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Recycling E-Waste and the Sustainable Economy: A Bibliometric Exploration

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Abstract: In an era marked by rapid technological advancements and the pervasive presence of the electronics industry, electronic waste (E-waste) has become a prominent global concern. This study utilizes a rigorous bibliometric analysis to thoroughly investigate the extensive body of literature in this field, shedding light on the current state of research and development in E-waste recycling. The study dissects and visualizes research trends, trajectories, and advancements. It meticulously examines a dataset comprising 3267 records extracted from the Web of Science Core Collection, specifically the Science Citation Index Expanded. The analysis highlights China's pivotal role in E-waste recycling research, contributing 41% of the total research papers in this field. Additionally, the British journal 'Waste Management' emerges as a standout among academic publications, with an impressive count of 241 articles, constituting 7.38% of the entire corpus. Notably, Zeng, X.L., emerges as the most co-cited author, underscoring their significant influence and contributions to the scholarly discourse. Tracing the evolution of E-waste recycling research from 1990 to 2022, the study uncovers the field's inception in 1993 when the first research paper on this subject was published. This nascent domain has since experienced exponential growth, culminating in an impressive 408 papers published in 2022. The research identifies and distills three compelling research trends that have captured significant attention within the E-waste recycling domain. Firstly, it highlights the paramount concern regarding the environmental impact of organic pollutants from E-waste, emphasizing the urgent need for sustainable solutions. Secondly, it delves into the intricate issue of managing and recycling E-waste in developing countries, where unique challenges necessitate innovative approaches. Lastly, the analysis underscores the growing interest in recovering and recycling materials from discarded electronic devices, highlighting the imperative necessity of harnessing the valuable resources within E-waste. In synthesis, this research not only provides an overview of the current landscape of E-waste recycling but also offers a clear path forward for future studies and interventions. It serves as a critical guide for addressing the environmental and socio-economic repercussions of E-waste, ultimately fostering a more sustainable and economically viable future.

Keywords: E-waste recycling; bibliometric analysis; research trends; environmental impact; sustainable solutions

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1. Introduction

The current period is characterized by swift technical progress and the growing prevalence of electronic gadgets, giving rise to a noteworthy global issue known as electronic waste or E-waste [1]. The environmental consequences of this phenomenon are significant, as it is fueled by shortened product lifecycles and widespread use of consumer electronics [2]. Concurrently, electronic waste (E-waste) represents a complex convergence of environmental preservation and commercial viability [3]. E-waste refers to the collective category of electronic products that have been abandoned, including computers, office equipment, electronic entertainment devices, mobile phones, televisions, and refrigerators. According to Shagun and Arora [4], the term "used electronic devices" refers to electronic equipment that are intended for various purposes such as reuse, resale, rescue, recycling, or disposal. The range of E-waste encompasses a broad spectrum, including consumer electronics such as smartphones and laptops, as well as intricate industrial machinery [5,6].

Significantly, it is worth noting that E-waste frequently comprises valuable resources such as rare metals and reusable components, highlighting its dual nature as both a hazardous waste stream and a potential economic asset [7,8]. According to Finnveden and Johansson [9], the management of E-waste is crucial from both an ecological standpoint and as a means to achieve sustainable economic development. Based on the findings of the Global E-waste Monitor, it is evident that the global production of E-waste reached a staggering 53.6 million metric tons in 2019 [10]. This figure represents a concerning growth rate of 21% during five years. According to projections, the generation of E-waste is anticipated to exceed 74 million metric tons by 2030, exhibiting a nearly twofold increase within 16 years. According to a study by Forti and Balde [10], the observed rise corresponds to an estimated annual generation of nearly 2 million metric tons of electronic garbage. The enormous quantity of E-waste raises concerns over its environmental impact. Inadequate waste management techniques can influence the environment and public health significantly. Consequently, there is a need to develop waste-to-energy and recycling technologies [11–13]. Although burning is a frequently employed approach for waste-to-energy conversion, recycling is less efficient and more expensive than incineration [14].

The act of recycling encompasses a thorough procedure that encompasses the gathering, categorization, treatment, and application of discarded materials to produce fresh goods. An example is recycling steel, which has yielded notable energy conservation, diminished air pollution, reduced water consumption, lowered water contamination, minimized mining residue, and lessened reliance on primary resources [15] (Cui and Forssberg, 2003). The contribution of recycling E-waste to environmental preservation and its good impact on the economy is apparent, in contrast to the alternative of disposing of it in landfills. According to Lasoff [16], recycling technologies can preserve essential resources, decrease energy consumption, and mitigate environmental consequences.

Scholars from various countries have investigated various facets of E-waste recycling. These investigations have encompassed topics such as recycling techniques employed in the manufacturing sector of developing nations [7,17] as well as the examination of consumer behavior regarding E-waste recycling [18–20]. Nevertheless, there is a need for more scholarly articles that have thoroughly examined the present state and anticipated future directions about E-waste. This deficiency is particularly evident in the limited utilization of bibliometric analysis techniques to offer a complete field survey.

The present study utilizes bibliometrics as a quantitative methodology to analyze scholarly articles. The ability to identify trends, growth trajectories, and critical contributions within academic disciplines has become increasingly prominent [21]. When applied within the context of E-waste study, this approach provides a distinctive viewpoint for comprehending the complex dynamics associated with this crucial topic. The objective of our research is to examine the changing academic environment in the field of E-waste by utilizing bibliometric techniques. Our study will focus on identifying essential contributors to the field and identifying emergent research topics. Furthermore, our research aims to investigate the mutually beneficial association between managing E-waste and sustainable economic paradigms. The primary research goals that guide our work are: (1) to identify the nations and academic publications that have the most extraordinary proclivity towards investigating the domain of E-waste recycling; (2) to explore the authors, journals, and referenced papers that exhibit the highest co-citation rates within the domain of E-waste recycling; (3) to examine the progression of research on the recycling of E-waste from the year 1990 to 2022; (4) to examine the prevailing research concerns within the global domain of E-waste recycling; (5) to offer significant insights into the complex landscape of E-waste research and its role in promoting sustainable economic development, using rigorous bibliometric analyses that include academic publications, citation networks, and co-authorship patterns; (6) to find out the ecological impact of electronic consumption and disposal, emphasizing the pressing need to address the issue of E-waste [22].

Our work highlights the growing scope of E-waste research, emphasizing the urgent requirement for well-informed policies and industry practices that rely on evidence to address the environmental consequences and capitalize on economic prospects. In the ensuing sections, the study shall delineate our chosen data collection and analysis methodology, present the discerned findings from the E-waste bibliometrics scrutiny, and expound upon the sustainable economy perspective within this context. It seeks to contribute substantively to comprehend E-waste management challenges and provide actionable recommendations to guide decision-makers, researchers, and industry stakeholders toward a more sustainable and prosperous future.

2. Literature Review

E-waste recycling represents a critical domain within waste management, with significant environmental and economic implications. Researchers from various regions and nations have undertaken many studies addressing diverse aspects of E-waste recycling. The literature review provides an in-depth examination of the existing body of knowledge and research in E-waste recycling and its implications for building a sustainable economy.

2.1. E-Waste Recycling: A Sustainable Imperative

Recycling E-waste offers an eminently sustainable alternative to traditional disposal methods such as incineration or landfilling [23]. This practice involves the systematic collection, disassembly, and recovery of valuable materials from discarded electronic devices [24]. These materials, ranging from precious metals like gold and copper to various plastics, can then be reintegrated into the production cycle, thus reducing the need for virgin resources and minimizing the environmental footprint of electronics manufacturing [25]. By adhering to the principles of a circular economy, E-waste recycling not only curtails the depletion of natural resources but also mitigates the environmental impact associated with mining and manufacturing new electronics [26].

2.2. E-Waste Recycling Behavior

The influence of consumer behavior is significant in determining the dynamics of E-waste recycling. The paper of Arain and Pummill [18] investigated the impact of consumers' choices and preferences on the demand for new electronic devices and the subsequent disposal of obsolete ones. Consumer choices surrounding the management of electronic trash encompass more than technology preferences. These decisions are intricately linked to environmental awareness, as well as perceptions of convenience and risk. Bai and Wang [19] highlighted the significance of consumer data security concerns in the context of smartphone recycling. The study's findings indicate that consumers place a high level of importance on protecting their personal and sensitive data when disposing of electronic gadgets. The findings above highlight the necessity of implementing secure data erasure procedures and emphasize the significance of consumer education in advocating for the recycling of electronic trash. Zhang and Wu [27] investigate the impact of risk perception on consumer behavior. Consumers who possess an increased perception of risk, specifically in the safeguarding of data privacy and security, need more motivation to participate in E-waste recycling endeavors. This observation underscores the need to acknowledge customer apprehensions and foster a sense of confidence in recycling procedures. A study by Islam and Huda [20] provides insight into the diverse aspects that impact consumer decision making regarding E-waste recycling. The factors encompassed in this context are the presence and ease of access to recycling facilities, educational endeavors, awareness campaigns, and the economic dimensions associated with recycling. The research highlights the necessity of implementing comprehensive logistical and awareness-building measures to promote E-waste recycling behaviors.

2.3. Research Trends in E-Waste Recycling

Within the domain of E-waste recycling, several discernible research trends have emerged, signifying the multifaceted nature of this field and its potential to foster a sustainable economy.

A significant body of research is dedicated to assessing the environmental consequences of E-waste recycling [24]. Scholars meticulously scrutinize the release of organic pollutants and hazardous substances into the environment, emphasizing the urgent need for sustainable solutions. Studies delve into issues such as organic pollutants from incineration processes, heavy metal contamination from improperly disposed E-waste, and the effect of flame retardants on environmental safety [26].

Another prominent trend focuses on the unique challenges and opportunities associated with E-waste recycling in developing countries [28]. In these regions, less stringent regulations and inadequate infrastructure pose distinctive challenges in managing E-waste. Research in this vein seeks innovative approaches, such as informal sector participation, to address these challenges [24]. The intersection of sustainable recycling practices, resource recovery, and socio-economic development becomes a focal point for exploration.

The recovery and recycling of valuable materials from discarded electronic devices are central to discussions of sustainability [23]. Researchers within this trend explore methods to maximize resource utilization and minimize the environmental impact through circular economy practices [26]. Techniques for materials recovery, such as the extraction of precious metals and efficient recycling processes, feature prominently in this research theme [24].

3. Research Methods

3.1. Data Collection

The data were extracted from the Web of Science (WoS) Core Collection database on 14 July 2023. The steps involved in data collection, processing, and analysis are as follows. In Step 1, the research used the following search formula with TS (Topic Search) as the abbreviated keyword for the WoS database where TS = (recycle OR recycling) AND TS = (electrical waste OR electrical wastes OR electronic waste OR electronic wastes OR e-waste OR waste electrical OR wastes electrical OR waste electronic OR wastes electronic OR electronic rubbish OR electronic garbage OR electrical rubbish OR electrical garbage OR waste electrical and electronic equipment).

In step 2, the data research are filtered, retaining only records extracted from the Science Citation Index Expanded (SCIE) category within the WoS database. The search and data extraction processes were conducted on the same day to avoid discrepancies in search results due to database updates within the WoS system. Furthermore, the team did not apply additional filters for article language, document type, or data classification, and included articles from various publication years.

3.2. Research Methodology

Bibliometric analysis is an innovative and quantitative methodology used to explore the realm of E-waste recycling. This approach allows researchers to uncover, analyze, and map the scholarly landscape of E-waste research [29]. Bibliometrics, a branch of scientometrics, applies quantitative and statistical methods to analyze scientific publications, citations, and collaboration networks [30]. By doing so, it assists in identifying critical research trends, influential authors, pivotal journals, and emerging topics within the domain [31]. Over the years, bibliometric analyses of E-waste recycling research have made substantial contributions to the field [1]. These studies provide comprehensive insights into the evolution of research trends over time, highlighting the geographic distribution of research activities [32]. Moreover, they help identify prolific authors and co-citation networks, thereby indicating influential figures in the field [33]. Additionally, these analyses aid in the recognition of top journals publishing research on E-waste recycling, offering valuable guidance to scholars, researchers, and practitioners [34].

3.2.1. Co-Citation Analysis

This method is employed in academic research to examine the relationships between scholarly articles based on their co-citation patterns. Co-citation analysis is a widely recognized methodology employed to classify scientific papers into smaller clusters that pertain to distinct topics [35,36]. The present approach aims to identify document pairings that are commonly mentioned together in other scholarly publications, hence examining the cognitive structure of the respective academic discipline. The co-cited documents exhibit shared themes and insights, establishing a foundation for subsequent inquiry. The study utilized co-citation analysis to illustrate the intellectual framework surrounding E-waste in the context of E-waste recycling. Establishing a network of nodes and clusters to represent journal articles and scientific papers has facilitated the investigation of research trends and promoted interdisciplinary cooperation within the respective sector. Co-citation analysis has proven to be a beneficial method for gaining insights into the interconnections among authors, identifying research trends, and highlighting significant challenges in E-waste recycling.

3.2.2. Analysis of Co-Occurrence

The co-occurrence analysis emphasizes the occurrence of keywords inside papers and articles, intending to uncover conceptual linkages by observing the frequent occurrence of particular terms [37]. Keywords play a fundamental role in comprehending the primary themes of a research subject and are utilized by authors to encapsulate the core principles of their work. The approach was employed in the study to examine the co-occurrence patterns of critical terms such as E-waste, recycling, and E-waste disposal. The present study facilitated the identification and exploration of crucial research issues, their interconnections, and the comprehensive extent of research on E-waste recycling. The utilization of co-occurrence analysis offered an enhanced viewpoint on the research landscape, facilitating a more profound comprehension of the interconnections between aspects pertinent to the recycling of E-waste.

3.2.3. Analysis of the Topic

The utilization of topic analysis, a technique in natural language processing (NLP), was implemented to identify and extract the main subjects or themes from the research corpus. The proposed methodology is designed to detect and condense core subjects within the given dataset autonomously. Topic analysis is commonly conducted using two primary methods: topic classification and topic modeling.

The process of topic classification entails categorizing documents into predetermined topic groups. The allocation of documents to specific subjects is based on a preset inventory, as stated by Rodrigues and Chiplunkar [38].

Topic modeling is a statistical technique that identifies latent themes or subjects within textual data without requiring a priori specification of specific topics. This process aids in identifying the primary themes present in the dataset and ascertaining the associated terms for each theme. According to a study conducted by Vayansky and Kumar [39], it is observed that each document has the potential to cover multiple themes to variable extents.

The study employed topic modeling to automatically detect and display the main subjects within the dataset on electronic trash. The utilization of this methodology, facilitated by sophisticated data analysis techniques, has facilitated the identification of crucial subject matters that may be explored in the realm of E-waste recycling.

Through the utilization of these approaches, the objective of the study was to offer a thorough examination of research on the recycling of E-waste, thereby illuminating significant topics, collaborations, and trends that exist within this domain.

4. Results and Discussion

4.1. Data Visualization

Based on the 3267 records extracted from the SCIE category in the WoS Core Collection, our team analyzed several characteristics of scientific research articles, including language and document type. Out of the total dataset, 3241 articles (99.20%) were written in the English language. This aligns with our expectations, as English is the widely adopted language for global communication and research. Table 1 presents a breakdown of the specific languages used in articles with two or more references in our dataset.

Table 1. Statistics of languages used in research papers with two or more citations on the topic of E-waste recycling.

Languages	Number of Docs	Ratios
English	3241	99.20%
Portuguese	6	0.18%
German	5	0.15%
Spanish	5	0.15%
Chinese	2	0.06%
Japanese	2	0.06%

In terms of document classification, the majority of the dataset consists of research papers categorized as articles, totaling 2736 papers (accounting for 83.75% of the dataset). Following that are review papers, amounting to 357 (comprising 10.93%). Other document classifications such as editorial material, letters, corrections, and others make up 5.32% of the total data. Table 2 and Figure 1 provide a comprehensive breakdown of the various document classifications present in the dataset.

Table 2. Document classification statistics.

Type	Documents
Article	2736
Review	357
Proceedings paper	61
Article; early access	38
Editorial material	23
Review; abstract	14
Meeting; abstract	12
News item	12
Letter	5
Correction	4
Review; book chapter	4
Retraction	1
Total	3267

Valuable insights into the leading countries in terms of research papers about E-Waste recycling are offered in Figure 2 and Table 3, as indicated by the data presented in Table 3. China, located in the Asian region, is particularly noteworthy for its leading position in terms of research papers. Specifically, China has a total of 1342 papers, which represents 41.08% of the overall 3267 records. The United States, in the North American continent, occupies the second position with 366 papers, accounting for 11.02% of the overall representation. India ranks second in the Asian region, following the United States, with 285 research papers, accounting for 8.72% of the overall research output. In addition to the aforementioned leading countries, several other nations, including Australia, the United Kingdom, and Japan, have made noteworthy contributions to E-waste recycling, producing more than 100 research papers. The top positions in this ranking are occupied by China, the United States, and India, primarily due to their significant contributions as major producers of E-waste on a global scale. The statement above highlights the criticality and significance of E-waste recycling as an imminent and top-level concern in these specific areas and jurisdictions.

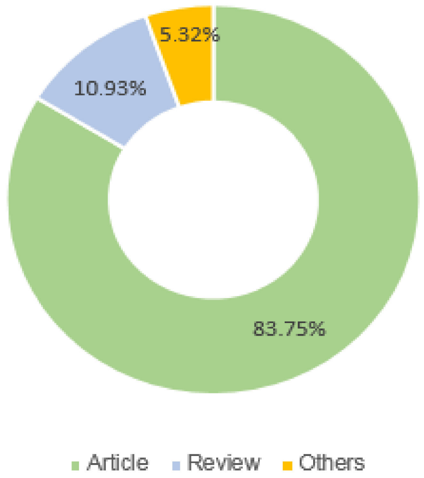

Figure 1. Classification of documents in papers on E-waste recycling.

Figure 2. A 3D map displaying the positions of the top 10 most publishing countries.

In the realm of scholarly journals dedicated to E-waste recycling, the research team has meticulously curated a catalog of the top 10 journals that have contributed in Table 4. Waste Management and Journal of Cleaner Production: These two U.K.-based journals lead the list with a high number of articles, 241 and 200, respectively. While Waste Management has a slightly higher H-index (201), the Journal of Cleaner Production boasts a higher Impact Factor (IF) of 11.072. Both journals have strong standings in the field.

Table 3. Top 10 countries with the highest research paper contributions.

Country	Region	Documents	Ratios
China	Asia	1342	41.08%
United States	Americas	366	11.20%
India	Asia	285	8.72%
Australia	Australia	198	6.06%
United Kingdom	Europe	149	4.56%
Japan	Asia	143	4.38%
Germany	Europe	123	3.76%
Italy	Europe	119	3.64%
Canada	Americas	105	3.21%
Netherlands	Europe	82	2.51%

Table 4. Leading journals in E-waste recycling research.

Journal	Research Areas	Docs	Country	H-Index	IF	SJR
Waste Management	Environmental science	241	U.K.	201	8.816	1.75 Q1
Journal of Cleaner Production	Business, management, and accounting; energy; engineering; environmental science	200	U.K.	268	11.072	1.98 Q1
Environmental Science and Pollution Research	Environmental science; pharmacology	170	Germany	154	5.19	0.94 Q1
Science of the Total Environment	Environmental science	168	The Netherlands	317	10.754	1.95 Q1
Resources, Conservation, and Recycling	Environmental science; economics, econometrics, and finance	161	The Netherlands	170	13.716	2.86 Q1
Environmental Pollution	Environmental science; pharmacology; toxicology and pharmaceutics	117	U.K.	275	9.988	2.11 Q1
Sustainability	Computer science; energy; environmental science; social sciences	102	Switzerland	136	3.889	0.66 Q1
Environmental Science & Technology	Chemistry; environmental science; pharmacology	99	U.S.A.	456	11.357	3.12 Q1
Chemosphere	Chemistry; environmental science; pharmacology	96	U.K.	288	8.943	1.73 Q1
Journal of Hazardous Materials	Environmental science	80	The Netherlands	329	14.224	2.57 Q1

Environmental Science and Pollution Research and Science of the Total Environment: These journals have similar article counts (170 and 168) but differ in terms of origin. The former, from Germany, has a respectable IF of 5.19, while the latter, based in the Netherlands, boasts a higher IF of 10.754. Both have robust research impact as indicated by their H-indexes.

Resources, Conservation and Recycling and Environmental Pollution: Both of these Dutch journals are well regarded in the field. Resources, Conservation, and Recycling has a high IF of 13.716, whereas Environmental Pollution has an equally impressive H-index of 275. Both contribute significantly to research in environmental science.

Sustainability and Environmental Science & Technology: These journals cover a wide range of fields. Sustainability, a Swiss journal, has a lower article count (102) but an appreciable H-index of 136. On the other hand, Environmental Science & Technology from the U.S. has fewer articles (99) but a remarkably high H-index (456) and IF (11.357). These journals cater to diverse disciplines.

Chemosphere and Journal of Hazardous Materials: Both of these U.K. and Netherlands-based journals are pivotal in the field. Chemosphere boasts an impressive H-index of 288, while the Journal of Hazardous Materials has an even higher H-index of 329. Both contribute significantly to the realm of environmental science and pharmacology.

These journals play crucial roles in E-waste recycling research. While some excel in terms of high article counts, others stand out with strong research impact metrics such as H-index and IF. The choice of which journal to follow depends on the specific research focus and requirements of researchers, as each journal has its own advantages.

According to Table 4, the top 10 journals listed all belong to Quartile Q1, which signifies the highest quality. Specifically, the journal Environmental Science & Technology, despite being ranked 8th in terms of the number of research articles published, has the highest SJR (SCImago Journal Rank) with an impressive SJR value of 3.12. This indicates that the articles published in Environmental Science & Technology are of outstanding quality, surpassing those in other journals.

4.2. Author Citation Productivity

Author citation productivity refers to the impact and influence of an author's work based on the number of times their publications are cited by other researchers. It is an important metric for evaluating the scholarly contributions of individual researchers. This research limited their analysis to authors who had a minimum of 100 citations, meaning that only authors with a significant level of influence in the field of E-waste recycling were considered. This approach allowed them to focus on the impact of the most prominent authors in the research area. In total, the team identified 158 out of 56,590 authors who met this criterion. These 158 authors were grouped into three clusters based on their citation patterns, as depicted in Figure 3. Cluster 1 (red) represents one group of authors with similar citation patterns. The authors in this cluster likely share common research themes or collaborate closely in their work. Authors in cluster 2 (green) exhibit a different citation pattern from cluster 1, suggesting that they may have distinct research foci or work independently from the first cluster. Cluster 3 (blue) encompasses authors with yet another unique citation pattern. These authors may explore different aspects of E-waste recycling or have their own research networks. In addition to clustering the authors, the research team also calculated the H-index for the top 10 most highly cited authors in the field of E-waste recycling. The H-index is a measure of an author's cumulative research impact, considering both the number of publications and the number of times those publications have been cited by others. For example, if an author has an H-index of 50, it means they have at least 50 publications, each of which has been cited at least 50 times. The H-index provides valuable insights into an author's overall influence and contributions to the field. It is an effective way to assess the long-term impact of a researcher's work, with higher H-indices typically indicating greater influence and productivity. By examining the clustering of authors and the H-indices of top authors, the research team gained a comprehensive understanding of the research landscape and the key contributors in the field of E-waste recycling. This approach allows for a more nuanced analysis of author productivity and impact.

The top 10 authors with the highest number of citations in the field of E-waste recycling are shown in Table 5. The authors are affiliated with institutions around the world, including Canada, Hong Kong, China, India, the United States, and Nigeria. The H-index, which measures a researcher's impact, varies among these authors, reflecting their contributions to the field. Additionally, the total link strength (TLS) metric provides information about the extent of collaboration or co-citation among these authors in the research community. The top authors in this field are characterized by their high citation counts, indicating that their research is highly relevant and influential. Researchers like Zheng, Li, and Kumar have not only produced a considerable volume of work but have also made substantial contributions to the advancement of knowledge in E-waste recycling. Their research is widely recognized and cited, and their H-indices reflect their long-lasting impact. Zheng, X.L. vs. Li, J.H.: Zheng and Li are the top two authors in terms of citation counts, with 595 and 473 citations, respectively. Zheng has a higher H-index (50) compared to Li's impressive H-index of 127. This indicates that while Zheng's work has been highly cited, Li's research has had a more profound and enduring impact, as reflected in the significantly higher H-index. Both authors are influential, but Li's work is recognized for its exceptional quality. Kumar, A. vs. Cui, J.R.: Kumar and Cui both have a high number of citations, with 374 and 502, respectively. However, Kumar's H-index is substantially higher at 152, reflecting the lasting impact of his research. Cui, on the other hand, has a lower H-index (12), indicating that while his work is cited often, it might be relatively recent or fewer in number. This comparison highlights the difference in the depth and breadth of their contributions. Leung, A.O.W.: Leung has an impressive citation count of 488, but his H-index is not provided due to the unavailability of a Google Scholar profile. While his work is widely recognized, it is challenging to assess the longevity and influence compared to authors with reported H-indices. Li, J.H. vs. Kumar, A.: Both Li and Kumar have high citation counts, with 473 and 374 citations, respectively. However, Li's H-index (127) surpasses Kumar's (152), indicating that Li's work has had a more substantial and long-lasting impact on the field, despite a slightly lower citation count. The remaining authors in the top 10 exhibit varying levels of citation counts and H-indices, reflecting their distinct contributions. Song, Awasthi, Li, Robinson, Nnorom, and others have all made significant impacts in the field, but the details of their work and influence can be further explored through their respective H-indices and specific research focus.

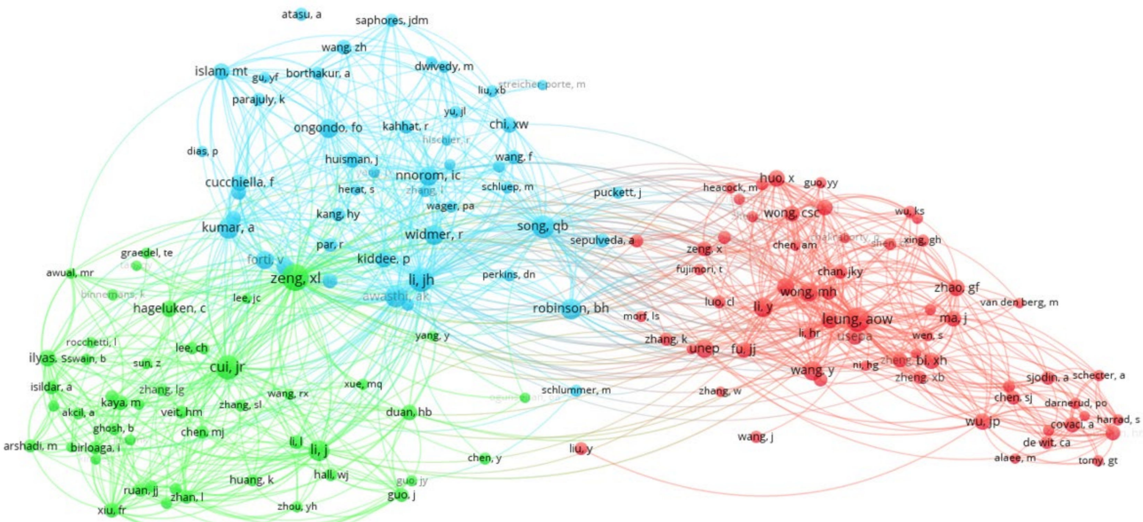

Figure 3. Scientific co-citation author map.

Table 5. Top 10 most cited authors.

Author	Affiliation	Country	Citations	TLS	H-Index
Zheng, X.L.	University of Calgary	Canada	595	10.343	50
Leung, A.O.W.	Hong Kong Baptist University	Hong Kong	488	8.557	N/A
Li, J.H.	Tsinghua University	China	473	8.376	127
Song, Q.B.	Macau University of Science and Technology	China	418	8.099	36
Awasthi, A.K.	Nanjing University Nanjing China	India	409	7.231	19
Cui, J.R.	University of Toronto	Canada	502	6.944	12
Li, J.	Tsinghua University	China	364	6.282	98
Robinson, B.H.	University of Washington	America	372	5.605	59
Nnorom, I.C.	Abia State University	Nigeria	319	5.568	31
Kumar, A.	IIT (BHU) Varanasi	India	374	5.306	152

4.3. Journal Productivity

A high number of articles might indicate productivity, but it is also crucial to consider the quality and impact of those articles. High-quality research is often associated with high-impact journals, but both productivity and impact should be considered when evaluating journals. This research conducted a study of co-citation helping researchers identify the degree of interconnections between academic journals and scholars within the field, highlighting those publications and authors that are influential and well-connected. They initiated the analysis by setting a minimum citation threshold of 100 citations for a source. The outcome revealed that 174 out of 28,535 sources met this criterion. These 174 sources were then analyzed, leading to their classification into three distinct clusters represented by different colors: red, green, and blue. These three color-coded clusters demonstrate the co-citation relationships between academic journals. Journals within the same cluster share a common research focus, leading to higher connectivity and a greater similarity in their research directions. Through this analysis of co-citation relationships, researchers gained insights into how these academic journals tend to connect during their research endeavors. Specifically, cluster 1 (red), cluster 2 (green), and cluster 3 (blue) comprise 84 sources (Appendix A, Figure A1A), 51 sources (Appendix A, Figure A1B), and 38 sources (Appendix A, Figure A1C), respectively. The strength of the connections among these journals is indicative of their reliability and the robust relationships between co-citing journals and co-citing researchers. This co-citation analysis offers valuable insights into how the most heavily co-cited journals and researchers play pivotal roles and exert substantial influence in shaping the research landscape within the field of E-waste recycling.

The findings in Table 6 and Figure 4 present the top 10 co-cited journals in the field of E-waste recycling. Notably, Environmental Science & Technology, categorized within cluster 2 (green cluster), emerges as the most frequently cited journal with 10,905 co-citations and a cumulative link strength of 480,086. Following closely in the second position is Waste Management, attributed to cluster 3 (blue cluster), boasting 8779 co-citations and a total link strength of 403,737. Chemosphere, also nestled in cluster 2 (green cluster), secures the third spot with 6085 co-citations and a total link strength of 354,244. In addition to these distinguished journals, other publications such as Science of the Total Environment, Journal of Cleaner Production, and numerous others exhibit substantial co-citation counts and robust linkages. These findings underscore the significant role these journals play within the co-citation network, demonstrating their collective contribution to the advancement of E-waste recycling research.

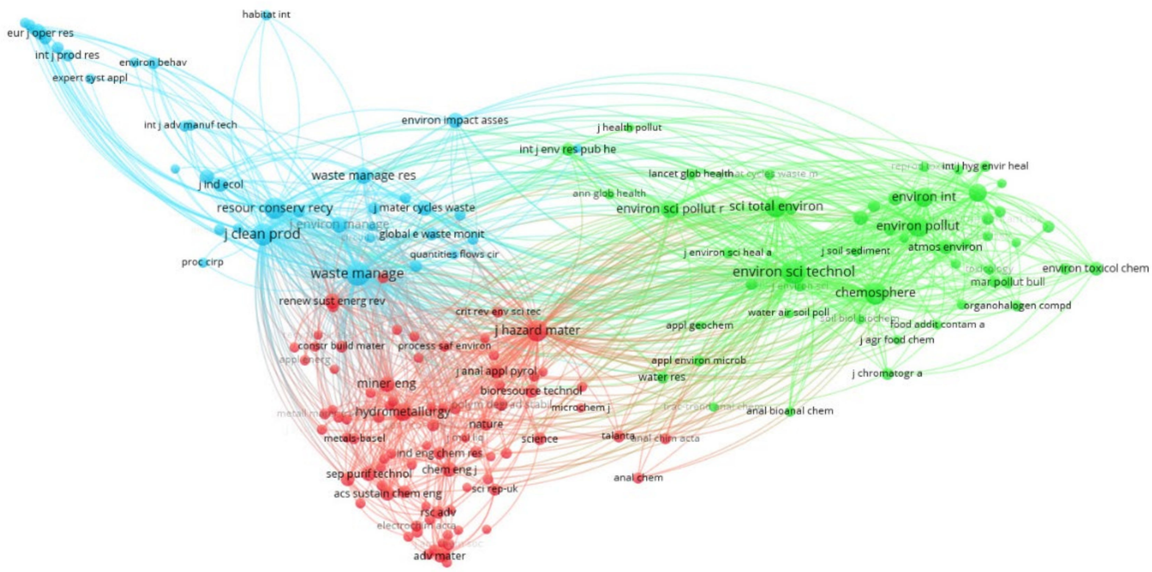

Figure 4. Scientific co-citation network of journals.

Table 6. Top 10 highly co-cited journals.

Journal	Citations	TLS
Environmental Science & Technology	10,905	480.086
Waste Management	8779	403.737
Chemosphere	6085	354.244
Science of the Total Environment	5557	309.698
Journal of Cleaner Production	6466	296.141
Journal of Hazardous Materials	5411	287.585
Resources, Conservation, and Recycling	5393	243.209
Environmental Pollution	3985	225.700
Environment International	3816	221.645
Hydrometallurgy	2447	142.551

4.4. Research Theme

The data analysis regarding the publication years of research articles reveals a noteworthy trend of increasing interest in the field of E-waste recycling. Over the period from 2014 to 2022, there has been a consistent and substantial growth in the number of research articles addressing this subject (as depicted in Figure 5). In the present context, the year 2022 emerges as the peak year for scientific articles on E-waste recycling, with a total of 408 publications. This surge in interest is indicative of the escalating global concern for environmental conservation, waste reduction, and, in particular, the recycling of E-waste.

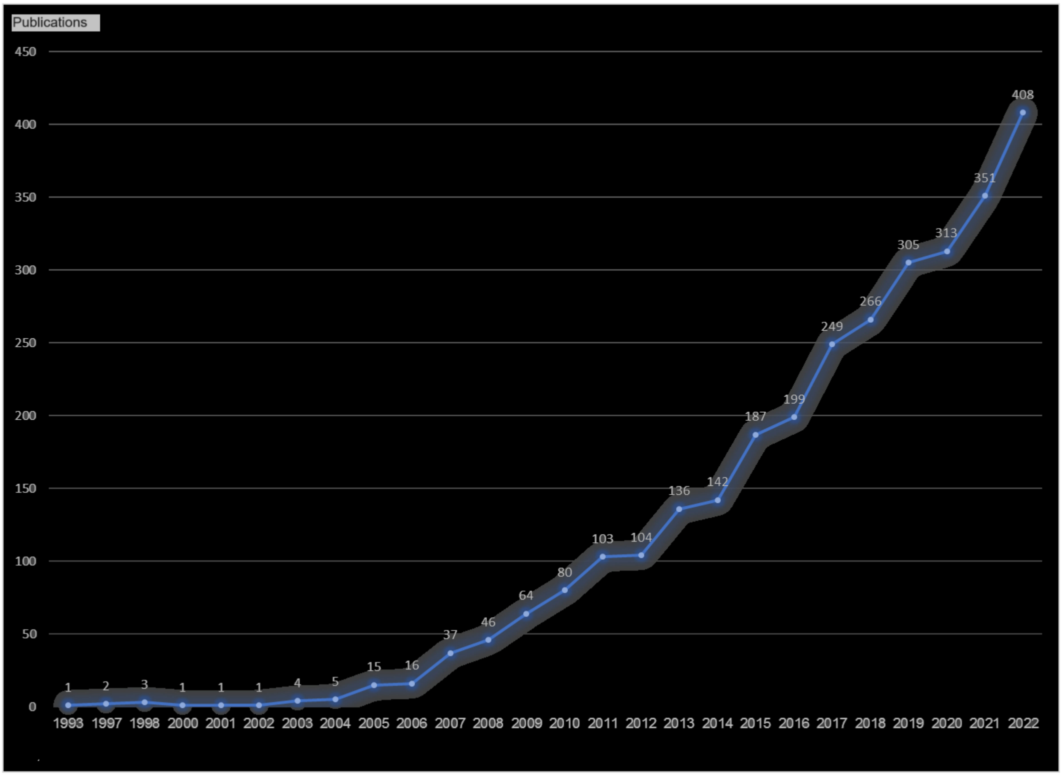

Figure 5. Statistics on number of published papers during the period 1990–2022.

Furthermore, in the realm of research articles, the year of publication reflects a noteworthy pattern, with an increasingly heightened interest in E-waste recycling. Throughout the period spanning from 1990 to 2022, there has been a consistent and robust surge in the number of scholarly articles, as depicted in Figure 5. Notably, 2022 marked a pinnacle, with the highest count of 408 research articles. This upswing can be attributed to the global attention and commitment to addressing environmental concerns, waste management, and E-waste recycling, which has gained momentum during this timeframe. Moreover, the volume of research articles published in 2023 maintains an upward trajectory, indicating a sustained interest in the subject. As of the research group's data extraction date on 14 July 2023, the number of research articles dedicated to E-waste recycling has reached 228, representing approximately 55.8% of the year 2022. A significant positive correlation has been observed between the number of research publications and the publication year. Therefore, it is plausible to anticipate that research endeavors about E-waste recycling will continue to advance in the upcoming years, driven by the heightened global consciousness of environmental preservation and resource conservation. With a vast repository of 10,671 keywords, 144 met the stringent threshold requirement of appearing at least 35 times in the dataset. Subsequently, the research group excluded keywords related to specific countries and regions, such as China, South China area, and India, due to their lack of direct relevance to the research topic. The result yielded a curated list of 140 keywords that met the specified criteria. Table 7 provides an overview of the top 10 most frequently encountered keywords. Notably, the keyword E-waste emerges as the most prominent, with an impressive tally of 903 appearances. Acknowledging that E-waste is another high-frequency keyword, securing the second position with 728 occurrences is crucial.

Table 7. Top 10 highly frequent keywords.

Keywords	Frequency	TLS
E-waste	903	4.461
Electronic waste	728	3.508
Polybrominated diphenyl ethers	460	2.683
Recycling	585	2.500
Recovery	505	2.422
Brominated flame retardants	312	1.741
Management	344	1.728
WEEE	355	1.681
China	293	1.674
Printed—circuit boards	290	1.635

Using VOSViewer software 1.6.20, this study conducted a comprehensive analysis considering both positive and negative aspects, as elaborated in Table 8 and Figure 6. The analysis led to the visualization of three distinct clusters, encompassing a total of 5261 connections with a cumulative link strength of 37,218. To provide a detailed understanding of these clusters, let us delve into each one.

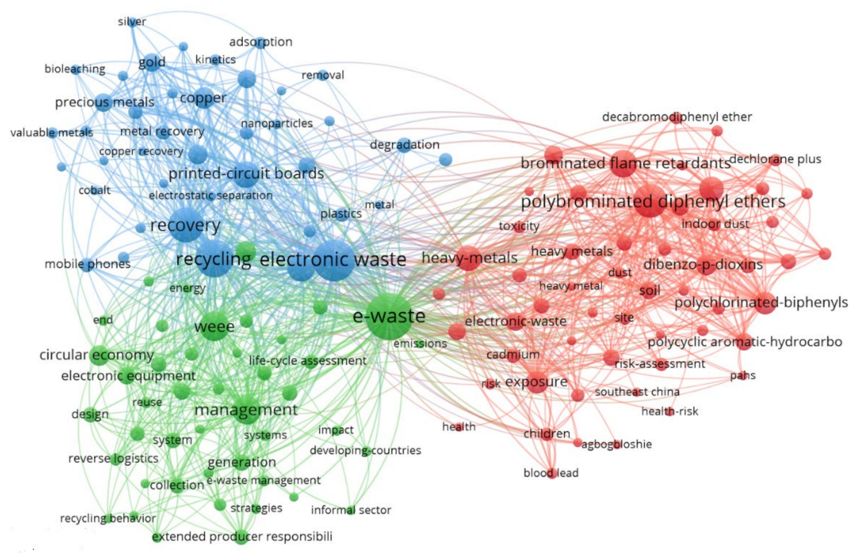

Figure 6. Scientific knowledge map of co-occurrence analysis.

Table 8. Analysis of two contrasting aspects in the co-occurrence cluster.

Cluster	Keywords	Pros	Cons
Cluster 1 (red)	Polybrominated, exposure, children, dibenzo-dioxins, heavy metals, lead, brominated, flame retardants	Exploring the influence of E-waste on human health through a deeper understanding of health impacts can lead to community health awareness. By emphasizing factors related to the impact of E-waste on human health, community awareness of this issue is raised. Furthermore, these discoveries regarding the impact of pollutants can promote health protection measures against the adverse effects of E-waste, further strengthening the link between them.	The challenges related to data completion in research can potentially result in information loss or errors in data collection and analysis. It, in turn, may lead to an inaccurate understanding of health impacts. Additionally, while findings on health impacts can promote protective measures, they may also bring about behavioral change challenges, as changing behaviors and habits may face difficulties and require adjustments. Therefore, the challenges of data completion and potential information loss are interconnected and can influence the effectiveness of promoting health protection measures and behavioral change.
Cluster 2 (green)	E-waste, management, WEEE, circular, economy, equipment, sustainability, performance	The increasing adoption of recycling and system improvement strategies in the E-waste industry can not only create competitive opportunities but also drive innovation and creativity. Furthermore, these strategies can help businesses minimize production costs and reduce E-waste by reusing electronic devices. As a result, they make significant contributions to both cost optimization and environmental protection.	The successful implementation of recycling and system improvement strategies within businesses and management can face various challenges, such as difficulties in execution and the need to change the organizational culture. Moreover, consumers play a crucial role in shaping recycling approaches, and their willingness to alter habits may only sometimes be forthcoming. Additionally, while these strategies can potentially reduce production costs, their economic effectiveness may require an initial investment in training and technology updates.
Cluster 3 (blue)	Electronic, waste, recycling, recovery, mobile phone, efficiency, classification	Addressing these challenges in implementing recycling and system improvement strategies is essential for promoting sustainable practices. Implementing these strategies within businesses and management may sometimes be complicated and can involve difficulties in execution, along with the need to change the organizational culture. Moreover, achieving success in changing the approach to recycling often requires active engagement and interaction from consumers, who may only sometimes be willing to alter their habits. Furthermore, while these strategies have the potential to reduce production costs, they may also necessitate an initial investment in training and technology updates, making economic effectiveness a critical consideration in their adoption.	Overcoming the technological and process challenges associated with recovering and recycling materials from used electronic devices is a crucial step in promoting sustainability. These challenges may entail the development and implementation of complex technologies and processes, making it essential to invest in research and innovation. Ensuring the quality of materials recovered from used electronic devices is another challenge that needs to be addressed to guarantee the safety and effectiveness of recycling and reuse processes. Additionally, promoting recycling and material recovery from old electronic devices involves changing consumer and business habits and raising awareness about the importance of these practices for a sustainable future. These interconnected challenges necessitate collaborative efforts and innovative solutions to drive positive change in the E-waste recycling landscape.

Cluster 1 (in red)—Influence of organic pollutants

In this cluster, the keyword "polybrominated" stands out with the highest frequency of 460 occurrences. This emphasis underscores the significant influence of organic pollutants resulting from incineration and melting processes on human health [40]. Furthermore, this cluster contains keywords such as "exposure", "children", "dibenzo-dioxins", "heavy metals", "lead", and "brominated flame retardants", all of which collectively depict the impact of organic pollutants and heavy metals on human health (see Appendix A, Figure A2A).

Cluster 2 (in green)—E-waste management and recycling in developing nations

Within this cluster, the keyword "e-waste" appears in 457 documents and is interconnected with 903 keywords. Associated keywords such as "management", "WEEE", "circular economy", "equipment", "sustainability", and "performance" collectively indicate the cluster's primary focus on issues related to the management and recycling of E-waste in developing nations. These regions face unique challenges in the disposal and processing of electronic devices due to less stringent regulations [28]. The emphasis here lies in transforming administrators' mindsets, behaviors, and perspectives to enhance systems and implement electronic device recycling strategies in developing countries. This transformation contributes to heightened competition within the E-waste market, fostering a synergy of supply–demand behavior among consumers, businesses, and electronic device reuse supply chains, particularly across nations (see Appendix A, Figure A2B).

Cluster 3 (in blue)—Research on recovery and recycling of used materials

In the blue cluster, the keyword "electronic waste" takes center stage with a frequency of 728 occurrences, highlighting the pivotal focus of this cluster. Closely associated keywords include "recycling", "recovery", "mobile phone", "efficiency", and "classification". As technology rapidly advances, electronic products have become integral in daily life. From mobile phones to various electronic devices, their production and consumption continue to rise. With this surge in electronic products comes the pressing concern of E-waste and the methods for reclaiming materials from it, making this cluster particularly significant. Research in this cluster is dedicated to the recovery and recycling of used materials, contributing to the optimization of resource utilization, reduction of environmental impacts, and the promotion of a circular economy. This approach aims to preserve the value of electronic products through multiple usage cycles (see Appendix A, Figure A2C). These clusters and their respective emphases provide valuable insights into the various facets of E-waste research, paving the way for future research directions and informed policy decisions.

A crucial study component (Figure 7) builds upon the preceding results by showcasing the outcomes of the topic modeling process conducted on a subset of our comprehensive dataset. Specifically, this dataset comprises the first 500 research documents from 3267 research papers. The primary objective of this analysis was to extract vital insights from the data, identify essential keywords, and group these keywords into clusters representing significant and frequently encountered topics in E-waste management and recycling. This data-driven approach has enabled us to unveil latent subjects and pinpoint distinct keywords that offer a more nuanced understanding of the research landscape. Its understanding has laid the groundwork for the exploration of pertinent research clusters. The research elucidates these keyword clusters in the broader research landscape, highlighting their relevance and contribution to the field.

The primary focus of this study involves an examination of several key terms, including "polymer, recycling, WEEE; near-infrared sorting, mechanical properties". The identification of this cluster prompted our investigation into enhanced methodologies for the retrieval of polymer components from electronic devices that have been discarded [41]. This study presents a comprehensive analysis of several recycling techniques. The evaluation focuses on the viability and efficacy of employing near-infrared sorting methods for polymer recycling within the framework of Waste Electrical and Electronic Equipment (WEEE) guidelines. This study investigates the techniques and examines the viability and long-term viability of reusing polymer materials derived from E-waste, considering their mechanical characteristics and potential applications in different scenarios.

Figure 7. Topic modeling visualization.

In a study conducted by Grigore and Ion [42], the keyword cluster "high impact polystyrene; melt compounding; polystyrene fraction from WEEE; styrene–butadiene–styrene (SBS); styrene–ethylene–butylene–styrene grafted with maleic anhydride (SEBS-g-MA)" was utilized to investigate the enhancement of mechanical qualities in recycled polystyrene obtained from electronic devices. The researchers have conducted investigations to improve the mechanical properties of this material by the utilization of melt compounding techniques, with particular emphasis on boosting qualities such as elasticity and durability.

Finally, the present study also investigates the keyword cluster encompassing the topics of "Low voltage fuse-links recycling", "High voltage fuse-links recycling", "WEEE Directive", "Materials recovery", and "Industrial wastes reduction". The investigation of this cluster has prompted a study of significant significance in the mitigation of industrial waste by implementing advanced recycling methodologies [43]. The scope of this study extends beyond the recycling of fuse connections at various voltage levels, as it also underscores the significance of compliance with regulations about the management of E-waste, specifically the WEEE Directive. The focus of this study is centered on the extraction of materials from industrial waste, which plays a substantial role in reducing waste generation and fostering sustainability within the industrial domain.

The knowledge obtained from these groupings of keywords further expands upon the groundwork established by our prior findings. The authors offer a comprehensive viewpoint on the management of E-waste, encompassing recycling practices and the enhancement of material qualities using modern technologies. Through an examination of these clusters, our work makes a significant contribution toward the reduction of waste, the optimization of resource consumption, and the advancement of sustainability within both industrial and environmental contexts. It aligns with the overarching research objectives within this particular topic.

5. Conclusions

Quantitative analysis of scientific research papers on E-waste recycling has drawn considerable interest within the scientific community. The primary objective of our research group is to employ comprehensive quantitative analysis techniques to investigate and explore the current status and potential future trends in global E-waste recycling.

Presently, the challenge of mitigating the volume of E-waste remains a critical issue. Consequently, research on E-waste recycling has become increasingly pivotal. It is our earnest expectation that this research endeavor will provide valuable, pragmatic evidence to address pertinent E-waste concerns, including environmental and human health issues at E-waste recycling sites. This research initiative is paramount, given the escalating global E-waste problem.

In addition to providing the contextual background, research objectives, and methodology, we executed a systematic search, as elucidated in Section 3.1. This search yielded a comprehensive dataset, comprising 3267 research papers related to E-waste recycling, sourced from the SCIE category of the WoS database. The data extraction occurred on 14 July 2023.

5.1. Summary

In the pursuit of our objectives, predicated upon the analysis of the 3267 compiled datasets, our research group conducted a series of analyses, encompassing vocabulary analysis, author co-citation analysis, reference co-citation analysis, and journal co-citation analysis. The results of these analyses provided a foundation for our observations, thereby enabling the evaluation of the relationships among research papers in the domain of E-waste recycling and the provision of insights into our research questions.

Question 1: Which countries and journals exhibit the most robust research activity in E-waste recycling?

China has demonstrated the most significant research activity in E-waste recycling, with 1342 research papers. The United Kingdom's "Waste Management" journal stands out as the most prolific publication in E-waste recycling, comprising 241 papers out of the 3267 research papers. These findings underscore the keen interest of researchers in China, the U.K., and the United States in E-waste recycling, particularly in nations that contribute substantially to the global E-waste volume. Researchers in these countries are acutely aware of the deleterious environmental and human health impacts wrought by E-waste and are deeply committed to exploring and addressing these pressing issues. Consequently, E-waste research has emerged as a burgeoning and impactful research trend, not only within the aforementioned countries but also across the international landscape, including countries such as India, Japan, and Canada.

Question 2: Who are the most highly co-cited authors, the journals, and the references in the field of E-waste recycling?

Author Zeng, X.L., garners the highest co-citations among research papers in the field of E-waste recycling, with a tally of 595 citations. The journal "Environmental Science & Technology" from the United States ranks as the most frequently co-cited journal, accumulating an impressive 10,905 citations.

These extensively co-cited authors, journals, and references have indubitably exerted substantial influence and impact within the domain of E-waste recycling. They play a pivotal role in establishing a web of co-citations interlinking researchers, journals, and organizations across the globe, thereby laying the groundwork for future scientific research.

Question 3: How have E-waste recycling studies evolved from 1990 to 2022?

The inception of E-waste recycling research transpired with the publication of the first research paper in 1993. Before 2005, research paper output was limited to fewer than six publications. Following 2005, there was a gradual upswing in research paper publications until 2013. Subsequently, there was a marked upward trajectory commencing in 2014 and extending through 2021, reaching its zenith in 2022. The increased volume of research papers corroborates the growing concern surrounding E-waste and its associated environmental and health implications, particularly within the context of the fourth industrial revolution (Industry 4.0). While there were approximately 46 research papers in 2008, the figure surged to 408 in 2022, emblematic of the promising trajectory of this research field.

Question 4: What are the prevailing research trends in the global E-waste recycling domain?

Based on the findings of vocabulary analysis, three predominant research trends have emerged within the ambit of E-waste recycling. (1) Examination of the influence of organic pollutants: This research trend casts its focus on the repercussions of organic pollutants, often emanating from incineration and smelting processes, on human health, with a particular emphasis on the effects of organic and heavy metal pollutants, specifically on children.

(2) Research into E-waste management and recycling in developing countries: This research trend centers on the disposition and repurposing of E-waste in developing countries, underscoring the exigency for more stringent control and regulation. (3) Investigation into material recovery and recycling of used materials: This research trend underscores the importance of recovering and recycling materials from previously used electronic devices. The objective is to optimize resource utilization, curtail environmental impact, and uphold the value of electronic products over multiple usage cycles.

These research trends reflect the heightened awareness of the E-waste issue as an integral facet of broader environmental preservation and sustainability endeavors. Research and exploration into methods for processing, recycling, and mitigating the adverse impacts of E-waste can be deemed of paramount significance within this domain.

5.2. Contribution

This groundbreaking article, dedicated to systematically analyzing the research literature on E-waste recycling, has diligently fulfilled its initial objectives, comprehensively responding to the research inquiries. The pursuit of research endeavors concerning E-waste recycling has grown increasingly imperative and is a pivotal contributor to fostering a robust international research network. This network offers vital scientific resources that hold significance for the broader field of E-waste recycling, with profound implications for global environmental preservation.

In an era where global awareness of the far-reaching consequences of E-waste is on the rise, this research assumes heightened practical importance. By conducting an in-depth analysis of author co-citation networks, this study equips researchers interested in this realm with the tools needed to identify suitable and high-caliber collaborators. Furthermore, it aids in pinpointing journals that are academically relevant to environmental concerns and the intricacies of E-waste. Ultimately, E-waste research plays a pivotal role in contributing substantially to the interconnected domains of healthcare and environmental resource conservation.

Moreover, this research article is an invaluable theoretical cornerstone for enterprises motivated to explore and expand recycled resource reservoirs. In doing so, they contribute to heightening environmental awareness and enhancing the well-being of consumers within the realm of electronic products and devices.

5.3. Limitations and Future Research

While this analysis has provided valuable insights into the landscape of E-waste recycling research, it is important to acknowledge the study's limitations. Firstly, this study focused predominantly on the WoS as the primary data source. Expanding the scope of data collection to include additional databases, such as Scopus, could offer a more comprehensive view of E-waste research, potentially yielding different trends and insights. Secondly, this research primarily delved into E-waste research at a global scale. Future research efforts should consider a more granular approach, investigating E-waste recycling on a regional or continental basis, such as in Asia, Europe, and the Americas. This would enable researchers to gain a deeper understanding of the unique challenges and priorities in each region. Additionally, there is a growing volume of research on E-waste, with countries like China, the United States, and India leading the way. As a result, researchers are now challenged to explore new avenues and multidimensional perspectives that surpass the quality and completeness of previous research publications. Future studies should strive to offer fresh insights, making a substantive contribution to the field. For future research, there is a multitude of unexplored avenues within the realm of E-waste recycling. Some of these could include studying country-specific recycling methodologies, devising strategies to mitigate environmental and public health hazards at recycling sites, and investigating the regulatory framework, such as the feasibility of imposing penalties for improper E-waste recycling practices. Additionally, research can extend into the health risks associated with working in E-waste recycling environments, and potential remedies or protective measures for the workforce in these areas.

Author Contributions: Conceptualization, M.-H.L.; Methodology, M.-H.L.; Validation, W.-M.L.; Formal analysis, J.-C.C.; Data curation, M.-H.L. and J.-C.C.; Writing—original draft, M.-H.L. and J.-C.C.; Writing—review & editing, W.-M.L. and J.-C.C.; Visualization, W.-M.L.; Supervision, W.-M.L.; Project administration, W.-M.L. All authors have read and agreed to the published version of the manuscript.

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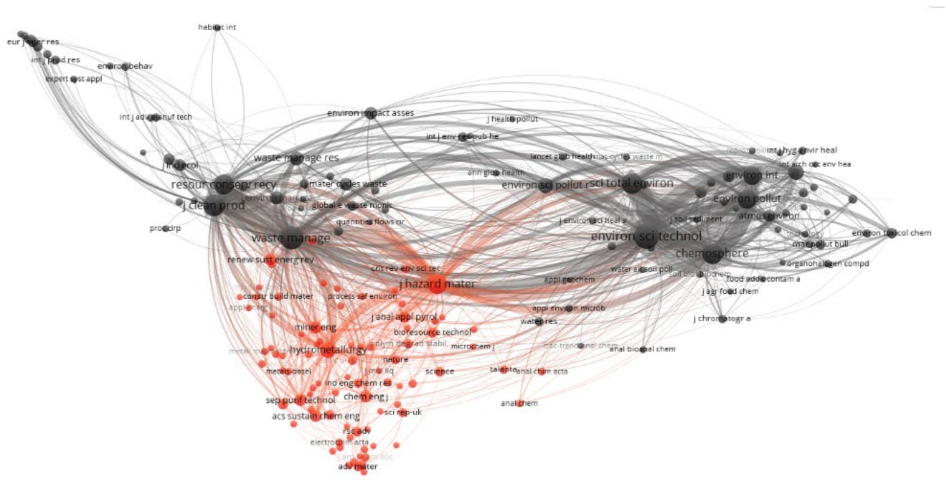
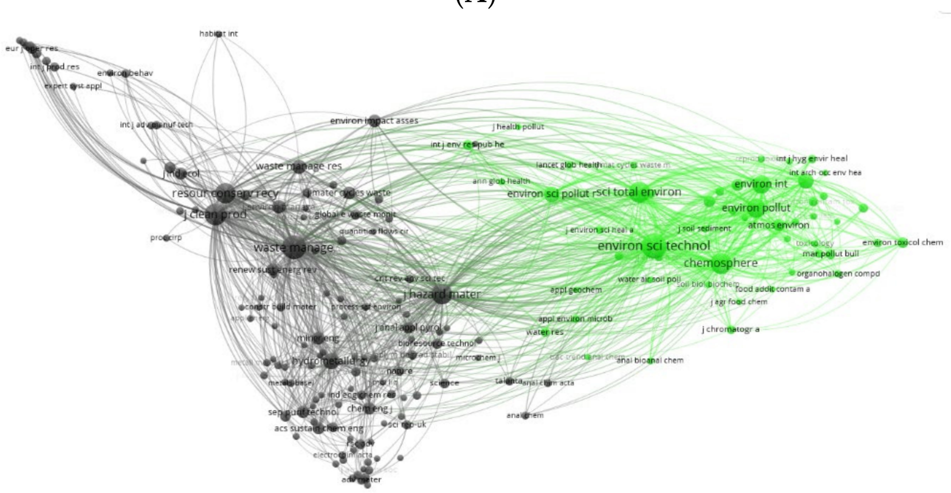
Appendix A

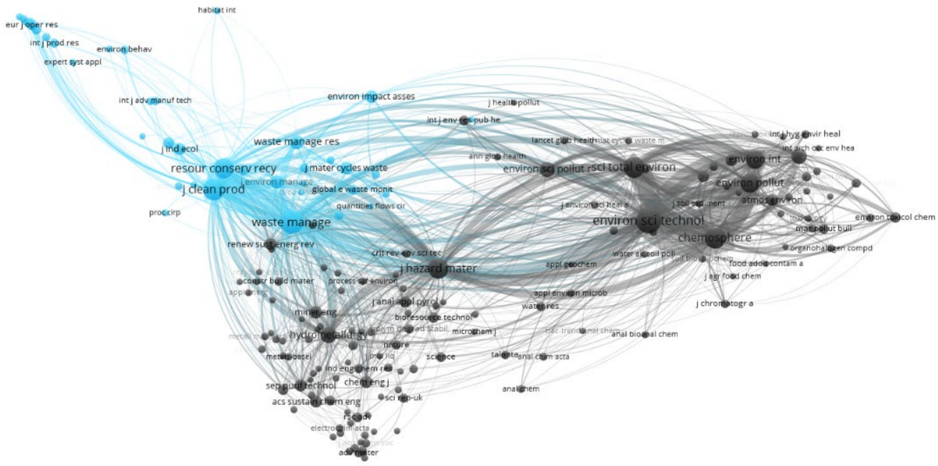


(**A**)



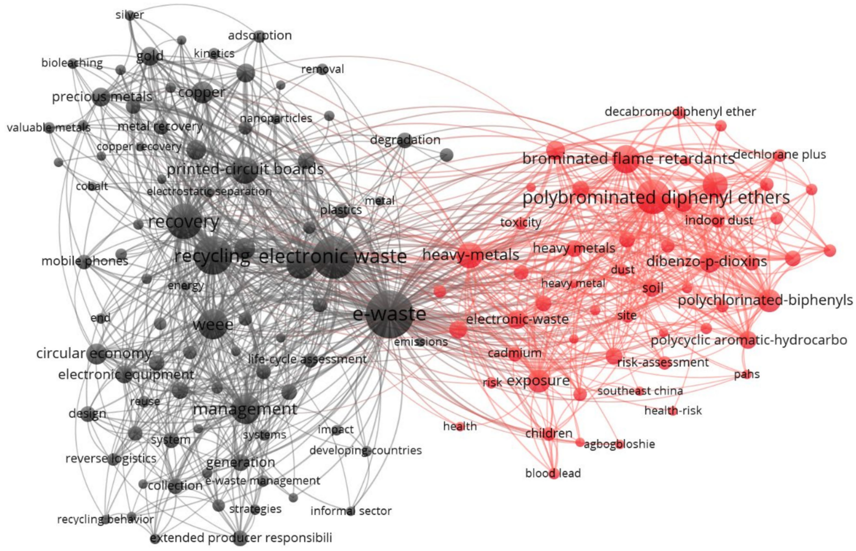
(**B**)

Figure A1. *Cont.*

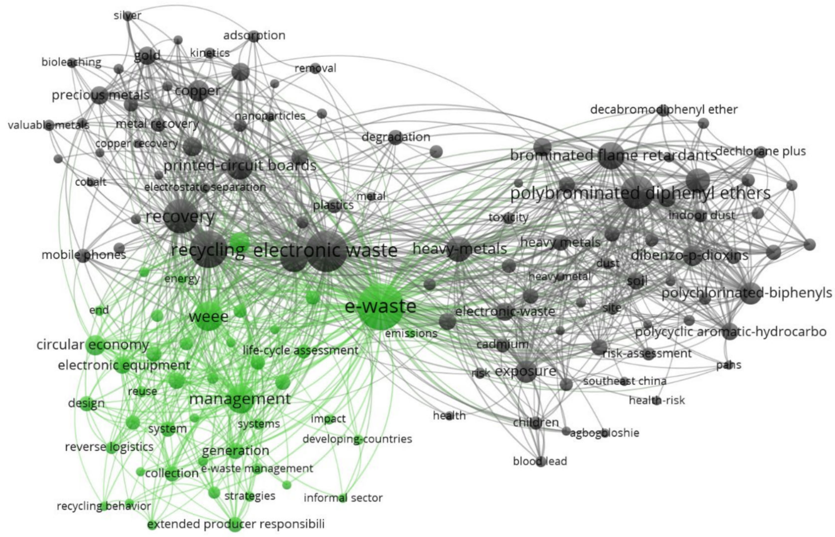


(**C**)

Figure A1. (**A**) Cluster 1; (**B**) Cluster 2; (**C**) Cluster 3.

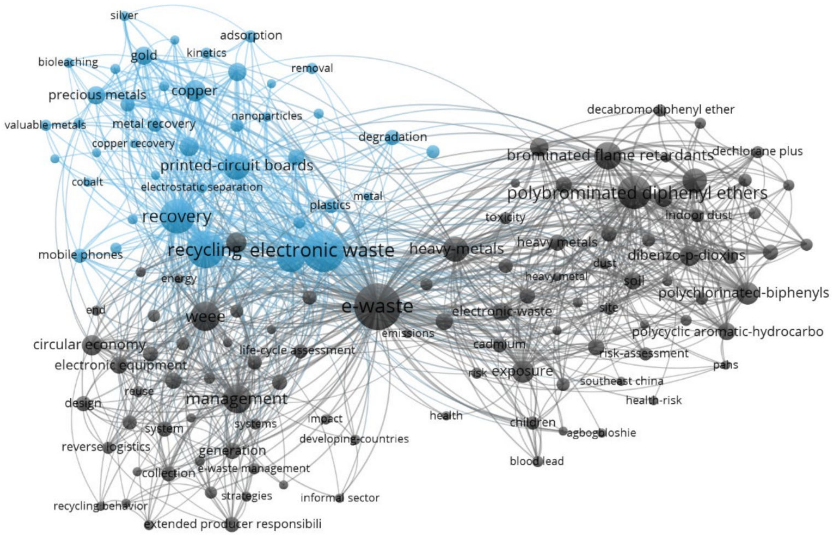


(**A**)



(**B**)

Figure A2. *Cont*.



(**C**)

Figure A2. (**A**) Cluster 1; (**B**) Cluster 2; (**C**) Cluster 3.

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