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ELECTRONIC WASTE MANAGEMENT RESEARCH FRONTS AND EMERGING DIRECTIONS: A BIBLIOMETRIC ANALYSIS

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Abstract:

The rapid rise in electronic waste (e-waste) generation has arise as a major global environmental and sustainability issue, driven by inadequate management, recycling, as well as disposal of electronic and electrical equipment. As global consumption of digital devices continues to rise, research on e-waste management has expanded substantially; however, the field remains fragmented, with a limited understanding of its knowledge structure, evolution, and emerging research directions. This study aims to chart and analyze worldwide research trends, influential authors, countries, as well as thematic developments in e-waste management through a bibliometric approach. Data were collected from the Scopus database employing the advanced search string TITLE ("electronic waste" OR "e-waste" OR "WEEE" AND "management"), limited to English-language publications between 2020 and 2025. The final refined dataset comprised 598 articles, which served as the foundation for analysis. The Scopus Analyzer was employed to extract and visualize statistical patterns such as annual publication growth, authorship distribution, and country contributions. OpenRefine was utilized to clean and harmonize bibliographic data, ensuring consistency and accuracy, while VOSviewer software was used to perform network visualizations of co-authorship, keyword co-occurrence, and citation linkages. The results revealed a sharp increase in research output after 2020, with India, China, and the United States emerging as leading contributors. Frequently occurring keywords included electronic waste, recycling, sustainable development, circular economy, and environmental management, indicating strong alignment with sustainability and policy-oriented research. The visualization maps further identified six major research clusters encompassing technological innovation, environmental health, policy implementation, and circular resource recovery. Overall, this study provides a comprehensive overview of global research dynamics in e-

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waste management, offering valuable insights into current research fronts and emerging directions that can inform future policy, industry practice, and academic collaboration.

Keywords:

E-waste Management, Bibliometric Analysis, VOS viewer, Scopus Data

Introduction

The swift progress of technology and widespread use of electronic devices have resulted in a marked increase in electronic waste (e-waste) generation, introducing substantial environmental as well as health challenges. Here, e-waste encompasses disposed electronic and electrical equipment, which consists of both toxic and valuable materials. The inadequate disposal and management of e-waste have become critical global concerns, necessitating innovative and sustainable solutions. This study aims to explore the research fronts and emerging directions in e-waste management through a comprehensive bibliometric analysis. By examining the current trends, key themes, and upcoming research orientations, this analysis provides useful findings into the evolving landscape of e-waste management and highlights the importance of interdisciplinary approaches to address this pressing issue.

The management of e-waste has attracted substantial attention recently, with an expanding body of literature dedicated to understanding and addressing the obstacles connected with e-waste generation and disposal. A bibliometric analysis of 441 peer-reviewed papers between 2012 and 2021 revealed key themes such as recycling, sustainability, and circular economy, with economy, policy, environmental, social, as well as technology identified as the five dimensions of enablers in e-waste management (Soesanto et al., 2023). The analysis also highlighted the importance of policy and human health, particularly in developing countries, where e-waste management strategies are vital for reducing environmental and health issues (Soesanto et al., 2023).

The international output of e-waste exceeded 52 million metric tonnes in 2020, with only 20% being properly recycled, underscoring the need for effective management strategies (Maphosa & Maphosa, 2022). Research hotspots in the field have evolved, focusing on soil, health, environmental effect, recovery, as well as waste electronic and electrical equipment (Maphosa & Maphosa, 2022). The shift towards circular economy principles and the development of sustainable recycling technologies are critical for discussing the environmental as well as socio-economic consequences of e-waste (Le et al., 2023). China has appeared as a major contributor to e-waste recycling research, with significant advancements in the recovery and recycling of materials from discarded electronic devices (Le et al., 2023).

Technological innovation plays a pivotal role in e-waste management, offering inventive solutions for the collection, reprocessing, and disposal of outdated electronic equipment. The integration of artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) in automated e-waste processing has shown promise in optimizing recycling processes and reducing environmental impacts (Vijayalakshmi et al., 2024). Additionally, the application of biotechnological approaches, such as bioleaching, was explored for the recovery of valuable metals from e-waste, highlighting the potential for eco-friendly and sustainable recycling methods (Priya, 2024). The shift towards a circular economy, which emphasizes the reuse,

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remanufacturing, as well as recycling of electronic devices, is crucial for minimizing e-waste generation and fostering resource efficiency (Cui & Jørgen Roven, 2011).

Despite the advancements in e-waste management technologies, several setbacks remain, which include the lack of uniform regulations, improper infrastructure, as well as high costs associated with recycling processes (Elgarahy et al., 2024). The informal recycling sector, particularly in developing countries, have substantial issues to human health as well as the environment given the deploy of toxic pollutants (Owusu-Sekyere & Aladago, 2023). Addressing these setbacks requires a comprehensive approach that includes the development of effective policies, the incorporation of the informal sector into formal recycling systems, and the promotion of consumer awareness and education (Ahirwar et al., 2025). Extended producer responsibility (EPR) plays a vital role in encouraging sustainable approaches to product design, disposal, and recycling, thereby enhancing e-waste management (Ilyassova et al., 2021).

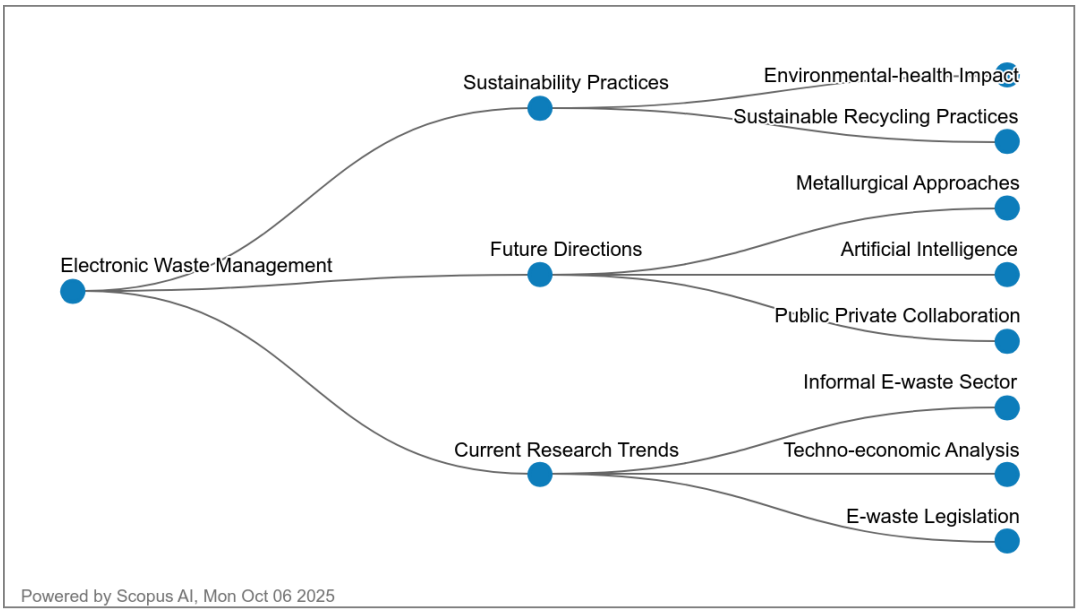

Figure 1: Thematic Map of Emerging Research Clusters in Electronic Waste Management

Source: Scopus.com

Figure 1 shows a conceptual mapping of Electronic Waste Management that reveals three major thematic clusters that represent the evolution and focus of research in this field. The first cluster, Sustainability Practices, highlights the integration of environmental health impact and sustainable recycling practices, emphasizing the global shift toward eco-friendly and circular approaches. The second cluster, Future Directions, underscores the role of emerging technologies and collaborations through artificial intelligence, metallurgical approaches, and public–private partnerships, signifying innovation-driven strategies for efficient e-waste handling. Meanwhile, the third cluster, Current Research Trends, encompasses critical issues such as the informal e-waste sector, techno-economic analysis, and e-waste legislation, reflecting ongoing efforts to balance economic viability with regulatory enforcement. Overall, the figure illustrates a clear trajectory of e-waste research moving from environmental

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sustainability to technological advancement and governance integration, suggesting a multidisciplinary approach as the foundation for future progress.

To conclude, the management of e-waste is an intricate issue that requires coordinated efforts from policymakers, researchers, and industry stakeholders. The incorporation of advanced technologies, the adoption of circular economy principles, and the development of effective policies are essential for addressing the environmental and health risks correlated with e-waste. Upcoming studies should emphasize on optimizing recycling processes, exploring innovative and cost-effective solutions, and promoting sustainable practices to ensure a more sustainable and economically viable future for e-waste management.

Research Questions

RQ1: What are the research trends in these studies according to the year of publication?
RQ2: What are the top 10 most cited articles?
RQ3: Where are the top 10 countries based on the number of publications?
RQ4: What are the popular keywords related to the study?
RQ5: What are the co-authorship by countries' collaboration?

Methodology

Bibliometrics is a systematic methodology for gathering, organizing, and analyzing bibliographic data obtained from scientific publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). While conventional bibliometric indicators often emphasize descriptive measures such as determining core journals, tracking publication years, as well as profiling leading authors (Wu & Wu, 2017), contemporary approaches extend further by employing cutting-edge methods such as document co-citation analysis to map intellectual linkages and research frontiers. Conducting a strong literature review, therefore, demands a iterative and systematic process that includes choosing precise keywords, refining search strategies, and carrying out in-depth analysis to ensure comprehensive coverage and reliable results (Fahimnia et al., 2015). Building on this framework, the current study deliberately focused on influential publications, acknowledging their ability to provide meaningful findings into theoretical frameworks that guide the development of the field. To ensure accuracy, Scopus was selected as the principal database due to its global scope and scholarly reliability (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). Furthermore, to retain methodological rigor, only peer-reviewed journal articles published between 2020 and 2025 were included, while books and lecture notes were omitted to preserve quality and consistency (Gu et al., 2019).

Data Search Strategy

The data collection for this bibliometric study on electronic waste (e-waste) management was conducted using the Scopus database, accessed in October 2025 through its advanced search feature to ensure accuracy and reproducibility. The search string applied was TITLE (("e-waste" OR "electronic waste" OR "WEEE") AND "management") AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (LANGUAGE , "English")). This search strategy was carefully designed to retrieve documents specifically focused on e-waste management, combining relevant synonyms such as electronic waste, e-waste, and WEEE (Waste Electrical and Electronic Equipment) to capture the broadest scope of research while maintaining

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thematic precision. To ensure the inclusion of the most current studies and technological developments, the publication years were limited to 2020–2025, a period that reflects heightened global awareness of sustainability, circular economy initiatives, and e-waste policy reforms. The dataset was restricted to English-language publications to maintain consistency and comparability across research outputs. Throughout the screening phase, exclusion and inclusion criteria were applied; only English publications within the 2020 - 2025 timeline were considered, while non-English documents and those published before 2020 were excluded. The ultimate refinement of search strings consisted of 598 articles that were utilised in the bibliometric analysis. This rigorous selection process ensured that only relevant, high-quality, and recent studies were included, resulting in a final dataset that accurately represents the evolving landscape of e-waste management research. The curated dataset serves as the foundation for subsequent bibliometric and visualization analyses, providing insights into research trends, collaboration networks, and emerging themes within the global e-waste management field.

Table 1: The Search String

Scopus	TITLE ((e-waste OR electronic waste OR WEEE) AND management) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (LANGUAGE , "English"))
Access date: October 2025	

Table 2: The Selection Criterion In Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2020 – 2025	< 2021

Data Analysis

VOSviewer is a commonly recognized bibliometric software designed by Nees Jan van Eck and Ludo Waltman at Leiden University, Netherlands [24], [25]. Developed for accessibility and analytical depth, the tool has become a standard in visualizing as well as exploring scientific literature. It focuses in producing user-friendly network visualizations, clustering related items, as well as generating density maps, which allow scholars to investigate co-authorship, co-citation, and keyword co-occurrence networks. These features provide a thorough overview of research landscapes, while their interactive design combined with continuous updates ensures efficient and dynamic analysis of extensive datasets. With the capability to measure bibliometric metrics, customize visualizations, as well as integrate data from multiple sources, VOSviewer remains a valuable tool for scholars examining complex domains of knowledge.

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One of its key strengths is its capability to change intricate bibliometric datasets into visually interpretable charts and maps. With a focus on network visualization, VOSviewer efficiently clusters pertinent items, evaluates keyword co-occurrence, as well as generates density maps that uncover underlying patterns in scientific output. Its adaptability makes it suitable for both novice and experienced researchers, while ongoing development ensures it stays at the forefront of bibliometric applications. In this research, datasets comprising publication year, title, author names, journals, citations, as well as keywords were retrieved in Plain Text format from the Scopus database, covering the period from 2020 to December 2025. These datasets were assessed employing VOSviewer version 1.6.20, employing clustering and mapping techniques to create visual knowledge maps. Unlike the traditional Multidimensional Scaling (MDS) approach, VOSviewer positions items in a low-dimensional space so that their proximity accurately mirrors their relatedness and similarity (van Eck & Waltman, 2010). While sharing conceptual similarities with MDS (Appio et al., 2014), it diverges by employing a highly effective normalization method for co-occurrence frequencies, namely the association strength (ASij), which is calculated as (Van Eck & Waltman, 2007).

$$AS_{ij} = \frac{C_{ij}}{w_i w_j}$$

which is "proportional to the ratio between on the one hand the observed number of co-occurrences of i and j and on the other hand the expected number of co-occurrences of i and j under the assumption that co-occurrences of i and j are statistically independent" (Van Eck & Waltman, 2007).

Findings

RQ1: What Are the Research Trends in These Studies According to The Year of Publication?

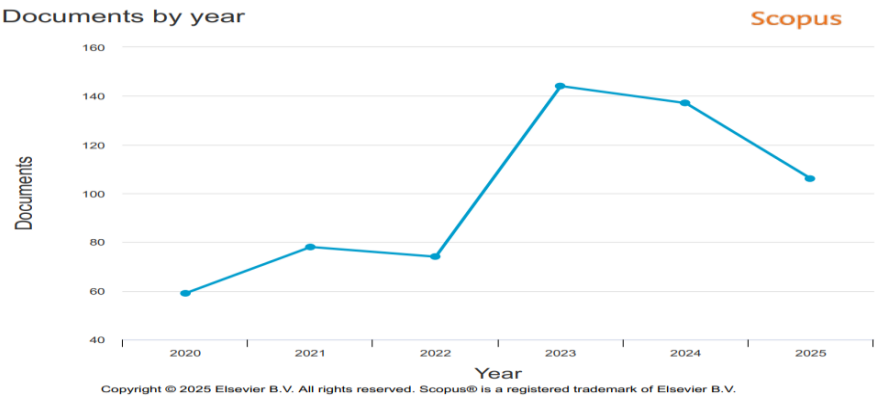

Figure 2: Number of Documents Based on Year of Publication

Source: Scopus.com

Figure 2 shows the publication trend on e-waste collection between 2020 and 2025, demonstrating a significant growth trajectory, with notable fluctuations that reflect shifting research priorities and global contexts. In 2020, the number of publications stood at 59, rising moderately to 78 in 2021 and 74 in 2022. A sharp increase occurred in 2023 with 144 documents, almost doubling the previous year's output, before stabilizing at 137 in 2024. Interestingly, 2025 shows a slight decline to 106, though still considerably higher than the

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output recorded in 2020–2022. Overall, the data reveal a clear upward momentum in academic interest in e-waste collection, underscoring its growing importance as both a research topic and a global sustainability concern.

Several factors explain this trend. The modest growth from 2020 to 2022 may be attributed to the disruption caused by the COVID-19 pandemic, where research funding and academic focus shifted temporarily toward health-related priorities. However, the surge in 2023 and 2024 aligns with increased international attention on sustainable development and circular economy initiatives, as many governments introduced stricter regulations and strategic frameworks for managing electronic waste. Moreover, technological advancements like IoT-enabled smart bins, blockchain traceability, and AI-driven waste management systems have expanded the scope of research, attracting interdisciplinary collaborations from environmental science, engineering, and social sciences. The slight dip observed in 2025 could reflect a natural correction following the publication boom, as well as the maturing of research themes where scholars consolidate findings rather than expand output. Nonetheless, the overall trend highlights that e-waste collection remains a dynamic and expanding field of study with strong potential for future exploration.

RQ2: What Are The Top 10 Most Cited Articles?

Table 3: The Most Cited from the Authors

Authors	Year	Source title	Cited by
Shittu et al. (2021)	2021	Waste Management	382
Rautela et al. (2021)	2021	Science of the Total Environment	283
Ahirwar & Tripathi (2021)	2021	Environmental Nanotechnology, Monitoring and Management	255
Dhir et al. (2021)	2021	Journal of Cleaner Production	245
Arya & Kumar (2020)	2020	Journal of Cleaner Production	241

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Parajuly et al. (2020)	2020	Resources, Conservation and Recycling	214
Sarojini & Kanchana, (2025)	2021	Environmental Technology and Innovation	210
Murthy & Ramakrishna (2022)	2022	Sustainability (Switzerland)	204
Gollakota et al., (2020)	2020	Journal of Environmental Management	182
Sharma et al. (2020)	2020	Environmental Science and Pollution Research	161

Table 3 depicts the top 10 most cited publications in e-waste management research reveal a concentration of highly influential works published between 2020 and 2022, with citations ranging from 161 to 382. The most cited paper is by Shittu et al. (2021), published in Waste Management, with 382 citations, reflecting its comprehensive global review of e-waste legislation, challenges, and future directions. Other frequently cited works, for instance, by Rautela et al. (2021) with 283 citations and Ahirwar & Tripathi (2021) with 255 citations, emphasize the health, environmental, and occupational hazards of e-waste, highlighting the urgent societal relevance of these issues. Behavioral dimensions of e-waste management are also represented, as seen in Dhir et al. (2021) (245 citations) and Parajuly et al. (2020) (214 citations), underscoring the importance of consumer behavior and recycling motivation in circular economy transitions. Collectively, the dominance of review articles and conceptual frameworks demonstrates that the most impactful contributions are those that synthesize knowledge, map global challenges, and provide policy or behavioral insights with broad applicability.

The reasons behind these citation patterns lie in both the timing and scope of these publications. The period between 2020 and 2022 coincided with an acceleration of global discourse on sustainability and the circular economy, with e-waste emerging as a critical issue due to increasing digitalization and short device life cycles. Papers focusing on human health, environmental hazards, and recycling processes gained rapid traction, particularly in journals with high visibility like Science of the Total Environment and Journal of Cleaner Production. Furthermore, works addressing behavioral change (e.g., recycling motivations) and governance frameworks attracted cross-disciplinary citations from environmental science, social sciences,

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and policy studies. Regional studies, such as Arya & Kumar (2020) and Sharma et al. (2020), also gained attention by contextualizing global issues within emerging economies like India, where e-waste challenges are acute. Thus, the high citation counts of these papers reflect both their thematic alignment with global sustainability goals and their ability to provide integrative perspectives that guide research, policymaking, and practical solutions in e-waste management.

RQ3: Where Are The Top 10 Countries Based On The Number Of Publications?

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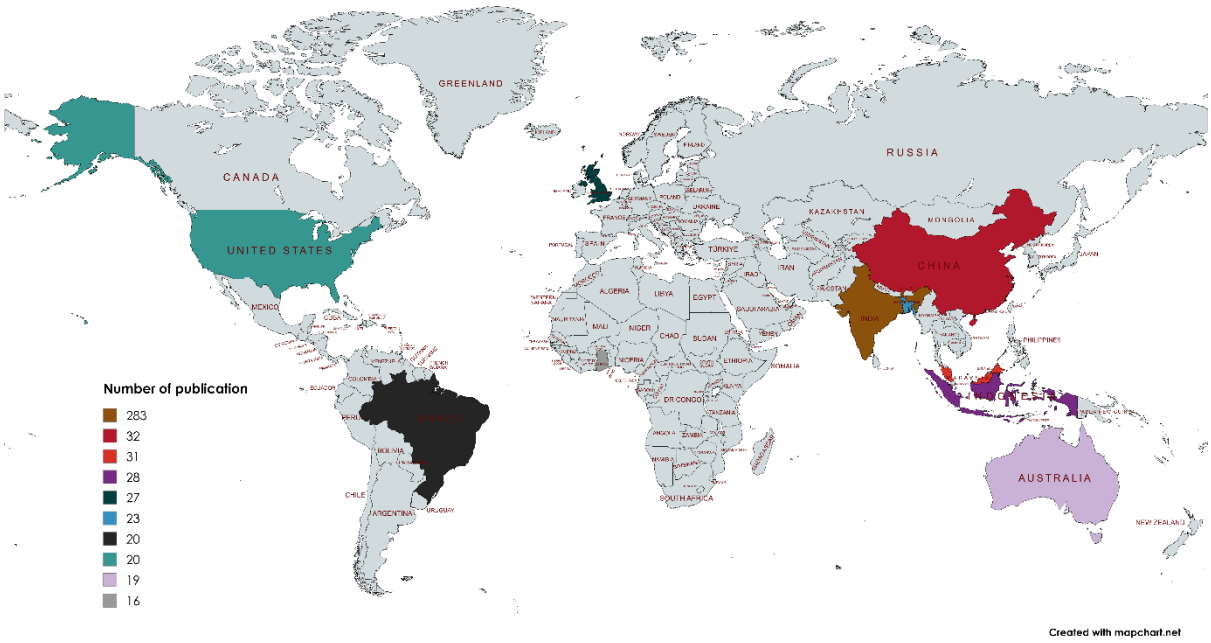

Figure 3: Global Distribution Of E-Waste Management Research Publications

The geographical distribution of publications on electronic waste management, as shown in Figure 3, reveals that India dominates global research output with 283 publications, significantly surpassing other nations. This is followed by China (32), Malaysia (31), Indonesia (28), and the United Kingdom (27), which represent key research hubs in Asia and Europe. Countries such as Bangladesh (23), Brazil (20), the United States (20), Australia (19), and Ghana (16) also contribute actively, though at lower magnitudes. The concentration of publications in Asian countries, particularly India and China, highlights the regional urgency of addressing e-waste generation and informal recycling practices, as both nations are among the world's largest producers and processors of discarded electronics. The involvement of countries such as Malaysia and Indonesia indicates growing academic interest in Southeast Asia, likely influenced by industrial expansion, importation of second-hand electronics, and emerging environmental regulations.

The results can be explained by several underlying factors. In India, strong research activity corresponds with national initiatives such as the E-Waste (Management) Rules 2016 and its subsequent amendments, which have encouraged studies on collection, recycling, and policy frameworks. Similarly, China's academic engagement stems from its dual role as a major electronics manufacturer and recycling hub, driving investigations into sustainable disposal and circular economy strategies. Malaysia and Indonesia's participation reflects growing

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regional collaboration on waste management under the ASEAN frameworks. Meanwhile, contributions from developed countries like the United Kingdom, the United States, and Australia are largely policy- and technology-driven, focusing on formalized recycling systems, life-cycle assessments, and sustainable innovation. The inclusion of nations like Ghana and Brazil signifies growing recognition of e-waste as a global environmental and socio-economic challenge, with these countries serving as focal points for studies on informal sector recycling, environmental health impacts, and transboundary waste flows. Collectively, the data demonstrate that e-waste management research is no longer geographically confined but rather represents a globally interconnected research domain shaped by economic development, regulatory enforcement, and environmental sustainability agendas.

RQ4: What Are the Popular Keywords Related to The Study?

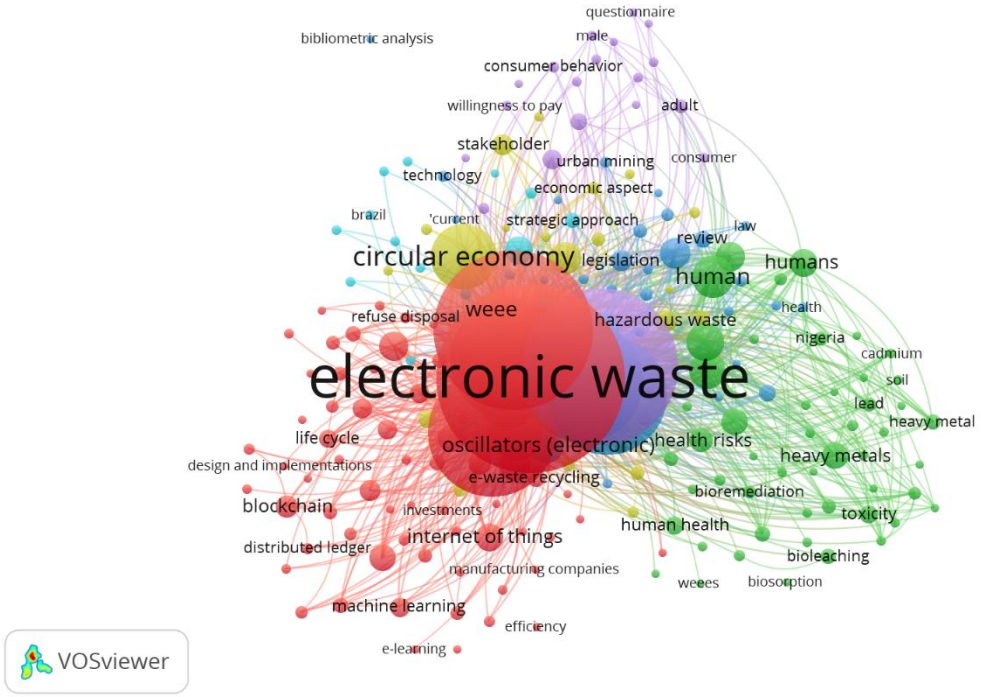

Figure 4: Network Visualization Map of Keywords' Co-occurrence

Co-occurrence analysis in bibliometrics refers to the study of how often two or more keywords appear together within a set of documents, and when applied to author keywords in VOSviewer, it helps map the conceptual structure of a research field by representing keywords as nodes and their relationships as links, where larger nodes reflect frequent terms and thicker links show stronger associations. In this study, the network visualization, as Figure 4, was developed utilising the full counting method, where every keyword occurrence is equally weighted, with a minimum threshold of five occurrences; from 2000 identified keywords, 219 met this threshold, and by setting a minimum cluster size of five, six clusters were formed to represent different thematic subdomains. The results highlight dominant keywords such as "electronic waste" (344 occurrences, link strength 3040), "waste management" (274; 2190), "e-waste" (267; 2236), "recycling" (190; 1814), and "sustainable development" (186; 1518), reflecting research concentration on sustainability frameworks and resource recovery strategies. Sub-themes, including circular economy, informal sector, and extended producer responsibility,

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alongside region-specific keywords like India, Ghana, and Nigeria, show the integration of both global policies and local case studies. At the same time, the presence of emerging technology-driven terms such as Internet of Things, artificial intelligence, blockchain, and machine learning reflects the growing application of smart and digital solutions in e-waste management, while health- and environment-related terms like toxicity, heavy metals, and public health underscore societal and ecological risks. Altogether, the analysis contributes to the body of knowledge by identifying core research fronts, emerging interdisciplinary directions, and policy–technology linkages, thereby offering valuable findings for future studies and sustainable e-waste management practices.

RQ5: What Are The Co-Authorship By Countries' Collaboration?

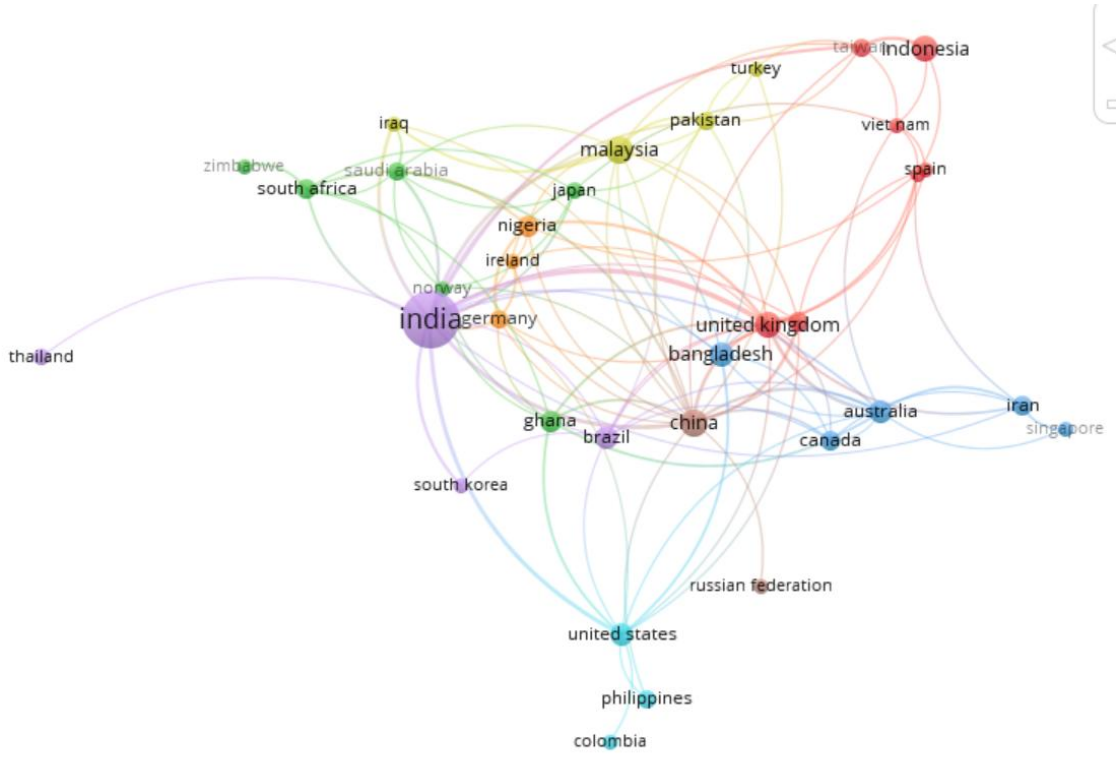

Figure 5: International Research Collaboration Based On Co-Citation Between Countries

Figure 5 shows the co-authorship analysis of e-waste research using VOSviewer reveals distinct global collaboration patterns, with India emerging as the dominant contributor, producing 284 documents, 3,331 citations, and the largest total link strength (55), underscoring both its productivity and extensive international partnerships. Employing the complete counting method with a minimum threshold of five documents, 34 out of 81 identified countries met the criteria, and by applying a minimum cluster size of five, the visualization generated eight clusters of collaborating nations. Countries such as the United Kingdom (27 documents, 739 citations, TLS 36) and China (32 documents, 539 citations, TLS 33) also demonstrate strong influence and active global linkages, while Malaysia, Nigeria, and Ghana represent emerging but increasingly important contributors due to their pressing local e-waste challenges

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and growing research capacity. Developed countries, including the United States, Germany, and Australia, remain significant in terms of citations and expertise but show relatively lower link strengths, suggesting more limited international co-authorship compared to India or the UK. The presence of active research from Africa (e.g., South Africa, Nigeria, Ghana) and Asia (e.g., Bangladesh, Indonesia, Vietnam) indicates that e-waste research is globally distributed, driven both by problem-oriented needs in developing countries and innovation in advanced economies. Collectively, these findings demonstrate that e-waste management has evolved into a global scientific agenda, where cross-country collaboration serves a crucial role in advancing knowledge, sharing expertise, and addressing sustainability challenges across diverse socio-economic contexts.

Conclusion

The primary goal of this study was to map and evaluate global research trends, knowledge structures, and emerging directions in electronic waste management using bibliometric techniques. Through an extensive analysis of 598 Scopus-indexed journal articles published from 2020 to 2025, the research aimed to identify publication trends, leading countries, influential works, and evolving thematic areas in this field. The findings revealed that the volume of scientific output on e-waste management has grown significantly in recent years, reflecting heightened global attention toward sustainability and circular economy initiatives. India, China, and the United States arise as the most active contributors, supported by strong policy frameworks, technological advancements, and growing environmental awareness. Core research themes identified through keyword co-occurrence and co-authorship analyses include sustainable development, recycling processes, circular economy, environmental management, and technological integration, such as IoT, artificial intelligence, and blockchain. These results indicate a transition from traditional waste treatment studies toward data-driven, policy-supported, and interdisciplinary approaches.

This bibliometric investigation contributes to the existing body of knowledge by offering a structured overview of how the e-waste management domain has evolved and where it is heading. The analysis extends prior literature by synthesizing fragmented research efforts and highlighting the interconnection between environmental sustainability, technological innovation, and policy development. In practical terms, the findings provide a foundation for policymakers, industry stakeholders, and academic institutions to design evidence-based strategies that promote sustainable e-waste practices, strengthen recycling infrastructure, and integrate digital tools into waste monitoring systems.

However, this study acknowledges certain limitations. The analysis relied solely on the Scopus database, which may exclude relevant publications indexed elsewhere. Moreover, the focus on English-language articles may limit regional perspectives, particularly from non-English-speaking countries with active e-waste management initiatives. Future research could expand this scope by incorporating multi-database analyses, applying longitudinal mapping across extended timelines, and integrating scientometric indicators such as citation bursts or thematic evolution tracking. Such efforts would provide deeper insights into the shifting intellectual landscape of e-waste research.

In summary, the bibliometric evidence confirms that electronic waste management is an increasingly dynamic and multidisciplinary research domain with direct implications for environmental policy, industrial innovation, and societal well-being. The study underscores the

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importance of bibliometric analysis as a strategic tool for understanding global research patterns, identifying gaps, and guiding future scientific inquiry. Continued exploration of technological, behavioral, and policy-driven approaches will be essential for fostering sustainable solutions to the escalating e-waste challenge worldwide.

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