste generated in 2019 reaching as high as $57 billion USD. Therefore, strengthening mechanisms for the collection and recycling of electronic waste is crucial for developing economies reliant on imported critical minerals such as copper, cobalt, and nickel. This not only helps limit over-exploitation and reduce import dependency but also effectively addresses price hikes, monopolies, and strategic behavior by exporters, thus safeguarding economic stability. One of the greatest advantages of electronic waste recycling is the reduction in demand for metals extracted from primary mining. It is estimated that iron and copper reserves in geological storage are nearing depletion. Therefore, the urgent priority is to shift towards large-scale resource recycling to

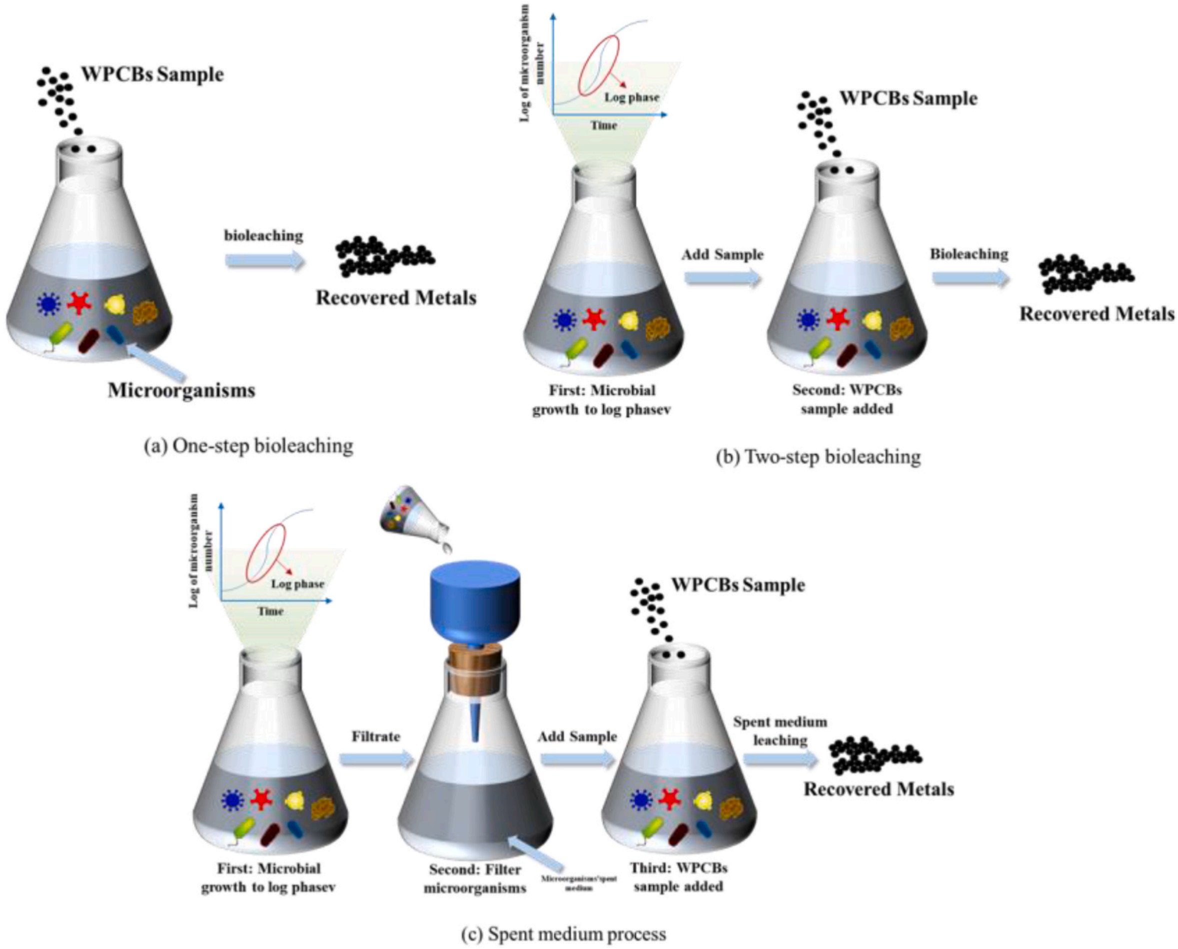

Fig. 15. Different methods of bioleaching WPCBs(Dong et al., 2023)

Table 4
The advantages and disadvantages of the three recycling technologies(Dong et al., 2023).

Methods	Advance	Disadvantage
Pyrometallurgical process	High efficiency, can handle many forms of WPCBs	High energy consumption; The incineration process produces harmful gases such as dioxins that cause air pollution
Hydrometallurgical process	Low infrastructure requirements; Good control process	Produce large amounts of highly toxic wastewater containing cyanide or halide; Low stability of non-cyanide or non-halogenated leaching solvents, high cost; High consumption of extraction reagents
Bioleaching process	Simple operation; Reduce energy demand and operating costs, Reduce the need for skilled labour; detoxify efficiently; Reduce secondary pollution; and be environmentally friendly	Time consuming; Expertise intensive; Slow process

safeguard the remaining natural resources (Ahirwar et al., 2021; Zeng et al., 2018; Krook and Baas, 2013). Liu et al. (2023a). conducted a multidimensional classification of electronic waste and integrated it into a comprehensive framework. They summarized the management, regulations, treatment methods, and cross-border movement of electronic waste from various perspectives, revealing the current status and challenges of electronic waste recycling. In support of sustainable global electronic waste recycling, they advocate for enhanced regional cooperation, improved legislation, promotion of technological advancements, and adoption of environmentally friendly designs.

5. Review methodology

A significant portion of this research review draws upon data from the Web of Science and ScienceDirect databases, with complementary contributions from PubMed and Wiley databases, as well as reports issued by research institutions. The key search terms utilized include: e-waste, electronic scrap, metal recovery, copper, hydrometallurgy/hydro-leaching, pyrometallurgy, bioleaching, environmental impacts, and recovery methods. The review primarily considers data within the last five years, with a preponderance of sources from the past three years, though older literature references are also incorporated where relevant and informative (see Fig. 16).

In comparison with other comprehensive reviews on e-waste recycling themes (Xavier et al., 2023; Zou et al., 2024; Suresh et al., 2018; Chen et al., 2022b; Agrawal et al., 2023), this review paper exhibits a stronger focus, undertaking an extensive study specifically targeted at the recovery of metallic copper from e-waste. It not only delves into the recovery techniques and methodologies in meticulous detail but also provides a comprehensive elaboration on the economic, environmental, and societal impacts of copper recovery from electronic waste, such as policy guidance and environmental benefit assessments. Furthermore, it offers a more detailed exposition on future prospects.

Table 5
Biometallurgical recovery of copper.

Subject of Treatment	Process method	Efficiency of Cu Recovery	References
PCB	The new strategy optimized the reaction rate and overcame the leachate transfer obstacles.	The copper recovery rate increased from 50% to 80% within 6 h, significantly reducing the time required to achieve the same recovery rate.	Benzal et al. (2020)
referring to television circuit boards with low iron content.	The bioleaching process was investigated using a mixed culture of acidophilic bacteria, including A. ferrooxidans, L. ferrooxidans, and A. thiooxidans.	By adding Fe(II) ions, the copper recovery rate was successfully increased to 54%.	Bas et al. (2013)
The copper on the chelating resin.	Three chelating resins were employed to adsorb and desorb copper from acidic aqueous solutions produced during the bioleaching process of electronic waste. The desorption efficiency of copper from the chelating resins was compared using different concentrations of HCl, H_2SO_4, and NH_4OH.	The most favorable performance was observed with NH4OH, resulting in a highest copper recovery rate of over 65%.	Suwannahong et al. (2022)
WPCB	The strain USCT-RO10 was employed for bioleaching copper from WPCB, followed by electrochemical recovery of copper from the desorbed eluate.	The bioleaching process successfully extracted 85% of Cu, and 92.7% of Cu was electrochemically recovered from the desorbed eluate, with a purity reaching 95.4%.	Sinha et al. (2018)
WPCB	Utilizing NCNTs-modified electrodes and A. ferrooxidans enables the leaching of copper from WPCB.	The bioleaching efficiency of Cu reached 99%, representing a 20% improvement over the addition of A. ferrooxidans alone.	Gu et al. (2017)
spent telecommunications printed circuit boards (STPCBs)	A cyanogenic bacterium was isolated, and the optimal strain was capable of producing 12.3 ppm cyanide in NB medium with an initial pH of 7 and concentrations of glycine and cysteine at 7.5 g/l each. The bioleaching process was conducted in a one-step manner.	98.2% of Cu was recovered.	Beiki et al. (2023)
PCB	The PCB was crushed and separated into magnetic (M), non-magnetic (NM), and paramagnetic (MIX) samples. After 18 days of bioleaching, Fe was added in the presence of A. ferroxidans.	The Cu content in the three components was 217.8, 560.3, and 401.3 mg/g, respectively. After 18 days of bioleaching in samples with the addition of NM + Fe and MIX + Fe, the presence of A. ferroxidans increased the copper extraction rates by 2.6% and 7.2%, respectively.	Andrade et al. (2023)
PCB	The adapted Acidithiobacillus ferrooxidans was successfully employed for bioleaching of mixed electronic waste in a bubble column bioreactor.	On the fourth day of leaching, the extraction efficiency of Cu reached 100%.	Arshadi et al. (2021)
PCBs	Copper was recovered by using A. ferrooxidans, A. thiooxidans, and PCBs-adapted mixed culture of A. ferrooxidans and A. thiooxidans.	The experiments were conducted three times under optimal conditions, resulting in a Cu recovery rate of 94%.	Arslan (2021)
PCB	A two-step bioleaching process was employed. In the first step, chemolithotrophic acidophilic Acidithiobacillus ferrivorans and Acidithiobacillus thiooxidans were utilized, while in the second step, cyanide-producing heterotrophic Pseudomonas fuorescens and Pseudomonas putida were employed.	The recovery rate of Cu was 98.4%.	Işıldar et al. (2016)

6. Future prospects and research directions in copper recovery from electronic waste

6.1. Approaches to improve recycling rates and resource utilization

Technological Innovation and Upgrading: With the advancement of technology, new recycling techniques such as bioleaching, hydrometallurgy, and pyrometallurgy continue to emerge. These new technologies enable more effective extraction of copper from electronic waste, thereby increasing recycling rates. Additionally, through technological upgrades, energy consumption and environmental pollution in the recycling process can be reduced.

Enhancing Public Awareness and Engagement: By promoting education and raising public awareness of electronic waste recycling and resource circulation, individuals can be encouraged to actively participate in recycling activities. Furthermore, governments and businesses can establish incentive mechanisms for recycling, further stimulating public enthusiasm for recycling.

Establishing Comprehensive Recycling Systems: By establishing a nationwide electronic waste recycling network, it ensures that waste can be conveniently and quickly delivered to recycling centers. Moreover, collaboration with relevant enterprises to establish an Extended Producer Responsibility (EPR) system, where producers bear partial responsibility for recycling, facilitates a virtuous cycle of "recycling-reuse".

6.2. Methods to reduce costs and enhance economic benefits

Optimization of Recycling Processes: By improving recycling processes and reducing unnecessary intermediate steps, the cost of recycling can be lowered. Additionally, the introduction of advanced automation equipment and intelligent management systems can enhance recycling efficiency.

Development of High Value-added Products: Apart from directly selling recycled copper, further processing can lead to the production of high value-added products such as copper alloys (Zhou et al., 2024), copper-based composite materials (Yang et al., 2024), and so forth. This not only enhances economic benefits but also expands the application scope, increasing market demand. Furthermore, the co-extraction of other valuable metals from e-waste will also reduce costs and mitigate the environmental hazards posed by certain heavy metals. Lee, H et al. (Lee and Mishra, 2020) employed NaOH, H_2SO_4, CH_4N_2S, and HNO_3 as four-step leaching agents to selectively recover Al, Cu, Au, and Pb. This approach not only achieved a high recovery rate of 98% for Cu but also yielded 75.2% of the precious metal Au, while simultaneously mitigating the hazards posed by 77.5% of the heavy metal Pb. Ye, M et al. (Ye et al., 2022) introduced an asymmetric electrochemical system for the simultaneous and selective extraction of gold and copper from e-waste leachate. By leveraging the established CC/PANI//CC system, the CC/PANI anode electrode demonstrated high efficiency, selectivity, and rapid extraction of gold, accompanied by excellent reusability. Wang et al.(Wang and Yin, 2021) found that in an acidic and strongly oxidizing environment, the recovery rates of copper and other metals could reach 94.5% and 75.2%, respectively, indicating excellent recovery performance. Given the structural complexity of e-waste, it is crucial to not only focus on the recovery of copper but also on the recovery of accompanying precious metals and the degradation of harmful

Table 6
Waste electrical and electronic products disposal fund subsidy standard(Notice on Adjusting the Subsidy, 2021).

Product Name	Variety	Subsidy standard (RMB/SET)	Remarks
TV	Cathode Ray Tube (CRT) televisions, black-and-white or color, with screen sizes ranging from 14 inches to below 25 inches.	40	Cathode Ray Tube (CRT) televisions, black-and-white or color, with screen sizes below 14 inches, are not eligible for subsidies.
	Cathode Ray Tube (CRT) televisions, both black-and-white and color, with screen sizes 25 inches and above, as well as plasma televisions, liquid crystal display (LCD) televisions, organic light-emitting diode (OLED) televisions, and rear-projection televisions.	45	
microcomputer	Desktop personal computers (including the main unit and monitor), all-in-one desktop personal computers combining the main unit and monitor, and portable personal computers.	45	Subsidy standards for tablet computers and handheld computers will be determined separately.
washing machine	Single-tub washing machines and spin dryers (with a dry laundry capacity ranging from over 3 kg–10 kg).	25	Washing machines with a dry laundry capacity of ≤3 kg are not eligible for subsidies.
	Twin-tub washing machines, impeller-type fully automatic washing machines, and drum-type fully automatic washing machines (with a dry laundry capacity ranging from over 3 kg–10 kg).	30	
refrigerator	Refrigerators (cabinet), freezers (cabinet), and refrigerated cabinets (cabinet) with a capacity ranging from 50 L to 500 L.	55	Refrigerators under 50 L are ineligible for subsidies.
Air conditioner	Central air conditioners, split air conditioners, and multi-split air conditioners (including outdoor units and indoor units) with a cooling capacity of up to 14000 W.	100	

heavy metals during the recovery process. This holds significant meaning for promoting sustainable development and environmental protection.

Promotion of Synergistic Development in the Industry Chain: Strengthening cooperation between recycling enterprises and relevant upstream and downstream companies in the industry chain fosters close collaborative relationships. Through synergistic development, resource sharing and complementary advantages can be achieved, thereby reducing overall costs.

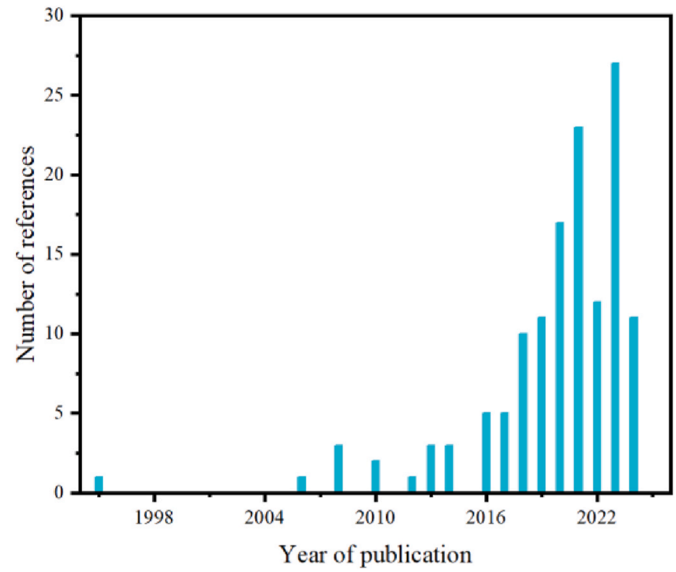

Fig. 16. Trends in the year and quantity of indexed articles and papers.

6.3. *Recommendations for improvement of policies, regulations, and standards*

Establishment of Stringent Recycling Standards: Governments should enact detailed electronic waste recycling standards, clarifying key indicators such as recycling rates and resource utilization rates, to ensure the effectiveness and sustainability of recycling activities.

Implementation of Incentive Policies: To encourage active participation in electronic waste recycling by enterprises and individuals, governments can introduce incentive policies such as tax breaks and subsidies to reduce recycling costs and enhance economic benefits.

Strengthening Supervision and Enforcement: Establishing a sound regulatory mechanism and enhancing supervision and enforcement of electronic waste recycling activities are essential. Strict penalties should be imposed on enterprises and individuals who violate regulations to ensure fair competition and healthy development of the recycling market.

6.4. *The importance of strengthening international cooperation and exchange*

Sharing of Technology and Experience: Through international cooperation and exchange, countries can share advanced recycling technologies and successful experiences, promoting progress and development in the global electronic waste recycling industry.

Market and Resource Expansion: International cooperation can provide recycling enterprises with broader markets and more resources, facilitating rapid development and growth of enterprises.

Addressing Global Challenges: Electronic waste recycling is a global challenge that requires collective efforts from all countries. Through international cooperation and exchange, concerted efforts can be made to address this challenge and protect the Earth's environment.

6.5. *Recovery of copper metal from electronic waste for the synthesis of catalysts*

Copper, as a significant catalytic material, possesses excellent electrical conductivity, thermal conductivity, and chemical stability. It plays a crucial role in various industrial and domestic sectors, such as in the treatment of VOCs and carbon dioxide, with promising applications. Exhibiting high catalytic activity, copper effectively catalyzes the conversion of carbon dioxide and the oxidation degradation reactions of

VOCs. The surface electronic structure and lattice defects of copper significantly influence its catalytic activity, which can be efficiently controlled by modulating the composition and structure of the catalyst. Furthermore, its chemical stability and corrosion resistance enable copper catalysts to exhibit high stability and durability in catalytic reactions, thereby facilitating long-term stable operation and reducing catalyst deactivation and regeneration costs, consequently lowering the overall cost of CO_2 and VOCs treatment. Recycling copper from electronic waste not only reduces the cost of catalyst preparation but also effectively reduces dependence on traditional mineral resources, thereby promoting resource sustainability and environmental protection.

7. Conclusion and discussion

In the face of the projected growth of 74.7 million tons in e-waste by 2030, coupled with a relatively low recycling rate, the global demand for refined copper has doubled over the past 50 years. Notably, e-waste, as a crucial component of "urban mining," encompasses at least a dozen valuable metals, including Au, Ag, and Cu, among others. Given Cu's strategic importance as an abundant yet inexpensive metal, this paper primarily focuses on the metal Cu and presents a series of deliberations. Mechanical-physical methods typically enrich a portion of copper, approximately 80%, albeit with low overall efficiency and operational complexity. Pyrometallurgical processes, on the other hand, exhibit high throughput but suffer from low copper recovery efficiency and purity, leading to high energy consumption and equipment maintenance costs. In contrast, hydrometallurgical methods, involving metal leaching through acidic or alkaline systems, offer high efficiency, generally exceeding 95%, yet they pose significant environmental challenges due to the discharge of large volumes of acidic or alkaline wastewater. Subsequently, bioleaching and other emerging technologies have made progress, albeit they are still in their infancy.

Furthermore, this paper delves into the economic value and socio-environmental benefits of metal copper recovery from e-waste, offering a detailed analysis. Looking ahead, the future of e-waste recycling necessitates policy incentives from governments, mobilizing enthusiasm for recycling efforts, promoting energy conservation and emission reduction, and exploring avenues for high-value reuse of recycled materials. This holistic approach aims to address the challenges posed by the burgeoning e-waste crisis and harness its potential as a valuable resource.

CRediT authorship contribution statement

Fan Yang: Writing – original draft. **Yufeng Wu:** Writing – review & editing. **Qijun Zhang:** Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of the manuscript entitled "***Towards Resource Regeneration: A Focus on Copper Recovery from Electronic Waste***".

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Data availability

Data will be made available on request.

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