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A scientometrics study of advancing sustainable metal recovery from e-waste: processes, challenges, and future directions

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The growing generation of electronic waste (e-waste) presents significant environmental and economic challenges while offering opportunities for resource recovery through the extraction of valuable metals. This study employs bibliometric analysis to examine global research trends in metal recovery from e-waste, identifying China, the United States, and India as the most productive countries, with *Journal of Hazardous Materials* and *Waste Management* being the leading publication venues. The analysis also reveals a strong collaboration network among key research institutions, contributing to advancements in recovery techniques. The study further explores various extraction methods, including pyrometallurgical, hydrometallurgical, and biometallurgical processes, assessing their efficiency and sustainability. Hydrometallurgical methods, particularly acid leaching and solvent extraction, show up to 95% metal recovery efficiency, while biometallurgical approaches demonstrate a potential 30–50% reduction in environmental impact compared to conventional chemical methods. The findings highlight the growing emphasis on sustainable recovery strategies, policy interventions, and circular economy principles. The study concludes that continuous technological innovation, strengthened regulatory frameworks, and increased public engagement are essential to advancing metal recovery technologies. By integrating efficient extraction methods with sustainable waste management policies, the global e-waste crisis can be mitigated while ensuring long-term resource conservation.

Sustainability spotlight

Metal recovery from e-waste stands at the intersection of technological innovation and environmental responsibility, offering a critical solution to the global sustainability challenge. By transforming discarded electronics into valuable resources, this field contributes to reducing the environmental footprint of mining, curbing hazardous waste, and fostering a circular economy. Advances in recovery technologies, supported by interdisciplinary research and strategic funding, pave the way for sustainable resource management. As the demand for critical and precious metals rises, the focus on environmentally friendly and energy-efficient recovery methods underscores the commitment to balancing industrial progress with ecological preservation.

1. Introduction

In an era marked by rapid technological advancements and the pervasive integration of electronic devices into everyday life, the generation of electronic waste (e-waste) has emerged as one of the most pressing environmental and economic challenges of our time. The Indian consumer electronics market is expected to see a significant rise in market size across various product categories from 2020 to 2030. The global consumer electronics market is forecasted to grow at a Compound Annual Growth Rate (CAGR) of 9.0%, reaching an estimated USD 1.9 trillion by 2028, as reported by Grand View Research and Globe Newswire, 2023. However, this rapid expansion underscores the environmental repercussions, drawing attention to the substantial accumulation of electronic waste (e-waste). The images depict piles of discarded electronic devices, such as circuit boards, mobile phones, and solar panels, alongside scenes of e-waste management efforts. The panel concludes with the stark reality that most electronic products ultimately end up as waste, posing a significant challenge to sustainable development.[1]

Globally, metal recovery from e-waste varies significantly across regions due to differences in infrastructure, technological investments, and regulatory frameworks. Developed economies such as the European Union (EU), the United States, and Japan have well-established e-waste collection and recycling systems supported by stringent policies like the WEEE Directive, which mandates proper collection, recovery, and recycling

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of electronic waste. The EU's Circular Economy Action Plan has further strengthened metal recovery by promoting advanced hydrometallurgical and biometallurgical techniques.[2,3] The U.S. follows a decentralized approach, where individual states enforce e-waste management regulations, with leading initiatives focusing on refining pyrometallurgical processes for efficient metal extraction. In contrast, emerging economies such as China, India, and Brazil face challenges related to informal recycling, inefficient recovery methods, and limited policy enforcement. China, as one of the largest producers and recyclers of e-waste, has implemented Extended Producer Responsibility (EPR) policies that hold manufacturers accountable for e-waste disposal, fostering innovation in urban mining technologies. India's E-waste Management Rules, first introduced in 2011 and amended in 2022, emphasize formalizing the recycling sector and improving resource recovery efficiency. However, informal sector dominance and inadequate infrastructure remain significant barriers. Similarly, Brazil's National Solid Waste Policy (PNRS) encourages metal recovery but struggles with implementation due to gaps in collection networks and public awareness.

Regulatory policies play a crucial role in shaping metal recovery technologies. Strict compliance measures and incentives for sustainable practices in developed regions have driven advancements in high-yield recovery processes, such as solvent extraction and bioleaching. Meanwhile, emerging economies are increasingly adopting regulatory frameworks to transition from informal recycling practices to technologically advanced, eco-friendly recovery solutions. Strengthening enforcement, enhancing international collaboration, and investing in research-driven policy development will be key to harmonizing global efforts for sustainable metal recovery from e-waste.

The global generation of electronic waste (e-waste) has surged dramatically over the past two decades, driven by rapid technological advancements, increasing consumer demand, and shorter product lifecycles. According to recent reports, global e-waste reached approximately 53.6 million metric tons in 2019 and is projected to exceed 74 million metric tons by 2030, making it the fastest-growing waste stream worldwide. Economically, e-waste contains valuable metals such as gold, silver, palladium, and rare earth elements, offering a significant opportunity for resource recovery and circular economy initiatives. Studies estimate that the potential value of recoverable materials in global e-waste exceeds $57 billion annually, yet only a small fraction is efficiently recycled. The lack of proper recycling infrastructure in many regions leads to the loss of critical raw materials, increasing reliance on virgin resource extraction and contributing to geopolitical supply chain vulnerabilities.

From an environmental perspective, improper disposal of e-waste poses severe hazards. Informal recycling practices, particularly in developing countries, involve rudimentary methods such as open burning and acid leaching, which release toxic pollutants, including dioxins, heavy metals, and greenhouse gases. These pollutants contaminate soil, water, and air, posing serious health risks to both workers and surrounding communities. Additionally, e-waste contributes significantly to carbon emissions due to energy-intensive mining and refining of virgin metals. Sustainable metal recovery solutions, including hydrometallurgy, biometallurgy, and AI-driven recycling optimization, are therefore crucial to mitigating these environmental impacts. To address these challenges, international policies and regulatory frameworks, such as the Basel Convention and Extended Producer Responsibility (EPR) programs, have been implemented to enhance e-waste management. However, enforcement remains inconsistent across regions, necessitating further advancements in policy, technology, and global collaboration. By incorporating a circular economy approach, improving metal recovery efficiency, and investing in green technologies, e-waste management can transition from a growing environmental threat to a sustainable resource recovery opportunity.

E-waste, a term encompassing a wide array of discarded electronic devices such as computers, smartphones, televisions, and other consumer electronics, is growing at an alarming rate globally.[4–7] The United Nations estimated that in 2019, approximately 53.6 million metric tons of e-waste were generated worldwide, a figure expected to escalate to over 74 million metric tons by 2030 if current trends persist. The exponential increase in e-waste production poses significant environmental threats, as these discarded devices contain hazardous substances such as lead, mercury, and cadmium, which can leach into the soil and water, causing severe ecological damage.[8–11] However, e-waste is not merely a source of environmental contamination; it also represents a substantial untapped reservoir of valuable resources.[12,13] Electronic devices are rich in a variety of metals, including precious metals like gold, silver, and platinum, as well as critical and rare earth metals such as palladium, cobalt, and indium. These metals are essential components in the manufacturing of new electronic devices, renewable energy technologies, and other high-tech industries. The concept of metal recovery from e-waste, therefore, not only addresses the environmental issues associated with e-waste but also presents a significant opportunity to recover these valuable resources, thereby contributing to a more sustainable and circular economy. The proliferation of electronic devices, driven by continuous innovation, shorter product lifecycles, and consumer demand for the latest technologies, has led to an unprecedented accumulation of e-waste.[14,15] The challenge of managing this growing waste stream is multifaceted, encompassing environmental, economic, and social dimensions.[10] Environmentally, improper disposal and inadequate recycling of e-waste result in the release of toxic substances into the environment, contributing to pollution and posing health risks to humans and wildlife.[16–18] Economically, the loss of valuable metals through landfilling or suboptimal recycling processes represents a missed opportunity for resource recovery and economic gain. Socially, the informal recycling sector, prevalent in many developing countries, often operates under hazardous conditions, exposing workers to toxic substances and perpetuating cycles of poverty. Addressing these challenges requires a holistic approach that integrates effective e-waste management practices with advanced metal recovery technologies.[19–21] By doing so, it is possible to mitigate the environmental impacts of e-waste, recover valuable materials for reuse, and create economic opportunities through the development of sustainable recycling industries.[22,23]

The concept of metal recovery from e-waste is grounded in the principles of sustainability and resource efficiency. Metals extracted from e-waste can be reintroduced into the manufacturing supply chain, reducing the need for virgin materials and the environmental impacts associated with mining and metal extraction from primary sources.[24] This is particularly important for precious and critical metals, which are finite resources with significant supply chain vulnerabilities. For instance, the majority of the world's supply of rare earth elements, which are crucial for the production of high-tech electronics and renewable energy technologies, comes from a limited number of countries, making the global supply chain susceptible to geopolitical tensions and market fluctuations.[25,26] Moreover, metal recovery from e-waste contributes to the circular economy, an economic model that aims to minimize waste and make the most of resources by keeping products and materials in use for as long as possible. In a circular economy, the recovery and recycling of metals from e-waste can reduce the environmental footprint of electronic devices, decrease dependence on virgin materials, and foster innovation in recycling technologies and product design.[27–29] Metal recovery from e-waste involves a variety of physical, chemical, and biological processes designed to extract metals from discarded electronic devices. These processes can be broadly categorized into three main approaches: pyrometallurgical, hydrometallurgical, and biometallurgical. Pyrometallurgy involves the use of high temperatures to separate metals from other materials in e-waste. This process typically involves smelting, where e-waste is heated in a furnace to melt the metals, which are then separated from the slag (non-metallic waste materials). Pyrometallurgical processes are well-established and capable of recovering a wide range of metals, including copper, gold, silver, and palladium. However, they are energy-intensive and can generate harmful emissions, such as dioxins and furans, if not properly controlled. Hydrometallurgy involves the use of aqueous chemistry to dissolve and extract metals from e-waste.[30] This process typically includes leaching, where e-waste is treated with chemical solvents, such as acids or cyanide solutions, to dissolve the metals, followed by precipitation or electro-winning to recover the dissolved metals from the solution. Hydrometallurgical processes are particularly effective for recovering precious metals and are considered to be more environmentally friendly than pyrometallurgical processes, as they operate at lower temperatures and produce fewer emissions.[31,32] However, the use of hazardous chemicals in leaching processes poses potential environmental and safety risks. Biometallurgy, or bioleaching, is an emerging approach that employs microorganisms to facilitate the extraction of metals from e-waste. Certain bacteria and fungi are capable of producing organic acids or other compounds that can dissolve metals, making them accessible for recovery. Biometallurgy offers a more sustainable and environmentally friendly alternative to traditional metal recovery methods, as it operates at ambient temperatures and pressures and avoids the use of hazardous chemicals.[33–35] However, biometallurgical processes are still in the developmental stage and face challenges related to efficiency, scalability, and the specificity of microorganisms to different types of metals.

To provide a clearer comparison of metal recovery techniques, Table 1 summarizes the key differences between pyrometallurgical, hydrometallurgical, and biometallurgical processes in terms of extraction efficiency, cost, and environmental impact. Each method offers distinct advantages and limitations, influencing its feasibility for large-scale e-waste processing. Pyrometallurgy is a well-established technique with high metal recovery efficiency, particularly for base and precious metals. However, it is energy-intensive and generates harmful emissions, making it less environmentally sustainable. Hydrometallurgy, on the other hand, offers high recovery rates with lower energy consumption, but it relies on hazardous chemicals, requiring careful waste management. Biometallurgy is an emerging approach that minimizes environmental impact by using microorganisms for metal extraction, yet its scalability and efficiency remain challenges. To comprehensively assess the sustainability of these methods, life cycle assessment (LCA) can be utilized. LCA evaluates the environmental impact of metal recovery techniques across their entire life cycle, including raw material extraction, energy use, emissions, and waste management. Integrating LCA into e-waste recycling strategies can help identify the most sustainable recovery pathways while balancing economic and environmental considerations.[36,37]

While significant progress has been made in the development of metal recovery technologies, several challenges remain. One of the primary challenges is the heterogeneous and complex composition of e-waste, which varies widely depending on the type of electronic device and its components.[38–41] This complexity makes it difficult to design a one-size-fits-all approach to metal recovery, necessitating the development of tailored processes for different types of e-waste. Another challenge is the economic viability of metal recovery processes. The costs associated with collecting, transporting, and processing e-waste can be substantial, particularly in regions where e-waste generation is relatively low or where infrastructure for e-waste management is underdeveloped.[42–44] Additionally, the fluctuating prices of metals in the global market can affect the profitability of metal recovery operations, making it difficult for recycling companies to achieve consistent economic returns. Despite these challenges, the field of metal recovery from e-waste presents numerous opportunities for innovation and growth. Advances in technology, such as the development of more efficient and selective leaching agents, the use of artificial intelligence and machine learning for optimizing recovery processes, and the integration of renewable energy sources into recycling operations, hold the potential to enhance the efficiency and sustainability of metal recovery.[45,46] Moreover, the increasing demand for critical and precious metals in emerging technologies, such as electric vehicles, renewable energy systems, and advanced electronics, is likely to drive further investment and research in this area. The success of metal recovery from e-waste is also closely tied to the regulatory environment and the implementation of effective policies.

Table 1 Comparison of metal recovery techniques

Recovery method	Extraction efficiency	Cost	Environmental impact	Challenges
Pyrometallurgy	High (85–98%) for base & precious metals	High (due to energy-intensive processes)	High emissions (CO_2, dioxins, furans), slag generation	High energy consumption, emission control required
Hydrometallurgy	High (80–95%) for precious metals	Moderate (depends on chemical usage)	Lower emissions than pyrometallurgy but hazardous chemical waste	Chemical handling, wastewater treatment needed
Biometallurgy	Moderate (50–85%) for specific metals	Low (microbial cultures are cost-effective)	Environmentally friendly (no hazardous chemicals)	Slow reaction rates, limited scalability, metal specificity

Governments and international organizations play a crucial role in promoting e-waste recycling and metal recovery through the establishment of regulations, standards, and incentives. For example, the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive sets targets for the collection, recycling, and recovery of e-waste, providing a framework for the development of a circular economy in the electronics sector.[47–49] In addition to regulatory measures, there is a need for greater public awareness and engagement in e-waste management. Educating consumers about the importance of proper e-waste disposal and the benefits of recycling can help increase the collection rates of e-waste and support the growth of the metal recovery industry.

This study distinguishes itself from previous bibliometric analyses on metal recovery from e-waste by providing a more detailed examination of research themes, funding agency contributions, and interdisciplinary collaborations. Unlike prior studies that primarily focus on publication trends or citation networks, our analysis delves into the classification of metal recovery technologies, including pyrometallurgy, hydrometallurgy, and bio-metallurgy, while also assessing their environmental implications. Additionally, this work uniquely incorporates funding agency analysis, identifying major contributors and evaluating their impact on technological advancements. Through advanced bibliometric mapping, we highlight emerging research trends, underexplored subfields, and potential future breakthroughs. A comparative global perspective is also presented, contrasting research efforts across different regions and examining the influence of regulatory policies on technological progress. Furthermore, this study explores interdisciplinary collaborations, revealing the intersections of materials science, environmental engineering, and policy research in metal recovery—an aspect that has been largely overlooked in prior analyses. Unlike previous reviews, which primarily focus on technological advancements in metal recovery, our study adopts a bibliometric approach to analyze research trends, funding influences, and interdisciplinary collaborations.

For instance, the review by Dutta *et al.* (2022)[41] provides a comprehensive evaluation of metal recovery processes, including pyrometallurgy, hydrometallurgy, and biometallurgy, while also incorporating a bibliometric study on e-waste management from a green technology perspective. However, it does not systematically analyze global research trends, funding agency contributions, or interdisciplinary collaborations, which are central themes in our study. Similarly, the work by Oke and Potgieter (2024)[38] focuses on recent chemical methods for metal recovery from printed circuit boards, particularly emphasizing leaching techniques such as ionic liquids and deep eutectic solvents. While this review provides in-depth insights into chemical recovery methods, it lacks a bibliometric analysis of research trends and funding influences, which are critical for understanding the evolution of research in this field.

Additionally, the review by Jadoun *et al.* (2024)[40] discusses global e-waste production, metal recovery challenges, and case studies on sustainable recycling solutions. While it presents valuable data on e-waste generation and management, it does not provide a structured analysis of bibliometric trends, funding patterns, or regional research disparities—areas comprehensively addressed in our study. Another recent review by Oke and Potgieter (2024)[39] explores disassembly and sorting techniques for printed circuit boards, particularly focusing on mechanical and chemical disassembly processes. However, this review does not examine the role of funding agencies, interdisciplinary collaborations, or emerging research themes, which are key elements of our analysis. By addressing these research gaps, our study provides novel insights into metal recovery research trends. We systematically map interdisciplinary collaborations, highlight the role of funding agencies in shaping technological advancements, and offer a comparative analysis of global research efforts.

The recovery of metals from e-waste represents a critical opportunity to address the growing environmental and resource challenges posed by electronic waste. By developing and implementing advanced metal recovery technologies, we can reduce the environmental impact of e-waste, conserve valuable resources, and contribute to the creation of a more sustainable and circular economy. However, achieving these goals will require continued innovation, investment, and collaboration across multiple sectors, including industry, academia, government, and civil society. As the global demand for electronic devices continues to rise, the importance of metal recovery from e-waste will only become more pronounced, making it an essential component of sustainable development in the 21st century.

Despite the growing emphasis on metal recovery from e-waste, significant challenges remain, particularly in the extraction of rare earth elements (REEs) like lithium and cobalt, which are essential for advanced energy storage and electronic applications. Conventional recycling processes, such as pyrometallurgy and hydrometallurgy, often exhibit low recovery efficiencies for REEs due to their complex chemical associations and dispersion in multi-component electronic waste. Additionally, the lack of standardized collection and sorting mechanisms limits the economic feasibility of recovering these critical metals. The absence of efficient and scalable recovery methods contributes to continued reliance on primary mining, exacerbating environmental degradation and resource depletion. Addressing these challenges requires innovative extraction techniques, including green hydrometallurgy, bioleaching, and solvent-free separation methods, which could enhance the recovery efficiency of REEs while minimizing ecological impact. This study aims to bridge these gaps by assessing existing recovery methods, identifying limitations, and proposing pathways for sustainable advancements in e-waste metal recovery.

This study advances the understanding of metal recovery research trends by employing bibliometric analysis to systematically evaluate global research output, key contributors, and emerging themes in the field. By identifying the most productive countries, influential journals, and leading research institutions, the study provides a comprehensive overview of how knowledge in metal recovery from e-waste has evolved over time. Additionally, it highlights collaboration networks and funding agencies that play a crucial role in driving research innovation. Furthermore, this study goes beyond traditional literature reviews by integrating quantitative insights into the efficiency of different recovery methods, such as hydrometallurgical, pyrometallurgical, and biometallurgical processes. It underscores the shift towards more sustainable and eco-friendly extraction technologies, illustrating how policy interventions and circular economy initiatives influence research priorities. By mapping research trends and technological advancements, this study provides valuable direction for future investigations, helping researchers and policymakers focus on critical gaps and interdisciplinary opportunities in e-waste metal recovery. Ultimately, the findings serve as a foundation for developing innovative, high-efficiency recovery techniques that contribute to both economic sustainability and environmental conservation.

2. Methodology

The data collection process for the study on metal recovery in e-waste was conducted on August 29, 2024, using the SCI-Expanded section of the Web of Science (WoS) Core Collection. This globally recognized index database, curated by Clarivate Analytics, is renowned for its high-quality bibliographic information spanning a wide array of scientific disciplines.[50] The purpose of this data collection was to gather a comprehensive dataset of relevant publications in the field of metal recovery from e-waste, which would serve as the foundation for a detailed bibliometric analysis.

The bibliometric analysis was conducted using the Web of Science (WoS) Core Collection, a widely recognized database for high-quality academic literature. The following steps were taken to ensure a comprehensive yet focused dataset:

(a) Search query and keywords: the search was performed using a combination of keywords relevant to metal recovery from e-waste, including: ("electronic waste" OR "e-waste" OR "waste electrical and electronic equipment" OR "WEEE") AND ("metal recovery" OR "urban mining" OR "hydrometallurgy" OR "pyrometallurgy" OR "biometallurgy" OR "bioleaching"). Boolean operators were used to refine the search and capture studies across various disciplines.

(b) Database and timeframe: the search was restricted to the Web of Science Core Collection, covering Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Emerging Sources Citation Index (ESCI). The analysis considered publications from 2000 to 2024, ensuring the inclusion of both foundational and recent advancements in the field.

(c) Filters applied: document type: only articles and reviews were considered to maintain scientific rigor. Conference proceedings, book chapters, and editorials were excluded. Language: only english-language publications were included to ensure accessibility and consistency. The search was refined to include studies from relevant disciplines such as materials science, environmental science, engineering, and chemistry while excluding unrelated fields.

(d) Exclusion criteria: studies that focused solely on general e-waste management without discussing metal recovery were excluded. Articles related to policy discussions without technical insights into recovery methods were filtered out. Duplicates and non-peer-reviewed sources were removed to maintain data quality.

2.1. Search strategy

To ensure that all pertinent research publications were captured, a robust search formula was employed. The key terms used in the search were meticulously selected to cover the various expressions and terminologies associated with metal recovery and e-waste. The search formula included terms such as "metal recovery", "metal extraction", "metals recovery", "metal extraction technologies", "metal recovery technologies", "metals recovery technologies", "metals extraction technologies", as well as terms related to electronic waste like "electrical waste", "electrical wastes", "electronic waste", "electronic wastes", "e-waste", "waste electrical", "wastes electrical", "waste electronic", "wastes electronic", "electronic rubbish", "electronic garbage", "electrical rubbish", "electrical garbage", "waste electrical", and "electronic equipment". These terms were chosen to encompass the commonly used expressions in the literature related to metal recovery from e-waste. The search formula was designed to ensure that any publication mentioning these keywords in the title, abstract, or keywords would be included in the dataset. This approach was critical in capturing a broad and inclusive range of studies, allowing for a more accurate and representative analysis of the research trends in this field. Photovoltaic (PV) waste is also considered a type of e-waste; however, in the present manuscript, we have not included it as the term "PV waste" is not addressed within the scope of this work. PV waste was excluded because its composition, recycling processes, and regulatory frameworks differ significantly from conventional electronic waste (e-waste). Unlike general e-waste, which primarily consists of printed circuit boards (PCBs), batteries, and consumer electronics, PV waste contains materials such as silicon, cadmium telluride, and perovskite-based compounds, necessitating specialized recovery techniques that fall outside the scope of our bibliometric analysis. Our study specifically focuses on the research landscape surrounding metal recovery from traditional e-waste streams, ensuring a more targeted and relevant discussion.

2.2. Timeframe and document types

The data collection focused on publications from 2010 to 2024, with the intention of capturing the most relevant and recent research developments in metal recovery from e-waste. Although the default starting year for the WoS database is 1900, the collection was specifically targeted at the period from 2010 onward.[51] This decision was made because the specific timeframe for relevant publications was not initially clear, and it was crucial to ensure that as much pertinent data as possible was collected. The types of documents considered were limited to "articles" and "reviews". This criterion was set to ensure that the dataset included only peer-reviewed research, which is considered "certified knowledge" with universal credibility. By focusing on these types of documents, the study aimed to include both original research contributions and critical evaluations of the field, providing a comprehensive overview of the current state of research in metal recovery from e-waste.

2.3. Data collection outcomes

The result of this data collection process yielded a total of 14 777 publications. It is important to note that these results are time-sensitive and can change slightly if the same search formula is executed on a different day. This variability is due to the continuous updates and expansions of the WoS database, which regularly adds new publications and adjusts records. As such, the dynamic nature of scientific research is reflected in the dataset, and any analysis based on this data should be understood as a snapshot of the research landscape at the time of collection.

2.4. Analysis tools and techniques

Following the data collection, bibliometric analysis was applied to the dataset. Bibliometric analysis is a quantitative approach to examining bibliographic elements and presents the results visually, offering a comprehensive understanding of research trends. This method allows researchers to delve into various aspects of the research on metal recovery from e-waste, including the most influential source journals, leading countries and institutions, prominent authors, and major research topics. One of the key aspects of bibliometric analysis is the study of co-citation references, which provides insights into how publications are interconnected through citations.[52–54] This approach helps uncover collaboration networks within the research domain, illustrating the relationships between countries, institutions, and authors, and showing how these connections evolve over time. While bibliometric mapping provides valuable insights into publication trends, research collaboration networks, and funding patterns, it does not capture the qualitative aspects of technological advancements, policy effectiveness, or real-world industrial applications. Furthermore, citation-based metrics may be influenced by self-citations, language biases, and database coverage limitations, potentially leading to an incomplete representation of the field.

2.5. Visualization with VOSviewer

For this analysis, VOSviewer, a specialized software tool for constructing and viewing bibliometric maps, was employed. VOSviewer enables researchers to visualize relationships among countries, institutions, authors, and research topics in the field of metal recovery from e-waste. This freely available program uses similarity visualization technology, relying on a similarity matrix based on the co-occurrence of key elements within the same document. By applying VOS mapping techniques to this similarity matrix, a two-dimensional map is constructed, effectively representing the data.[54,55] The resulting map can be translated, rotated, and reflected to better understand the relationships between various research elements. The distance between any two terms in the visualization represents the degree of similarity or relevance between them. This technique allows for an intuitive exploration of the research landscape, showing how different aspects of the field are connected and how they evolve over time. The data collection and analysis methods employed in this study were designed to capture a comprehensive and up-to-date picture of the research landscape in metal recovery from e-waste. The use of bibliometric analysis and VOSviewer facilitated a detailed and interactive examination of collaboration networks and research trends, offering valuable insights into the development of this critical field.

2.6. Limitations and uncertainties

Despite providing valuable insights into scientometric trends and environmental impact assessments, certain limitations and uncertainties must be acknowledged. One key challenge in scientometric analysis is the availability and coverage of bibliometric data, as not all relevant publications may be indexed in the selected database. Additionally, differences in citation practices across disciplines and language biases could influence the interpretation of research trends. To mitigate these uncertainties, future studies should consider cross-referencing multiple databases, such as Scopus, Web of Science, and Google Scholar, to ensure comprehensive data collection. Similarly, environmental impact assessments of metal recovery processes involve uncertainties due to variability in life cycle inventory data, assumptions in impact models, and regional differences in waste composition and processing technologies. Sensitivity analysis can help address these uncertainties by evaluating the robustness of results under different scenarios. Additionally, incorporating real-world operational data and industry case studies could enhance the accuracy of environmental impact evaluations. By recognizing these limitations and implementing methodological improvements, future research can improve the reliability and applicability of scientometric and environmental impact analyses in the context of sustainable e-waste management.

3. Results and discussion

3.1. Publication trends

The field of metal recovery from electronic waste (e-waste) has experienced remarkable evolution over the past two decades, reflecting heightened global emphasis on environmental sustainability and resource efficiency. This progression is evident in fluctuating research output, which provides critical insights into the growing focus on sustainable waste management. Publication trends from 2003 to 2024, particularly from 2012 onward, illustrate shifting priorities within the scientific community and broader societal concerns regarding e-waste's environmental implications. Fig. 1a highlights the publication trajectory, starting with minimal activity (2003–2012), marked by foundational research, followed by a steady rise (2013–2016) and culminating in exponential growth (2017–2021). This trend underscores the escalating importance of metal recovery, driven by increased awareness of e-waste's environmental and economic impacts and technological advancements enabling efficient recovery. Notable factors such as heightened global attention to e-waste and innovations in recycling technologies contributed to this surge. Although 2020 saw a slight dip due to the COVID-19 pandemic, the field rebounded swiftly, with sustained high activity in subsequent years. Beyond quantitative trends, open-access dissemination plays a pivotal role in knowledge sharing. Of 188 open-access publications, 100 are fully accessible *via* Gold Open Access, reflecting the field's commitment to equitable access. Other models, such as Green Open Access and hybrid approaches, further expand availability, ensuring widespread knowledge dissemination, especially in resource-constrained regions. The publication landscape reveals diverse contributions: 465 original research articles dominate, showcasing experimental advancements, while 117 review articles consolidate knowledge and guide future research. Conference proceedings, early-access papers, and interdisciplinary collaborations highlight the dynamic nature of the field and its adaptability to emerging challenges.

Key trends shaping the field include the push toward sustainable development, rapid technological advancements, and interdisciplinary approaches. Global collaborations are increasingly vital, fostering holistic solutions to the e-waste crisis. Open-access initiatives and emerging research areas, such as AI-driven optimization and novel recovery materials, promise to propel innovation, ensuring continued progress in sustainable e-waste management.

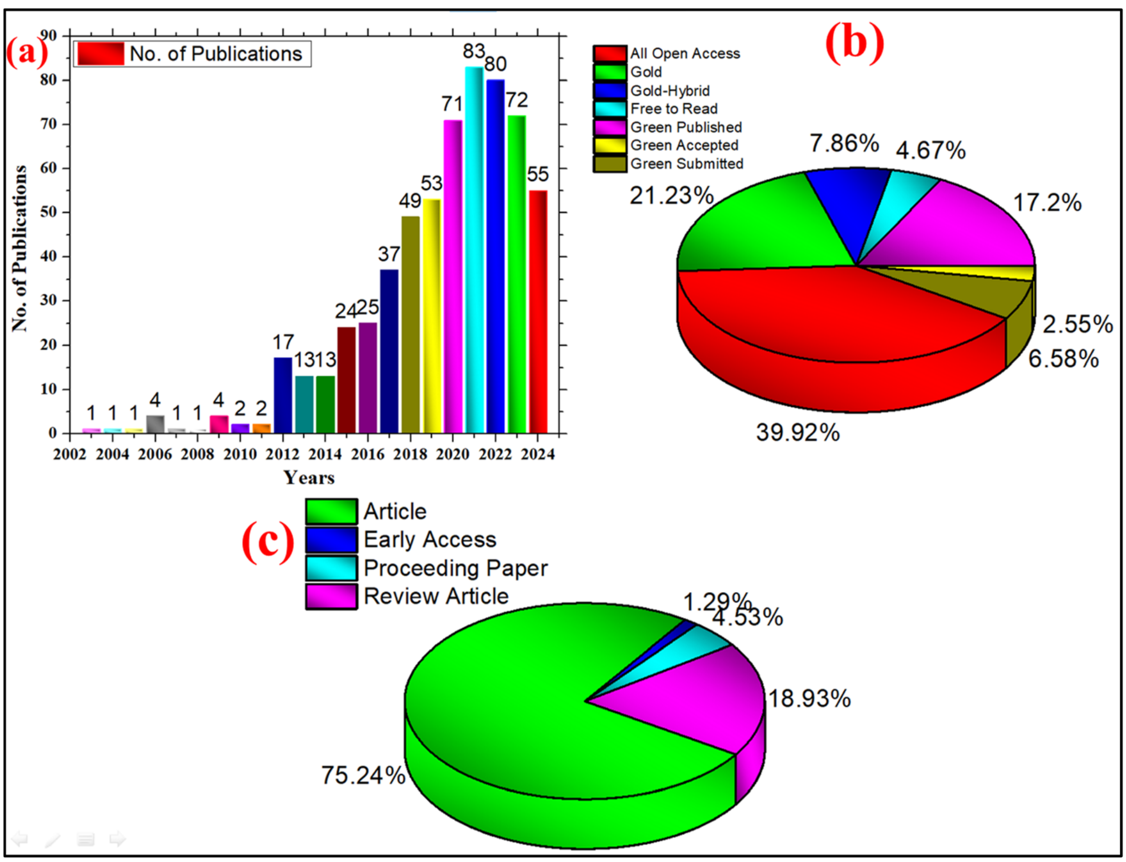

Fig. 1 (a)The trends of number of publication over the years for metal recovery in e-waste, (b) number of publication in open access and (c) type of article published in over the years.

3.2. Geographic distribution

The global research landscape on metal recovery from electronic waste (e-waste) underscores its critical importance, with significant contributions spanning diverse regions. Rapidly increasing e-waste generation, driven by surging electronic consumption, has spurred global efforts to develop sustainable and efficient recovery technologies. This research reflects varying levels of e-waste generation, economic development, and technological capacity worldwide.

China leads with 124 publications, driven by its massive e-waste challenge as the world's largest electronic producer and consumer. Chinese institutions, bolstered by government support and circular economy policies, focus on innovative recovery technologies to address this pressing issue. India follows with 116 publications, emphasizing cost-effective and environmentally sustainable solutions to combat informal recycling practices and escalating e-waste. Indian research benefits from international collaborations to enhance technological capabilities. The United States, with 43 publications, employs a multifaceted approach involving academia, industry, and government, prioritizing technological innovation and sustainable practices. Australia's 41 publications reflect its environmental commitment and regional collaborations in the Asia-Pacific. Italy, contributing 37 publications, aligns its research with European Union circular economy goals, leveraging expertise in materials science and industrial innovation. South Korea's 30 publications highlight advanced recovery processes supported by automation, AI, and strong government policies. Other contributors include Brazil (29 publications), focusing on scalable, low-cost solutions, and European nations such as England (24), Germany (20), and the Netherlands (17), driven by EU resource efficiency objectives. Iran, with 24 publications, develops cost-effective methods tailored to local constraints, offering insights for resource-limited regions.

Asia, particularly East and South Asia, dominates research due to high electronic consumption and production in China, India, and South Korea. Developing nations like Brazil and Iran prioritize adaptable solutions, while European countries maintain leadership in sustainability through circular economy integration. Global collaboration will be pivotal, fostering technology transfer and scalable solutions, with leaders like the U.S. and China driving innovation for regions with high e-waste but limited research capacity (Fig. 2).

The distribution of e-waste research globally reflects the differing priorities and challenges faced by developed and developing countries in managing electronic waste. Developed countries, including the United States, European Union (EU) nations, and Japan, have historically led in scientific publications, policy development, and technological advancements in e-waste management. Their research primarily focuses on advanced recycling technologies, life cycle assessments, and circular economy strategies, driven by stringent regulations such as the EU WEEE Directive and Extended Producer Responsibility (EPR) frameworks.

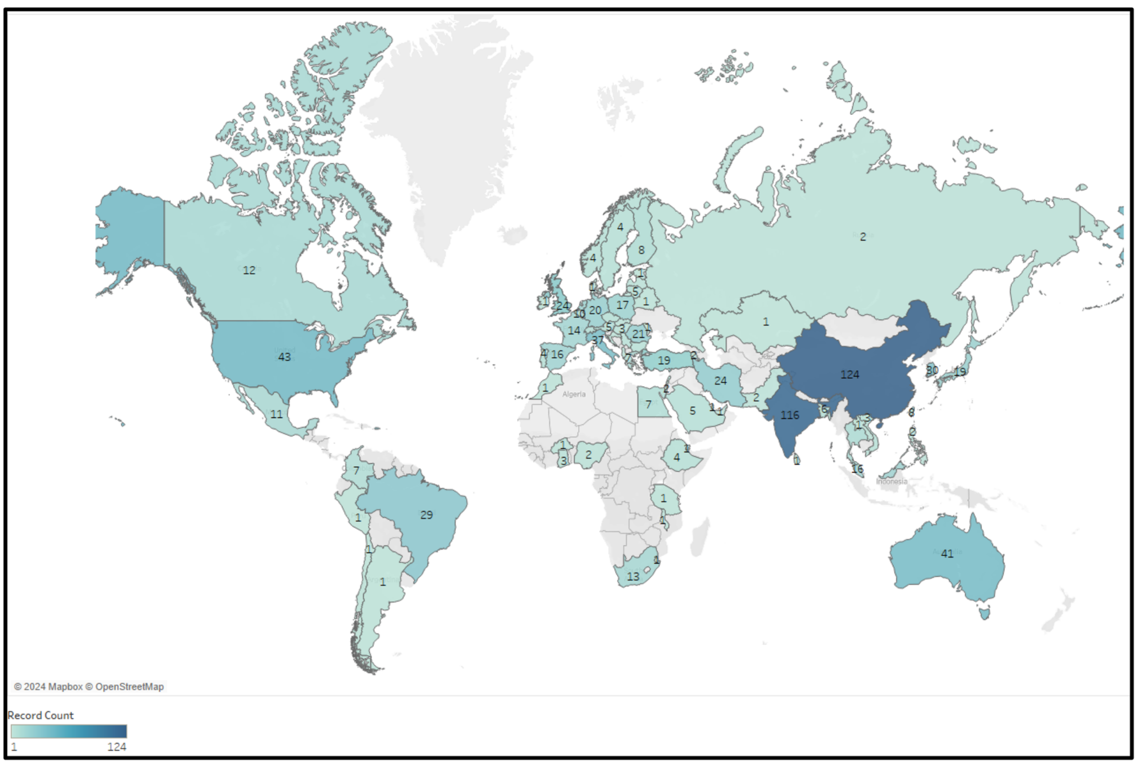

Fig. 2 Geographical map showing countries leading countries in metal recovery from e-waste. Disclaimer: this map is for representation purposes only. It is not intended to depict or endorse any political boundaries or territorial claims. All boundaries and names shown do not imply official endorsement or recognition.

In contrast, developing countries—particularly in Asia, Africa, and parts of South America—face growing e-waste accumulation but have limited research capacity and funding. Their studies often focus on informal recycling practices, environmental contamination, and health risks associated with improper e-waste handling. Countries like China and India have increased research output due to rising domestic e-waste generation and evolving policy measures. However, many regions still struggle with insufficient infrastructure, lack of enforcement mechanisms, and dependence on informal recycling sectors.

The research divide between developed and developing countries has significant policy and technological implications. Developed nations export large volumes of e-waste to developing countries, where inadequate recycling infrastructure often leads to environmental contamination and health hazards. However, emerging economies, particularly China and India, are investing in formal recycling facilities and policy frameworks to transition from informal processing to sustainable e-waste management. Strengthening international collaboration, technology transfer, and policy harmonization will be crucial for ensuring a balanced and sustainable global e-waste management system. By integrating this regional analysis and comparative Table 2, we provide a clearer perspective on how e-waste research is unevenly distributed, affecting the development of sustainable solutions and policies worldwide.

The VOSviewer map (Fig. 3a) illustrates the intricate network of international collaborations in research on metal recovery from e-waste, providing insights into global knowledge exchange and innovation. This analysis underscores the importance of information flow and resource sharing in advancing sustainable and efficient recovery technologies. The map highlights the global nature of this research, with node size representing research output and link thickness indicating collaboration strength. Key hubs, notably China and India, emerge as pivotal contributors due to their substantial research efforts and growing technological sectors. However, the lack of comprehensive e-waste legislation in many countries remains a critical gap (Fig. 3b).

China and India dominate the global collaboration network. China's leadership stems from its research capacity and position as the largest generator of electronic waste, while India's innovation-driven initiatives make it a critical player. Both countries maintain robust collaborative ties with nations like the U.S., South Korea, and European countries, reflecting a shared commitment to advancing e-waste solutions through international partnerships. These collaborations emphasize the global urgency of addressing e-waste challenges through cooperative efforts. The U.S. and Australia also hold strategic positions. The U.S. bridges research between Asia and the West, fostering partnerships with China, India, Germany, and England, which catalyze innovation. Australia connects Eastern and Western research networks, leveraging its focus on sustainability and collaborations with leading nations like China and the U.S. Europe features a dense research network, with Italy, Germany, and England as key players. These nations not only collaborate extensively within Europe but also extend partnerships globally, promoting standardized and scalable technologies. South Korea and Japan contribute significantly to the Asian research network. South Korea's advancements in materials science and technology, coupled with its global partnerships, underscore its critical role. Japan collaborates regionally with nations like Thailand and Taiwan, addressing e-waste challenges in Asia's burgeoning tech sector. Latin America, led by Brazil, also participates actively. Brazil's collaborations with the U.S. and Europe focus on solutions tailored to developing nations' needs, while Mexico shows emerging activity, fostering regional potential. Emerging players, including Iran, South Africa, Malaysia, and Egypt, demonstrate growing involvement in global collaborations. Although smaller in output, these nations benefit from partnerships with established hubs like China and India, enhancing their research capabilities. Strengthening these collaborations ensures a more inclusive and diverse research landscape.

Table 2 Global distribution of e-waste research and key focus areas

Region	Leading contributors	Primary research focus	Policy & regulatory influence	Challenges & implications
North America	USA, Canada	Advanced recycling technologies, AI-driven sorting, circular economy models	EPR policies, federal and state-level regulations	High research funding but limited domestic e-waste processing
Europe	Germany, UK, France, Sweden	Green metallurgy, policy-driven recycling, lifecycle assessments	WEEE & RoHS directives, strong regulatory frameworks	Stringent regulations driving innovation but high compliance costs
Asia	China, India, Japan, South Korea	Hydrometallurgical & biometallurgical recovery, informal recycling sector studies	Emerging EPR policies, e-waste import bans	Rapid e-waste growth, transitioning from informal to formal recycling
Africa	Nigeria, Ghana, South Africa	Environmental impact, informal sector studies, toxic exposure	Weak enforcement of international e-waste treaties	Heavy reliance on informal recycling, limited funding for formal research
South America	Brazil, Argentina, Chile	E-waste collection strategies, resource recovery potential	Limited national policies, few enforcement measures	Low research output due to funding and infrastructure gaps

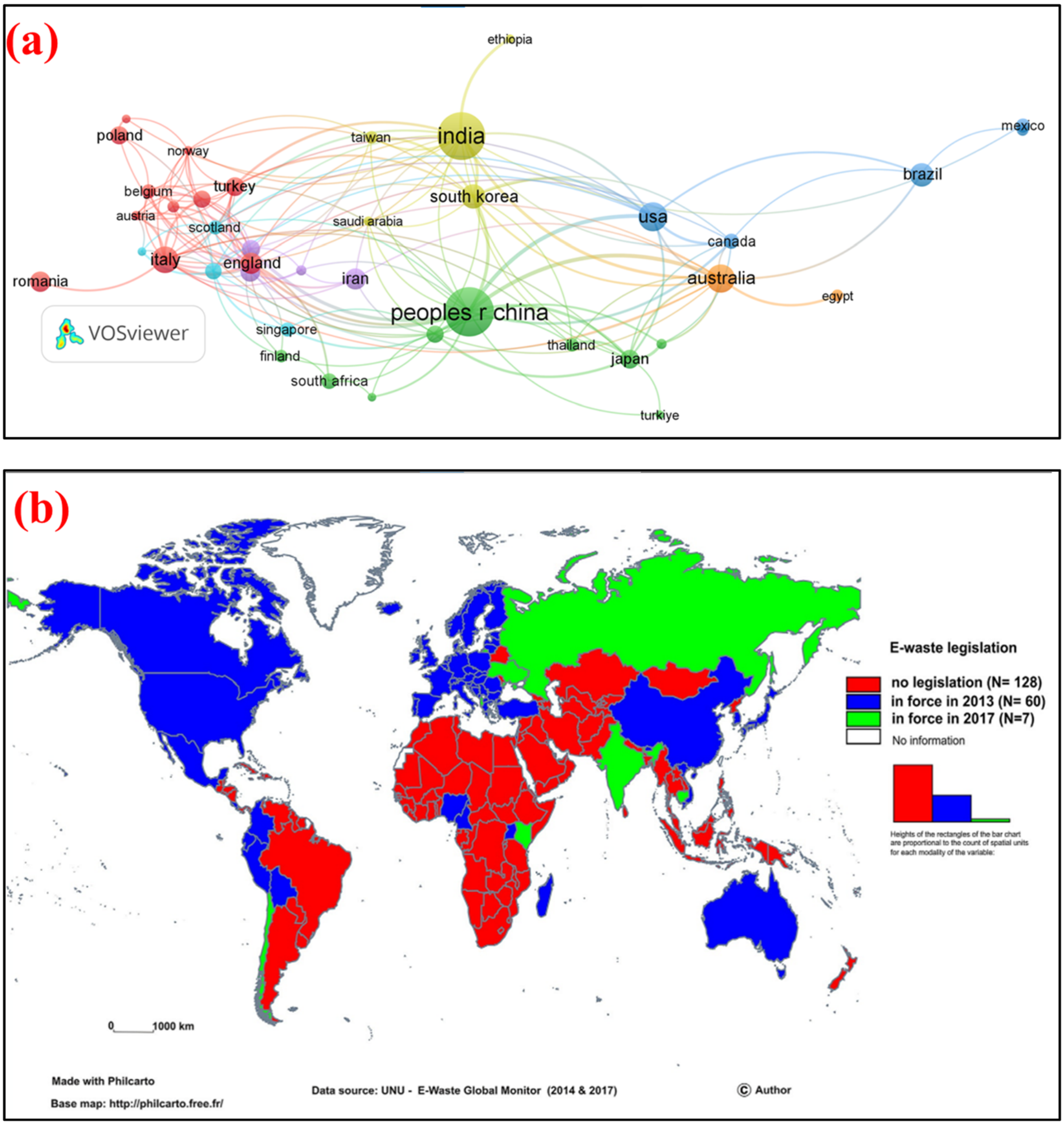

Fig. 3 (a) Virtual network diagram showing collaboration networks between countries, (b) e-waste legislation in many countries reproduced from ref. 56 Copyright © 2019 Elsevier Inc. Disclaimer: this map is for representation purposes only. It is not intended to depict or endorse any political boundaries or territorial claims. All boundaries and names shown do not imply official endorsement or recognition.

The globalization of e-waste research highlights the importance of North–South collaborations to facilitate technology transfer and develop cost-effective solutions for resource-limited settings. Expanding partnerships to underrepresented regions such as Africa, Latin America, and the Middle East can further diversify and enrich the research ecosystem. As the field evolves, fostering stronger, inclusive collaborations will be pivotal in addressing the complex and pressing challenge of global e-waste management.

China's leadership in e-waste metal recovery research can be attributed to several key factors. Firstly, China is the world's largest generator of e-waste, necessitating extensive research efforts to develop efficient recovery technologies. Additionally, the country's strong policy incentives, such as the Extended Producer Responsibility (EPR) framework and stringent recycling regulations, have driven research and industrial investment in sustainable metal recovery methods. The rapid growth of China's industrial sector, particularly in electronics manufacturing, has also spurred innovation in this domain, leading to a high volume of scientific output. Moreover, China's strategic focus on technological advancements, including hydrometallurgical and bioleaching techniques, has positioned it as a leader in this field. Industry collaboration plays a significant role in influencing publication output, as partnerships between academia and industry often lead to applied research with direct technological implementation.[57] Collaborative projects enable access to industrial-scale testing facilities, funding opportunities, and real-world data, which enhance the quality and impact of research. Countries with strong industry-academia linkages, such as China, the U.S., and Germany, exhibit high research productivity due to the integration of practical challenges into academic investigations. China's National Natural Science Foundation (NSFC) and the European Union's Horizon programs have significantly contributed to advancing e-waste recycling technologies. Higher funding availability often correlates with greater research output and innovation, but the effectiveness of funding mechanisms in improving research quality depends on factors such as interdisciplinary collaboration, commercialization potential, and long-term sustainability.

3.3. Author and institution analysis

The domain of e-waste metal recovery has witnessed significant advancements, propelled by the efforts of eminent researchers globally. Table 3 presents key contributors in this field, detailing their affiliations, countries, and publication counts. These experts are at the forefront of developing sustainable technologies to recover valuable metals from the ever-growing e-waste stream.

Kamal Kishore Pant of IIT Roorkee leads with 12 publications, emphasizing advanced chemical engineering techniques for sustainable metal recovery, positioning India prominently in this research area. Zhenming Xu of Shanghai Jiao Tong University, with 11 publications, has developed eco-friendly recovery processes, vital for addressing China's substantial e-waste challenges. Prashant Jadhao of IIT Delhi (10 publications) integrates materials science and chemical engineering to innovate novel recovery methods. Similarly, Mohammad Mousavi from Sharif University of Technology in Iran (10 publications) focuses on bioleaching and biotechnological approaches to enhance sustainability. Zhi Sun of Sun Yat-sen University (9 publications) has advanced scalable, environmentally friendly chemical and electrochemical recovery techniques, while Veena Sahajwalla of the University of New South Wales (9 publications) is renowned for transforming waste into valuable resources, impacting global sustainable waste management practices. Contributions by other scholars, including Subrata Hait, Joanna Willner, Krishna D. P. Nigam, Soheila Yaghmaei, and Denise C. R. Espinosa, underscore the collective global effort to address e-waste challenges. Their work is shaping the future of sustainable metal recovery technologies, ensuring efficient resource utilization and environmental stewardship (Table 3).

The field of metal recovery from e-waste thrives on a complex global network of institutional collaborations, advancing research, fostering innovation, and promoting sustainable practices. Key institutions in Asia, Europe, and Southeast Asia form the backbone of this interconnected research landscape, with the Chinese Academy of Sciences (CAS) at its core. CAS serves as a central hub, driving progress through extensive domestic and international partnerships, including collaborations with Tsinghua University, Delft University of Technology, and Nanyang Technological University (NTU).

CAS's leadership is evident in its pivotal role within China and its influence on global research. Domestically, its alliances with Tsinghua University, Shandong University of Science and Technology, and the University of Chinese Academy of Sciences solidify its status as a key player. Internationally, partnerships with institutions like Delft and NTU bridge continents, fostering cross-border research essential for tackling the e-waste challenge. Tsinghua University complements CAS's efforts with its strong focus on environmental science and sustainability. Its robust collaborations, both within China and globally, position it as a critical driver of innovation in e-waste recycling technologies. Delft University of Technology, a leader in Europe, extends its influence through strategic partnerships, particularly with CAS, enabling a global approach to advanced recycling methods. Similarly, NTU's collaborations with regional and global institutions enhance Southeast Asia's contributions to e-waste management, emphasizing sustainable and innovative practices. In China, the University of Science and Technology Beijing plays a prominent role in materials science and metallurgical engineering, advancing cutting-edge metal recovery techniques. Emerging institutions like Southwest University of Science and Technology are gaining prominence through collaborations with CAS, signaling their potential for significant future impact. The University of Chinese Academy of Sciences and Shandong University of Science and Technology further reinforce China's e-waste research landscape. While the former emphasizes academic excellence and policy-relevant innovation, the latter strengthens regional research networks, ensuring the dissemination and implementation of sustainable practices nationwide. Together,

Table 3 List of top authors, their countries of origin, and their affiliated institutions

Researcher name	Country	Institution	No. of publications
Kamal Kishore Pant	India	Indian Institute of Technology Roorkee	12
Zhenming Xu	China	Shanghai Jiao Tong University	11
Prashant Jadhao	India	Indian Institute of Technology Delhi	10
Mohammad Mousavi	Iran	Sharif University of Technology	10
Zhi Sun	China	Sun Yat-sen University	9
Veena Sahajwalla	Australia	University of New South Wales	9
Subrata Hait	India	Indian Institute of Technology Kharagpur	8
Joanna Willner	Poland	Warsaw University of Technology	7
Krishna D. P. Nigam	India	Indian Institute of Technology Delhi	7
Soheila Yaghmaei	Iran	Amirkabir University of Technology	7
Denise C. R. Espinosa	Brazil	Federal University of São Carlos	7

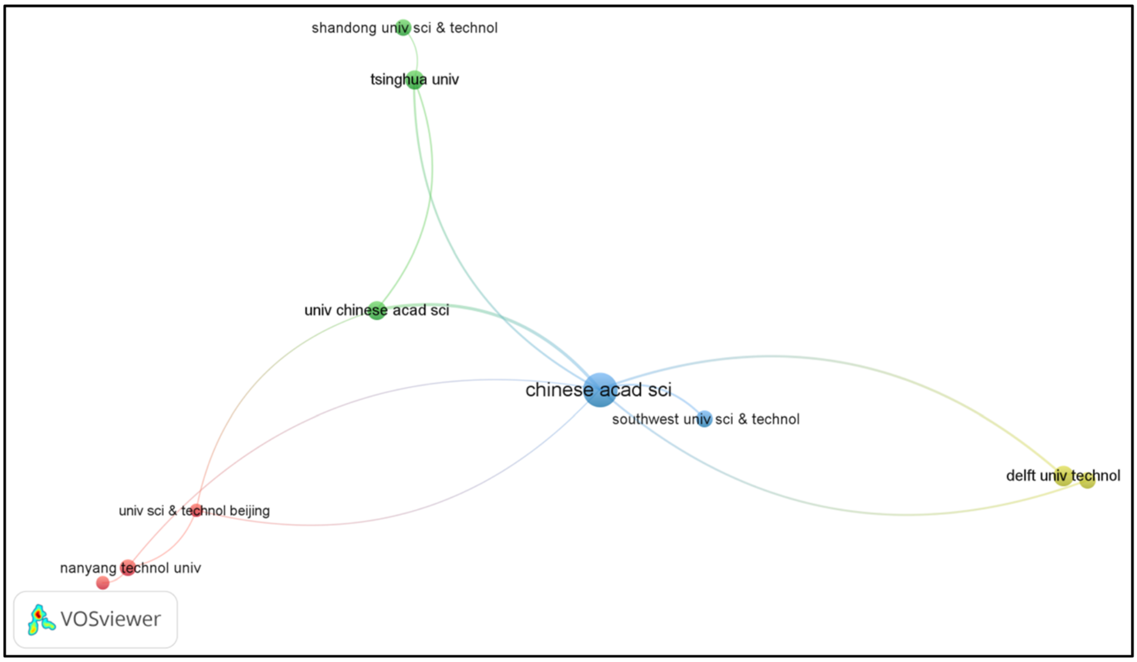

Fig. 4 Virtual network diagram showing collaboration networks between different universities for metal recovery in e-waste management.

these institutions form a dynamic, interconnected research network, driving global advancements in e-waste metal recovery through collaboration, innovation, and a shared commitment to sustainability (Fig. 4–6).

3.4. Citation analysis

In the dynamic domain of metal recovery from electronic waste (e-waste), citation analysis serves as a vital tool for identifying seminal works and assessing their influence on the field. Highly cited papers often shape future research and technological advancements, highlighting their critical role in advancing metal recovery technologies.

The most cited paper, "*Metallurgical Recovery of Metals from Electronic Waste: A Review*" (2008, *Journal of Hazardous Materials*), with 1210 citations, provides a comprehensive overview of metallurgical recovery methods, including pyrometallurgy, hydrometallurgy, and biometallurgy, establishing itself as a cornerstone in the field. Similarly, "*Aqueous Metal Recovery Techniques from E-Scrap: Hydrometallurgy in Recycling*" (2012, *Minerals Engineering*), with 530 citations, emphasizes aqueous hydrometallurgical methods, significantly advancing this domain. Another notable contribution, "*Recovery of Metals and Nonmetals from Electronic Waste by Physical and Chemical Recycling Processes*" (2016, *Waste Management*), with 478 citations, explores integrated physical and chemical recycling strategies, offering practical insights for industry applications. Regionally focused, the 2009 paper, "*Recycling of Waste Printed Circuit Boards: A Review of Current Technologies and Treatment*

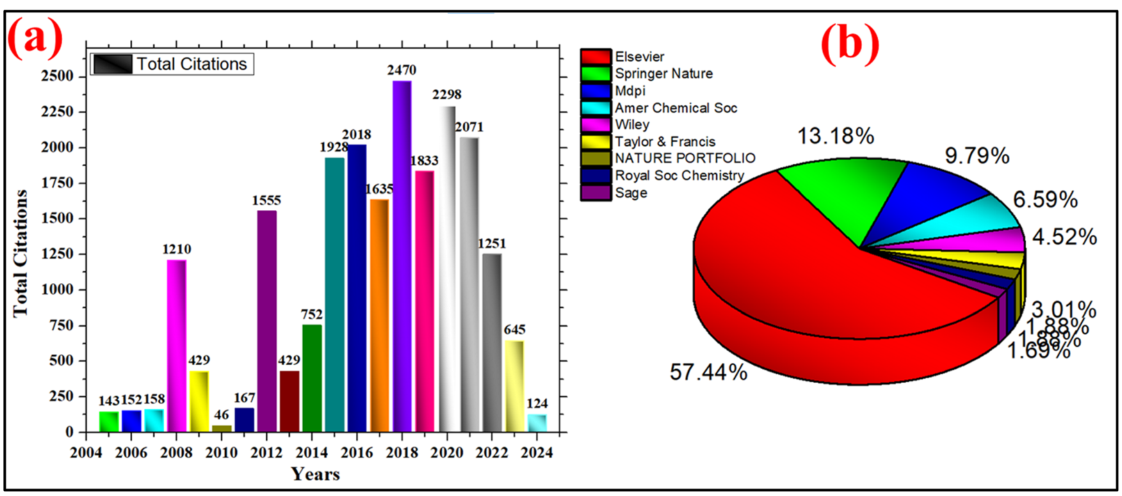

Fig. 5 (a) The trends of number of citations over the years for metal recovery in e-waste, (b) number of publication in different publishers.

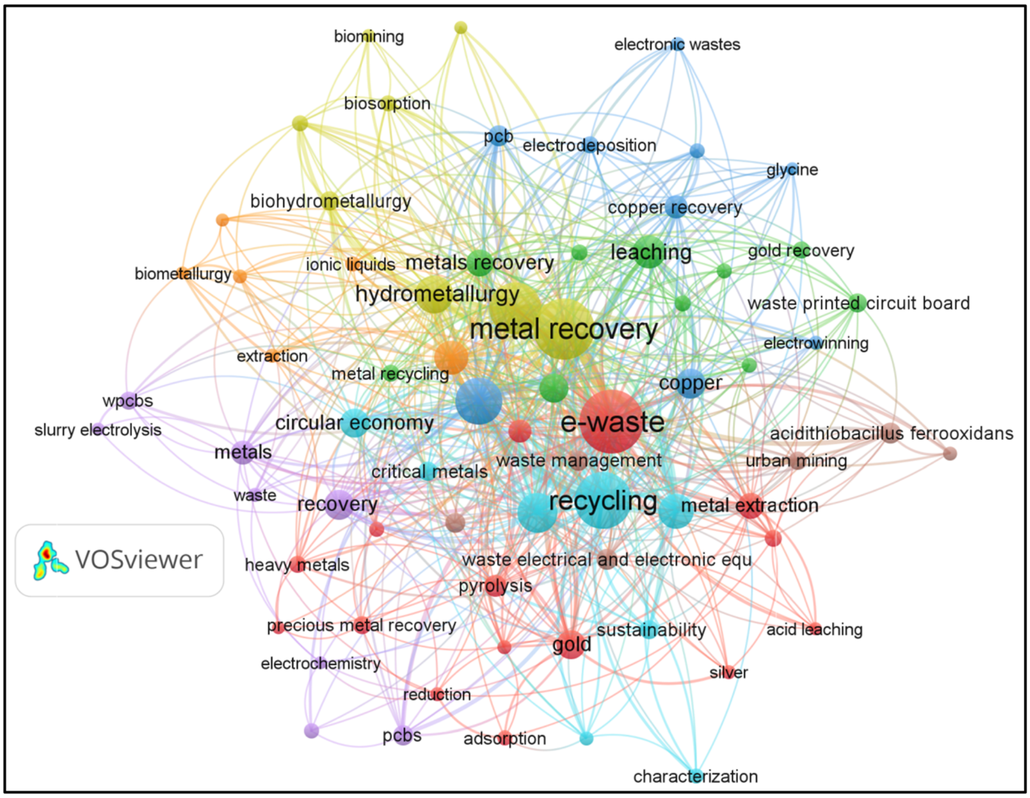

Fig. 6 Network diagram showing major keywords for metal recovery in e-waste management.

Status in China" (*Journal of Hazardous Materials*), with 413 citations, examines China's pivotal role in global e-waste recycling.

The 2015 review, "*Waste Printed Circuit Boards Recycling: An Extensive Assessment of Current Status*" (*Journal of Cleaner Production*), with 406 citations, provides a holistic evaluation of PCB recycling, incorporating environmental and economic perspectives. Additionally, "*Precious Metal Recovery from Waste Printed Circuit Boards Using Cyanide and Non-Cyanide Lixiviants*" (2015, *Waste Management*), with 338 citations, has advanced eco-friendly recovery techniques. Recent papers reflect a shift towards sustainability. The 2020 review, "*Advances in Sustainable Approaches to Recover Metals from E-waste*" (*Journal of Cleaner Production*), with 277 citations, underscores green technologies and circular economy principles. A global outlook is provided by "*E-waste in the International Context*" (2018, *Waste Management*), with 265 citations, which addresses trade flows, regulations, and value recovery technologies. Innovative biological methods are highlighted in "*Bio-Processing of Solid Wastes and Secondary Resources for Metal Extraction*" (2012, *Waste Management*), with 248 citations, and the hybrid approaches discussed in "*Chemical and Biological Extraction of Metals Present in E-waste*" (2012, *Waste Management*), with 233 citations, emphasizing eco-friendly solutions. This citation analysis underscores the transformative impact of these foundational works on e-waste metal recovery, guiding advancements in both research and industrial applications. These pivotal studies continue to drive innovation, fostering sustainable and environmentally responsible practices (Table 4).

The analysis of citation trends offers valuable insights into the academic impact and evolution of metal recovery research from e-waste. Spanning 2003–2024, the data illustrates the progression of this field, highlighting temporal citation distributions, major trends, and the role of leading publishers. In 2003, citations were modest (10), reflecting the nascent stage of research in e-waste management. A sharp rise in 2005 (143 citations) marked growing interest, culminating in 2008 with a significant surge to 1210 citations, attributed to foundational studies on metallurgical recovery processes. After a decline in 2009 (429 citations), a second wave emerged in 2012, driven by heightened global focus on sustainability. Peak activity was observed in 2018 with 2470 citations, reflecting the field's maturity and its intersection with materials science, environmental engineering, and sustainability. However, recent years have shown a decline, from 2071 citations in 2021 to 645 in 2023, suggesting a saturation point and a shift toward incremental advancements or emerging topics within waste management.

Elsevier dominates with 305 citations, supported by journals like *Journal of Hazardous Materials*. Springer Nature (70 citations) and MDPI (52 citations) also contribute significantly, leveraging interdisciplinary and open-access platforms, respectively. ACS (35 citations), Wiley (24), Taylor & Francis (16), and smaller yet impactful players like the Royal Society of Chemistry (10) further enrich the domain. Looking ahead,

Table 4 List of top cited papers, their journals, and publication year

Title	Source title	Publication year	Total citations
Metallurgical recovery of metals from electronic waste: a review	*Journal of Hazardous Materials*	2008	1210
Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling	*Minerals Engineering*	2012	530
Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes	*Waste Management*	2016	478
Recycling of waste printed circuit boards: a review of current technologies and treatment status in China	*Journal of Hazardous Materials*	2009	413
Waste printed circuit boards recycling: An extensive assessment of current status	*Journal of Cleaner Production*	2015	406
Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants – A review	*Waste Management*	2015	338
Advances in sustainable approaches to recover metals from e-waste-a review	*Journal of Cleaner Production*	2020	277
E-waste in the international context – A review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery	*Waste Management*	2018	265
Bio-processing of solid wastes and secondary resources for metal extraction – a review	*Waste Management*	2012	248
Chemical and biological extraction of metals present in e waste: a hybrid technology	*Waste Management*	2012	233

stabilization in citation trends may occur, but emerging areas such as bioleaching, circular economy approaches, and sustainable recovery methods are poised to reignite research activity. The growing influence of open-access publishing and interdisciplinary collaboration is likely to reshape citation dynamics, emphasizing the global relevance of metal recovery from e-waste in addressing critical environmental and economic challenges.

3.5. Funding agencies supporting research in metal recovery from e-waste

Funding agencies are crucial in advancing research on metal recovery from e-waste, providing essential financial support for innovative extraction methods, sustainability solutions, and technological advancements. Government bodies, particularly national science foundations, have historically been the primary funders, prioritizing projects with significant environmental and economic impact. Recently, there has been a shift toward international collaborations, with global organizations like the EU's Horizon programs and the UN supporting cross-border initiatives. The private sector is also increasingly involved, with corporations funding sustainable technologies aligned with corporate social responsibility. This combination of public and private funding has accelerated innovation in metal recovery. A review of funding acknowledgments in the Web of Science database highlights the key agencies driving this research, emphasizing the pivotal role of government and international contributions. The data in Table 5 showcases the most frequently acknowledged funding bodies in this field.

The National Natural Science Foundation of China (NSFC) is the primary contributor, funding 68 publications on metal recovery from e-waste. China's leadership in e-waste research reflects its status as a major e-waste generator and innovator in sustainable resource management, with NSFC investments focused on advancing recycling technologies and metal extraction efficiency. The European Union (EU) has funded 19 publications, playing a pivotal role in fostering international collaboration and promoting circular economy principles in e-waste management. Through initiatives like Horizon 2020 and Horizon Europe, the EU has driven innovation in environmentally sustainable and energy-efficient metal recovery technologies, encouraging multidisciplinary research and industry partnerships.

China's National Key Research Development Program, supporting 17 publications, underscores the government's commitment to addressing resource recovery challenges by

Table 5 Top funding agencies supporting research in metal recovery from e-waste

Funding agencies	Country	Number of publications
National Natural Science Foundation of China (NSFC)	China	68
European Union (EU)	European Union	19
National Key Research Development Program of China	China	17
Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)	Brazil	14
Department of Science and Technology (DST)	India	12
United States Department of Energy (DOE)	United States	11
Spanish Government	Spain	10
Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (TUBITAK)	Turkey	10
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Australia	9
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)	Brazil	9

developing technologies that recover valuable metals while minimizing environmental impact. Brazil's CNPq and CAPES, with 23 supported publications, focus on integrating resource recovery with sustainability, developing cost-effective technologies suited to the socio-economic context of Brazil and other developing nations. India's Department of Science and Technology (DST), supporting 12 publications, plays a key role in advancing metal extraction methods and industry partnerships in response to its growing e-waste problem. The United States Department of Energy (DOE), funding 11 publications, has been instrumental in developing high-efficiency recovery processes, particularly for rare earth metals essential for renewable energy systems. Spain and Turkey's funding bodies, contributing 10 publications each, focus on regional innovation and improving e-waste processing efficiency. Australia's CSIRO, with a commitment to industrial solutions, supports the development of cutting-edge metal recovery technologies.

These agencies have been crucial in driving advancements in metal recovery technologies, fostering international collaborations, and aligning research with global sustainability goals. Their funding has enabled the development of environmentally friendly, cost-effective recovery methods and the creation of interdisciplinary projects that span material science, engineering, and environmental policy, advancing sustainable resource management and innovation.

E-waste management is increasingly regulated through national and international policies aimed at mitigating environmental and human health risks while promoting resource recovery. Key regulatory frameworks worldwide include European Union (EU) directives, Extended Producer Responsibility (EPR) programs, and circular economy strategies, all of which aim to create a more sustainable approach to handling electronic waste.

The EU is at the forefront of e-waste regulation, implementing strict policies to ensure responsible collection, recycling, and disposal. The two key directives governing e-waste management in the EU are:

• Waste Electrical and Electronic Equipment (WEEE) Directive – This directive sets collection, recycling, and recovery targets for e-waste. It mandates that producers take responsibility for financing the collection and treatment of discarded electronics, ensuring that a significant portion of e-waste is diverted from landfills.

• Restriction of Hazardous Substances (RoHS) Directive – The RoHS directive restricts the use of toxic substances such as lead, mercury, cadmium, and brominated flame retardants in electrical and electronic equipment. By limiting hazardous materials, RoHS aims to reduce environmental and health risks associated with e-waste disposal.

The EU's Circular Economy Action Plan (CEAP) complements these directives by promoting sustainable product design, improved waste prevention, and higher recycling rates for electronic materials. The EU is also exploring regulations to enhance repairability and reusability, ensuring that devices have longer life cycles before becoming waste.

EPR is a policy approach in which producers bear the responsibility for managing the end-of-life impact of their products, including collection, recycling, and safe disposal. Many countries, including Japan, South Korea, Canada, and India, have adopted EPR frameworks to incentivize manufacturers to design products with recyclability in mind and finance e-waste management programs.

• Japan's Home Appliance Recycling Law (HARL) mandates that manufacturers and retailers take back and recycle electronic appliances such as TVs, refrigerators, and air conditioners.

• South Korea's Act on the Promotion of Resource Circulation enforces EPR obligations on producers, requiring them to meet recycling targets and invest in environmentally friendly production.

• India's E-Waste (Management) Rules, 2016 introduced mandatory EPR compliance, requiring electronics manufacturers to establish collection and recycling systems for discarded devices.

EPR policies encourage eco-design, closed-loop recycling, and material recovery, aligning with global sustainability goals to minimize e-waste pollution.

The shift from a linear economy (produce-use-dispose) to a circular economy is fundamental to modern e-waste management policies. A circular economy emphasizes resource efficiency, reuse, remanufacturing, and high-recovery recycling techniques to minimize waste and extend product life cycles.

• The EU's Circular Economy Strategy integrates right-to-repair laws, incentivizing manufacturers to design products that are easier to repair, upgrade, and disassemble for recycling.

• China's Circular Economy Promotion Law focuses on reducing resource consumption, improving recycling infrastructures, and developing urban mining industries for metal recovery.

• The United States follows a fragmented approach, where individual states like California and New York have electronics take-back programs, while federal-level regulation is still evolving.

As the global volume of e-waste continues to rise, international cooperation and harmonized policies will be critical in enhancing e-waste recycling efficiency, reducing illegal waste exports, and fostering sustainable development in the electronics industry.

3.6. Keyword and topic analysis

The keyword analysis in the domain of metal recovery from e-waste offers a comprehensive view of research progression and current trends. Utilizing VOSviewer for co-occurrence network visualization reveals the intellectual structure of the field, identifying core themes and the evolution of research focus. Keywords such as "metal recovery," "e-waste", "recycling", and "hydrometallurgy" emerge as central, highlighting their prominence in literature and their interconnections that underscore the interdisciplinary nature of the field.

"Metal recovery", located at the network's core, signifies the primary research focus on extracting valuable metals from discarded electronics. Its close association with terms like "hydrometallurgy", "leaching", and "copper recovery" reflects the emphasis on chemical and metallurgical methods. The keyword "e-waste" links to "recycling", "waste management", and "urban mining", pointing to broader concerns in e-waste management, including environmental and economic implications. The incorporation of "circular economy" and "sustainability" underscores a growing integration of holistic approaches. Hydrometallurgy, a dominant technique in metal recovery, is further supported by keywords such as "biohydrometallurgy" and "biometallurgy", which highlight a shift toward sustainable biotechnological methods. The focus on "recycling" and "circular economy" emphasizes material reintegration to reduce the need for virgin resources, aligning with sustainability goals. Over time, research has expanded beyond basic recovery processes, incorporating environmental and health concerns, with an increasing focus on sustainable practices. Recent developments in the field, marked by keywords like "biohydrometallurgy", "biometallurgy", and "biosorption", point to a rise in alternative, eco-friendly recovery methods. Keywords related to "critical metals" and "precious metal recovery" reflect growing interest in high-value metals, driven by their importance in electronics. Overall, the keyword network illustrates that while the core of research remains on efficient recovery methods, there is a notable shift towards sustainability, circular economy, and innovative techniques, positioning the field to address both resource conservation and environmental challenges as e-waste volumes and demand for critical metals grow.

The integration of artificial intelligence (AI), machine learning (ML), and blockchain is revolutionizing e-waste processing and supply chain transparency. AI-powered sorting technologies utilize computer vision and robotics to enhance the identification and segregation of valuable components in e-waste, increasing the efficiency of metal recovery. Machine learning algorithms optimize process parameters in hydrometallurgical and biometallurgical recovery methods, improving yield and reducing chemical waste. Blockchain technology is emerging as a key tool for tracking e-waste flows, ensuring compliance, and preventing illegal dumping. By maintaining decentralized and tamper-proof records, blockchain enhances supply chain transparency, enabling regulators, recyclers, and manufacturers to monitor material movement from collection to final recovery. Combined, these technologies drive the efficiency, sustainability, and accountability of e-waste recycling, aligning with circular economy principles.

Emerging topics and trends in metal recovery from e-waste reflect the evolving priorities in both environmental sustainability and resource efficiency. One key trend is the growing focus on biohydrometallurgy and biometallurgy, which utilize microorganisms to extract metals from e-waste. These methods are considered more environmentally friendly compared to traditional chemical processes, as they reduce the need for harsh chemicals and lower energy consumption. Another emerging trend is the integration of circular economy principles into e-waste management. Researchers are increasingly exploring ways to close the loop on material use, emphasizing the need for recycling processes that maximize resource recovery while minimizing waste. This approach aligns with global sustainability goals and aims to reduce the environmental footprint of electronic devices. Additionally, there is an increasing emphasis on recovering critical and precious metals, such as rare earth elements, which are essential for the electronics industry but are often difficult to recover. This focus on high-value metals drives innovation in recovery technologies, pushing the field towards more advanced and efficient methods. Overall, the field of metal recovery from e-waste is rapidly evolving, with a clear shift towards sustainable, efficient, and innovative recovery techniques.

Hydrometallurgy, a dominant technique in metal recovery, is further supported by keywords such as "biohydrometallurgy" and "biometallurgy", which highlight a shift toward sustainable biotechnological methods. The focus on "recycling" and "circular economy" emphasizes material reintegration to reduce the need for virgin resources, aligning with sustainability goals. Over time, research has expanded beyond basic recovery processes, incorporating environmental and health concerns, with an increasing focus on sustainable practices. Future research should focus on AI-driven optimization in recycling processes, leveraging machine learning algorithms to enhance sorting efficiency, predict metal recovery rates, and minimize waste. Advancements in bioleaching should explore genetically modified microorganisms capable of higher extraction efficiencies for critical metals. Additionally, modern hydrometallurgical techniques incorporating 21st-century green solvents—such as deep eutectic solvents and ionic liquids—can significantly reduce environmental impact while improving recovery rates. Hybrid recovery methods that integrate pyrometallurgy, hydrometallurgy, and biometallurgy should also be explored to enhance metal selectivity and efficiency. From a policy perspective, governments and regulatory bodies should implement stricter e-waste collection and recycling mandates, incentivize research on sustainable recovery technologies, and promote international collaboration for technology transfer. The establishment of extended producer responsibility (EPR) policies and subsidies for green recycling initiatives can accelerate the adoption of environmentally friendly recovery methods. These combined efforts will contribute to a more sustainable and economically viable e-waste management system, addressing both resource conservation and environmental challenges as e-waste volumes and demand for critical metals grow.

4. Research gaps and future directions

Despite significant advancements in metal recovery from e-waste, critical research gaps persist, offering substantial opportunities for further exploration. A key gap is the scalability of laboratory-based recovery methods. While many studies demonstrate effective metal recovery in controlled settings, the application of these methods on an industrial scale remains underexplored. The transition from small-scale to large-scale operations presents challenges related to cost-effectiveness, energy efficiency, and environmental impact, which have yet to be adequately addressed. Additionally, research on e-waste management is heavily concentrated in Europe, North America, and East Asia, with insufficient focus on developing countries where most e-waste is generated and processed. These regions often lack the infrastructure for safe recycling, posing significant environmental and health risks. There is a pressing need for localized solutions that consider the unique socio-economic and environmental conditions of these areas. Furthermore, the recovery of critical and rare earth metals is still under-researched. While methods for recovering common metals like copper, gold, and silver are well-established, the recovery of rare earth elements (REEs) remains a significant challenge. Current methods for REE recovery are often inefficient or environmentally damaging, highlighting the need for innovative approaches. Lastly, the environmental and health impacts of the recycling processes themselves require further investigation. While valuable materials are prioritized, the release of toxic substances during recycling poses significant risks to both human health and the environment.

Scaling up sustainable metal recovery methods from e-waste faces several technical and economic barriers that limit widespread adoption.

4.1. Technical constraints

Many sustainable recovery techniques, such as biometallurgy and green hydrometallurgy, are still in the experimental or pilot-scale phase. Their efficiency in extracting rare earth elements (REEs) like lithium and cobalt remains relatively low compared to traditional pyrometallurgical and hydrometallurgical methods. Additionally, material heterogeneity in e-waste complicates the standardization of recovery processes, requiring advanced pre-treatment and separation technologies. The lack of optimized leaching agents and bioleaching microbes further limits scalability, as these processes often exhibit slow reaction rates and low selectivity for valuable metals. Moreover, integrating automation and AI-driven sorting systems remains a challenge, as current methods struggle with the complex and evolving composition of electronic waste.

4.2. Economic constraints

The high initial investment required for establishing large-scale sustainable recovery facilities poses a significant barrier. Compared to conventional mining, e-waste recycling must compete with fluctuating metal prices, making profitability dependent on factors such as metal content, recovery efficiency, and processing costs. Additionally, chemical reagents and microbial cultures used in sustainable recovery methods can be costly and may require further optimization to be economically viable. The lack of robust collection and supply chain infrastructure also increases operational expenses, as fragmented recycling systems result in inconsistent feedstock availability. Furthermore, regulatory uncertainties and policy inconsistencies across different regions hinder large-scale investments, as businesses face unpredictable compliance costs and market fluctuations.

4.3. Addressing the barriers

Overcoming these challenges requires technological advancements in process efficiency, government incentives, and circular economy-driven policies. Investments in AI-driven sorting, eco-friendly leaching agents, and bioengineered microbes could enhance recovery rates and cost-effectiveness. Additionally, stronger public-private partnerships and policy frameworks, such as Extended Producer Responsibility (EPR) schemes and tax incentives, can drive industrial adoption and attract funding for scaling up sustainable recovery technologies.

To provide a comprehensive comparison of metal recovery processes, we have introduced Table 6. This table evaluates the production costs, market value of recovered metals, and economic feasibility of different techniques in contrast to primary extraction. The key factors considered include energy consumption, operational costs, environmental impact, and overall profitability.

Pyrometallurgy, while profitable, is highly energy-intensive, making it less attractive for low-value metals due to high carbon emissions and operational costs. In contrast, hydrometallurgy offers a more balanced approach in terms of cost, energy efficiency, and metal recovery, though it presents challenges related to chemical waste disposal. Biometallurgy stands out as the most environmentally friendly and cost-effective method; however, its longer processing times and lower metal recovery rates limit its widespread application. Nevertheless, when compared to primary extraction, all three recycling techniques provide significant economic and environmental advantages, particularly for high-value and rare metals such as

Table 6 Comparison of metal recovery techniques

Process	Production cost ($ per ton of e-waste processed)	Energy consumption (kW per h per ton)	Market value of recovered metals ($ per ton)	Environmental impact	Economic feasibility *vs.* primary extraction
Pyrometallurgy	800–1500	2000–4000	5000–10,000	High emissions, slag disposal issues	Profitable for high-value metals but energy-intensive
Hydrometallurgy	500–1200	500–1500	6000–12 000	Chemical waste management required	Economically viable with lower energy use
Biometallurgy	300–700	100–500	4000–8000	Low emissions, eco-friendly	Cost-effective but slow and lower yields
Primary extraction (mining)	1500–3000	5000–10 000	6000–12 000	High land degradation, pollution	Less sustainable due to high costs and emissions

gold, silver, and palladium. From an economic feasibility perspective, hydrometallurgy and biometallurgy demonstrate higher profit margins than primary extraction due to lower energy demands and reduced raw material costs. However, pyrometallurgical plants require high capital investments, making them viable primarily for large-scale e-waste processing with high metal concentrations. As global demand for critical metals continues to rise and environmental regulations on mining become more stringent, recycling is emerging as a competitive and sustainable alternative to conventional metal extraction.

Several promising research avenues are evident, particularly in emerging areas. One critical area is the development of eco-friendly and sustainable recovery technologies. Traditional methods like pyrometallurgy and hydrometallurgy are energy-intensive and involve toxic chemicals, making them environmentally harmful. Research into biohydrometallurgy and biometallurgy, which leverage biological processes for metal recovery, presents a more sustainable alternative. Another promising direction is integrating circular economy principles into e-waste management. This approach emphasizes recycling, reuse, and remanufacturing to extend the life cycle of materials. Exploring how metal recovery processes can align with circular economy frameworks may lead to more efficient resource use and reduced waste. Additionally, interdisciplinary research, combining material science, environmental engineering, economics, and policy, can generate more holistic solutions. For instance, integrating economic analysis with technical research could identify economically viable recovery methods. Social science research can also help overcome behavioral barriers to effective recycling. Finally, as e-waste composition evolves with technological advancements, ongoing research is needed to develop adaptable recovery technologies capable of processing new materials efficiently, ensuring the relevance and effectiveness of metal recovery processes.

Future research in metal recovery from e-waste should focus on the development of sustainable, cost-effective, and high-yield processes. One key direction is the application of green chemistry principles to replace hazardous reagents with environmentally benign alternatives, such as deep eutectic solvents (DESs), ionic liquids, and biodegradable leaching agents. These approaches aim to reduce chemical waste and improve recovery efficiency. Another promising avenue is the exploration of bio-based catalysts for hydrometallurgical and biometallurgical processes. Enzymatic and microbial catalysts could provide selective metal extraction while reducing energy demands and toxic byproducts. Furthermore, integrating renewable energy sources, such as solar, wind, and bioenergy, into metal recovery operations could lower the carbon footprint and improve sustainability. For instance, solar-driven electrowinning and photobioreactors for bioleaching could enhance process feasibility in resource-limited settings. By advancing these strategies, future studies can contribute to the development of economically viable, environmentally friendly, and scalable metal recovery technologies that align with circular economy principles.

5. Conclusion

The growing challenge of e-waste generation, driven by the rapid proliferation of electronic devices, presents significant environmental and economic implications. Metal recovery from e-waste emerges as a vital solution, addressing both the environmental hazards of improper disposal and the opportunity to reclaim valuable resources. This manuscript has explored the current methods of metal recovery, including pyrometallurgical, hydrometallurgical, and biometallurgical processes, highlighting their respective advantages and challenges. The integration of these technologies into e-waste management strategies is essential for mitigating environmental damage, conserving finite resources, and contributing to the development of a circular economy. However, challenges such as the complex composition of e-waste, economic viability, and regulatory frameworks must be addressed to fully realize the potential of metal recovery. Continued innovation, policy support, and public engagement are critical to advancing this field and ensuring sustainable management of e-waste in the future. As global demand for electronic devices grows, the importance of efficient and sustainable metal recovery from e-waste will become increasingly pivotal in promoting environmental sustainability and resource efficiency.

Data availability

All the data is presented in the manuscript. No ESI data is needed.

Author contributions

Peeyush Phogat: conceptualization, data collection, writing – original draft and formal analysis. Sushil Kumar: formal analysis and writing – review & editing. Meher Wan: supervision, writing – review & editing.

Conflicts of interest

It is declared that this article is original and written by the stated authors. There is no conflict of interest between the authors.

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