# E-Waste Generation, Recovery, and Recycling: Scientometric Insights into Sustainable Resource Management

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**Abstract.** With the rapid growth of electronic consumption worldwide, the generation of e-waste has become a major problem that presents serious environmental, economic, and social problems. The present study offers a scientometric evaluation of global e-waste management research between 2015 and 2025, illustrating trends in knowledge generation, technological advancements, and political campaigns. The analysis was conducted on 969 documents indexed in Scopus (with the help of Biblioshiny, VOSviewer, and OriginPro) to map the patterns of publications, most frequent authors, most influential institutions, and most frequent thematic groups. The findings indicate a 17.29 percent growth rate per year, robust global cooperation, and growing interest in recovery and recycling technologies, environmental consequences, and circular-economy models. The major areas of research are hydrometallurgical and pyrometallurgical metal recovery, new bioleaching and AI sorting innovations, and evaluations of the socio-economic risks of informal recycling. Sustainability, unsafe emissions, and green technological solutions were the most referenced topics. Although significant improvements have been made, loopholes remain regarding the involvement of developing countries, implementation of policies, safety of workers, and practical application of Industry 4.0 technologies. This discussion indicates the necessity of supporting the development of global e-waste governance, resource efficiency, and accelerated sustainable recycling through integrated multidisciplinary approaches. These findings offer valuable insights for researchers, policymakers, and industry stakeholders seeking to advance environmentally responsible e-waste management.

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# 1 Introduction

## 1.1 History and International Importance of E-Waste

The rapid expansion of the electronics market has transformed the fields of communication, entertainment, and productivity throughout the world. However, the technological boom is also a factor in the rapid increase in electronic waste generation, which is a significant global challenge [1]. Generally, E-waste can be viewed as an electrical or electronic machine discarded, such as a desktop computer, laptops, cellular phones, television, and appliances after it has reached the end of its life cycle [2]. The e-waste generation has increased significantly as the lifespan of modern gadgets is too short owing to ongoing advancements and consumer demand for the latest technologies. According to the Global E-waste Monitor 2024, over 60 million tons of e-waste is generated annually, and the recycling rate is less than one-fifth [3]. This scenario has created a high level of environmental, social, and economic difficulties across the globe.

E-waste contains both precious materials such as gold, silver, copper, and palladium, as well as dangerous elements such as lead, mercury, and cadmium. Mishandling or open burning of e-waste causes toxic chemicals to be emitted into the environment, polluting soil, air, and water, and posing health hazards to the human population, especially in developing countries, where informal recycling is the dominant aspect. The financial aspect of unrecycled e-waste is estimated to be worth more than 60 billion annually, which means that the potential of the involved resource recovery within a circular economy is immense. E-waste management involves informal labor sector, unsafe working conditions, and environmental justice. Therefore, sustainable management strategies are necessary to reduce these dangers, aimed at restoring resources of interest, reducing environmental footprints, and enhancing social status and economic effectiveness.

## 1.2 Recovery, Recycling, and Resource Efficiency

Responsibility based on resource management in the perspective of the transition to a circular economy and sustainable development is the effective recovery and recycling of e-waste. E-waste contains high percentages of metals and rare earth elements that can be recycled and repurposed into the production process, obviating the need to rely on primary extraction and conserving the available natural resources [4]. The process of recycling has made enormous steps towards making the process efficient and safe for the environment in terms of recovering the material. Mechanical recycling involves dismantling, shredding, and magnetic separation and is the first step in the majority of recycling chains. These are followed by metallurgical procedures, hydrometallurgical and pyrometallurgical processes, that extract metals through chemical extraction or smelting at high temperatures.

Selective metal recovery can be achieved through hydrometallurgy (which requires acid- or bio-based leaching agents) or bulk recovery in pyrometallurgy (however, with high energy demand and dangerous gases), although these methods have adverse environmental effects [5]. Bioleaching, the action of microorganisms to dissolve metals, has been used more recently as a greener alternative that provides low operational cost and low environmental impact. Integrating these processes facilitates the concept of resource efficiency in the optimal recovery and reduction of waste and pollution [6]. In addition, Industry 4.0 technologies, including artificial intelligence, robotics, and sensor networks, are increasingly being utilized in recycling facilities to enhance the precision of sorting, optimization of processes, and traceability of e-waste management systems.

The benefits of the successful reuse of e-waste on the environment are numerous: it would lead to a reduction in the greenhouse gases emissions associated with the extraction of virgin materials, reduction of landfills use, and eradication of the proliferation of harmful chemicals [7]. It is also useful in realizing the United Nations Sustainable Development Goals, especially SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). However, there is low global recycling due to issues in collection systems, consumer awareness, insufficiency of infrastructure, and weaknesses in policy enforcement systems [8]. These key challenges show that evidence-based approaches to the e-waste system must be streamlined and made circular [9].

The implementation of Industry 4.0 technologies has initiated changes in the conventional systems of e-waste management over the recent years. Alongside the outdated mechanical dismantling and metallurgical recovery processes, better efficiency, transparency, and sustainability are being pursued using digitally enabled solutions that are being explored, such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, robotics, and automation. This is performed by categorizing waste and maximizing the recovery of materials with the help of image recognition and machine learning algorithms to reduce the likelihood of human contact with hazardous materials [10]. IoT sensors also improve real-time tracking and traceable collection, processing, and transportation, which improves logistical coordination. The proposed blockchain systems would assist in the tracking of e-waste flows in formal and informal sectors in a transparent way and reducing the instances of illegal dumping and leakages. Robotics and automated dismantling technologies enable even more precise handling of hazardous materials. Although these developments are promising, the effective introduction of Industry 4.0 in e-waste management is still disjointed and under-researched, and requires systematic assessment in the global research arena.

### 1.3 Landscape of Research and Knowledge Gaps

The past decade has been characterized by a surge in the e-waste management research as individuals have increasingly been aware of its environmental and economic influence. Themes have been considered in the scientific community, such as recycling technologies and resource recovery, policy frameworks and consumer behavior [11]. The knowledge sharing in the international networks between countries, universities, and companies have improved the comparative research and technological progress.

Nevertheless, even in view of this growth, the research distribution is uneven. A huge proportion of global research is concentrated in the developed world, such as China, the United States, and the member states of the European Union, whereas the developing world in Africa, South Asia, and Latin America has been underrepresented [12]. This has some ramifications on the geographical differences in the knowledge of informal systems of recycling that prevail in e-waste management in most low-income countries. In addition, the available literature on technical research on material recovery is excellent, but the socio-economic aspect is more limited, such as the safety of workers, involvement of consumers, and efficiency of regulation. The latest technologies, such as AI-based waste classification, blockchain traceability, and IoT collection systems, have not received much active research in the past, but have not undergone any evaluation or implementation at a large scale [4]. The absence of these areas underscores the necessity of an interdisciplinary approach that considers technological, environmental, policy, and social aspects. Such knowledge gaps can be systematically researched through the application of scientometric mapping of international e-waste studies to measure publication patterns, landmark publications, and untapped thematic issues [13]. This understanding will be informative for future research and policy intervention priorities.

### 1.4 Identification of Research Gap and Study Contribution

Although previous studies have examined the technological, environmental, and policy aspects of e-waste management, a systematic scientometric mapping that integrates technological innovation (e.g., hydrometallurgy and bioleaching), circular economy strategies, socio-economic dimensions, and emerging Industry 4.0 applications within a unified analytical framework remains limited. The majority of current reviews consider either technology of material recovery or policy framework either in isolation, not quantitatively assessing research organization on a global scale, the rate of collaboration, thematic development, and technological convergence [14]. Moreover, the previous bibliometric surveys on e-waste research works have extensively mainly focused on the number of publications and citation performance without adequately relating the bibliometric metrics with thematic maturity, technological preparedness and geographical discrepancies in research with regard to the developed and developing economies where informal recycling is the order of the day.

Hence, the gaps in this study include the following.

1. Absence of a unified scientometric evaluation, incorporating technological, environmental and socioeconomic clusters.
2. The lack of quantitative mapping of Industry 4.0 integration in the e-waste management literature.
3. Minimized research on collaboration structures and their connection to knowledge diffusion.
4. Limited research on emerging themes out of the traditional recycling framework to AI-powered and circular-economy-based approaches.

By analyzing 969 Scopus-indexed documents using Biblioshiny, VOSviewer, and OriginPro, this study provides a structured intellectual map of global e-waste management research and identifies emerging research frontiers in this field.

### 1.5 Need for Scientometric Analysis

Scientometric and bibliometric methods have become familiar tools in assessing the organization and dynamics of scientific knowledge in certain domains of study [4]. When it comes to e-waste management, such analysis provides a rough overview of how the industry has developed over the years with the most prolific authors, institutions, countries, funding bodies, and important journals having determined the area of study. Networks of co-authorship, citation and keyword co-occurrence networks can be generated using visualization programs like VOSviewer and Biblioshiny which show intellectual structure and research clusters. Scientometric analysis measures publication patterns, the effect of a citation, and collaboration networks of a research and determines its productivity and impact, as well as the identification of new hot topics, such as urban mining, inclusion in a circular economy, and lifecycle assessment of electronic products. Although conventional literature reviews are more interpersonal in nature, a scientometric review offers an objective and data-driven view of the research environment. It allows for the determination of temporal and thematic changes, which allows the researcher to find the most common themes and new fields of interest [2]. This will be advantageous to policymakers and funding agencies to prioritize their investments and develop sustainability programs. The findings for academics have depicted possibilities of collaboration and integration across disciplines. Therefore, the current study uses scientometrics to map global research on e-waste generation, recovery, and recycling. It aims to unearth the intellectual framework, collaboration pattern, and theme development of this critical discipline in the next four to five years between 2015 and 2025. The outcomes will define a clear picture of the trend in e-waste studies, inform policies on sustainable resource management, and contribute to inspiring future innovations in circular economy practices [15].

## 2. Methodology

Figure 1 of this paper outlines a methodology of e-waste management research based on a scientometric approach with the Scopus database. Scopus was chosen due to its comprehensive coverage of scientific literature across various disciplines, its indexing of high-impact journals, and its widespread use in scientometric studies. The dataset is 2015-2025 and was chosen to reflect the post-SDG sustainability trends and the latest technological changes, such as Integration of Industry 4.0. Analytical tools were used to visualize the data (OriginPro, VOSviewer, and Biblioshiny). This real-time methodology can be used to determine new research trends, influential researchers, and networks. It ensures a general overview of the global development in the e-waste management research, thematic areas, technological progress as well as sustainability efforts that will be used to inform future policy and academic trends.

Search query: TITLE-ABS-KEY ( "E Waste management" ) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( EXACTKEYWORD , "Electronic Waste" ) OR LIMIT-TO ( EXACTKEYWORD , "E-waste" ) OR LIMIT-TO ( EXACTKEYWORD , "E-waste Management" ) )

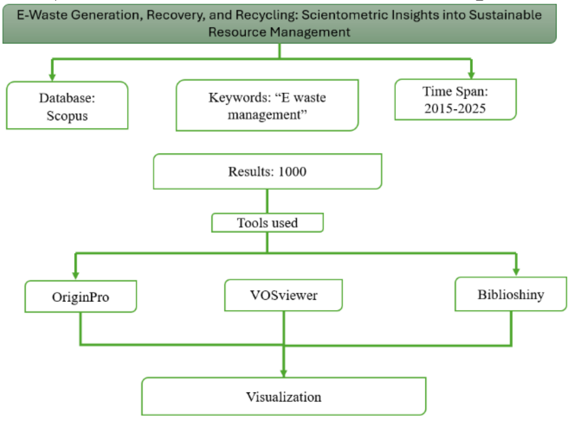


**Fig. 1.** Methodological Framework

## 3. Result and discussion

The bibliometric overview (2015-2025) provides 969 records out of 342 sources whose growth rate is 17.29 annually and average 23.41 per article. There is a high level of collaboration, average co-authors of 2,964 and average number of co-authors of 3.61 per document, and 23.84 percent of international collaboration. The most prevalent are articles (495) followed by conference papers (199) and reviews. The keyword numbers (5,852) indicate diversification of the research topics, indicating active participation of the international community and interdisciplinary interests in the creation of e-waste management research.

**Table 1.** Main Information Overview

| MAIN INFORMATION ABOUT DATA | |
|---|---|
| Timespan | 2015:2025 |
| Sources (Journals, Books, etc) | 342 |
| Documents | 969 |
| Annual Growth Rate % | 17.29 |
| Document Average Age | 3.4 |
| Average citations per doc | 23.41 |
| References | 5671 |
| DOCUMENT CONTENTS | |
| Keywords Plus (ID) | 4517 |
| Author's Keywords (DE) | 5852 |
| AUTHORS | |
| Authors | 2964 |
| Authors of single-authored docs | 65 |
| AUTHORS COLLABORATION | |
| Single-authored docs | 76 |
| Co-Authors per Doc | 3.61 |
| International co-authorships % | 23.84 |
| DOCUMENT TYPES | |
| Article | 495 |
| Book | 6 |
| Book Chapter | 134 |
| Conference Paper | 199 |
| Data Paper | 2 |
| Editorial | 3 |
| Letter | 1 |
| Note | 1 |
| Review | 127 |
| Short Survey | 1 |

The growth rate of 17.29% per annum shows long-term growth of global research in e-waste management over the next five years (2015-2025) and suggests that more academic and policy focus will be placed on resource recovery and sustainability issues. This increase can be attributed to the increased e-waste production worldwide, more effective policies on the circular economy, and technological advancements in recycling methods. The collaboration index of 3.61 co-authors per article reveals the interdisciplinary nature of the discipline, which combines environmental engineering, materials science, economics, and digital technologies. A cross-border partnership rate of 23.84% also indicates an increase in cross-border partnerships, especially between Asian and European institutions, to improve knowledge sharing and research publicity. The average number of citations per document (23.41) also indicates good scholarly involvement, showing that e-waste management has become a well-established sustainability research area. This minimal drop in 2025 publications can probably be explained by the lack of indexing of the publications and not by decreased research activity.

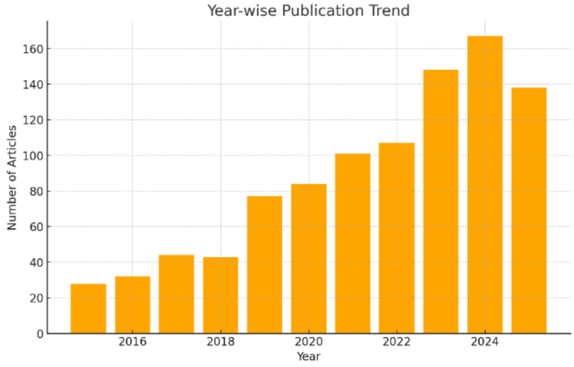


**Fig. 2.** Yearly Articles

Figure 2 depicts the increasing trend in the number of published articles between 2015 and 2025. During the initial years, 2015-2018, growth was not rapid, but it steadily increased every year, albeit only in minor amounts. Since 2019, research activity has increased sharply, indicating an increase in interest and productivity. The article count continued to grow exponentially, with a peak of 167 in 2024. Nevertheless, 2025 recorded a minor decline to 138, indicating a slight decline following many years of high growth. In general, the graph shows a growing passion and work in publishing over time in the field.

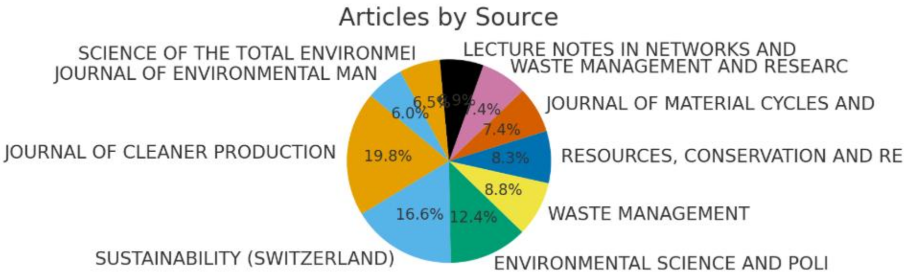


**Fig. 3.** Article produced by top sources

The pie chart in Figure 3 indicates the journals with the highest activity in terms of publishing research on environmental issues and sustainability. The Journal of Cleaner Production is at the forefront, so it can be assumed that it is one of the platforms consulted by researchers in the discipline. There is also a high presence of sustainability (Switzerland) and Environmental Science and Policy, which is evidence of increased attention to sustainable development. Other journals, such as Waste Management and Resources, Conservation and Recycling, add good information, although in small proportions. In general, the chart creates a clear image of the distribution of environmental research in the most prominent publications, with a focus on collaboration and innovation when addressing global ecological issues.

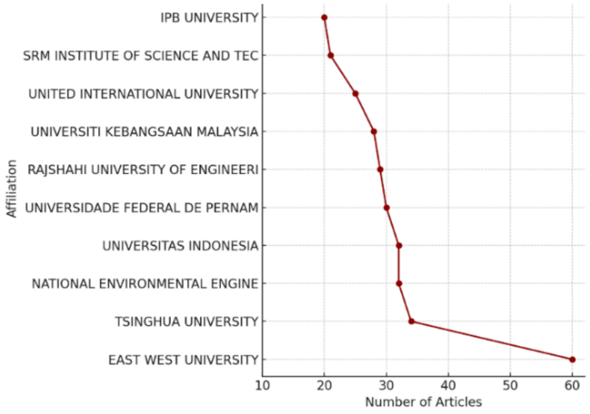


**Fig. 4.** Articles produced by Top Affiliations

Figure 4 shows the leading research-affiliated institutions that have contributed to e-waste management research. East West University tops with approximately 60 articles, and Tsinghua University and the National Environmental Engineering Institute have approximately 35 and 30 articles, respectively. Other players, such as Universitas Indonesia, Universidade Federal de Pernambuco, and IPB University, have moderate research outputs. This spread identifies high engagement at the regional level in Asia, especially in China, India, Indonesia, and Malaysia, and focuses on the development of academic interest in sustainable e-waste solutions and recycling innovations.

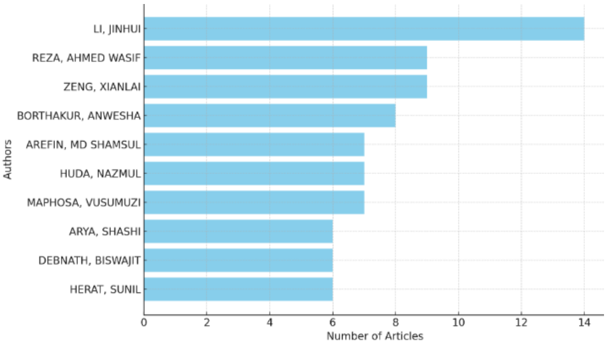


**Fig. 5.** Articles produced by Top Authors

Figure 5 presents the most prominent authors in E-waste Management research. Li Jinhui has the most publications with 14 publications and then comes Reza Ahmed Wasif and Zeng Xianlai with approximately 9 articles each. Borthakur Anwesha, Arefin Md Shamsul and Huda Nazmul have between 6 to 8 papers. This publication trend presents active international cooperation, and the authors have made a significant contribution, with researchers in China, Bangladesh, and India having a significant share in sustainable e-waste management research.

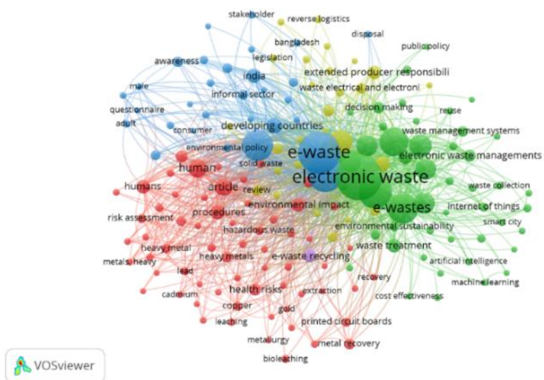


**Fig. 6.** Keyword Co-occurrence of author keywords

Keyword co-occurrence analysis (Figure 6) further validates the emerging presence of Industry 4.0 themes in the e-waste management research domain. Specific groups of terms related to artificial intelligence, IoT, blockchain, automation, smart waste management, and digital traceability signal that a technological change is occurring in a digitally integrated recycling ecosystem. Nonetheless, the visualization of the network demonstrates that these Industry 4.0-related keywords have relatively lower values of citation density and centrality in comparison to an overpowering tradable concept such as recycling, heavy metals, and environmental impact. This implies that digital technologies are gaining academic interest, but have yet to attain structural hegemony in the research network.

**Table 2.** Top Citations DOI's

| DOI | Total Citations |
|---|---|
| 10.1016/j.wasman.2016.08.004 | 679 |
| 10.1016/j.jclepro.2019.118815 | 400 |
| 10.1016/j.jclepro.2016.05.064 | 385 |
| 10.1016/j.wasman.2020.10.016 | 373 |
| 10.1016/j.envint.2016.10.002 | 366 |
| 10.1016/j.rser.2015.08.014 | 332 |
| 10.1016/j.spc.2018.01.002 | 310 |
| 10.1016/j.resconrec.2018.05.026 | 305 |

Table 2 highlights the most cited articles within the research topic of e-waste management, and the number of citations is high, indicating high scholarly impact. The article cited the most (DOI: 10.1016/ j.wasman 2016.08.004 ) had 679 citations, which allows emphasizing its influence. The range of other journals with high citations such as those in the Journal of Cleaner Production, Renewable and Sustainable Energy Reviews, and Waste Management range between 262-400 citations. Sustainability, recycling technologies, and the environmental impact are the main arguments of these papers, which indicates that the academic community is interested in the discussion of the strategies of a circular economy and the responsible attitude to e-waste. The growing number of references is the sign of the growing global topicality and interdisciplinary interest of the research on e-waste management.

**Table 3.** Top source's h, g, m indexes with citations and articles produced

| Source | h_index | g_index | Total Citations | Total Aricles |
|---|---|---|---|---|
| Journal Of Cleaner Production | 30 | 43 | 3493 | 43 |
| Environmental Science and Pollution Research | 19 | 27 | 1399 | 27 |
| Resources, Conservation and Recycling | 16 | 18 | 1122 | 18 |
| Sustainability (Switzerland) | 16 | 32 | 1069 | 36 |
| Science Of the Total Environment | 13 | 14 | 1330 | 14 |
| Waste Management | 12 | 19 | 1708 | 19 |
| Waste Management and Research | 10 | 16 | 313 | 16 |

The prevalence of journals like the Journal of Cleaner Production, Waste Management and Resources is a sign of the thematic concentration of e-waste research in the very well-known sustainability and environmental science journal arena. The h-index (30) and the total citations (3493) of the top journals signify their performance with the h-index over time and their intellectual maturity in the sphere. This is confirmed by the high g-index values since it has high-impact publications, and not a few highly cited publications. The uniformity of the academic control over the main journals in Table 3 suggests that e-waste management ceased to be a research problem of fragmented nature; it has become a research topic with policy implications. The presence of the key journals within the themes of circular economy, environmental risk, and resource efficiency also indicates that sustainability paradigms dominate the intellectual realm of the field, which in turn leads to its strategic importance in the research of waste governance at a global level.

## 4. Conclusion

This study offers a comprehensive overview of the evolving field of e-waste management, highlighting significant trends in research and technological advancements between 2015 and 2025. The increased number of publications is associated with the development of more efficient recovery technologies, including hydrometallurgical and bioleaching, and the implementation of Industry 4.0 technologies in recycling tasks, such as AI and robotics. Although such improvements have been made, the research also reveals that there are still significant gaps, particularly in developing countries, where informal recycling activities remain predominant. The findings reveal that further interdisciplinary research on sustainable practices, policy development, and worker safety is necessary. Moreover, the application of AI-related waste sorting, blockchain tracking, and IoT-enabled collectors has not been explored in depth, and they present significant research opportunities in the future. This research highlights the value of applying technological, environmental, and socio-economic approaches to solving the global e-waste problem and aiding in the transition to a circular economy.

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