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A Decade of E-Waste Unplugged: Decoding the Landscape of Global Research and Challenges

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ABSTRACT

The paper provides an in-depth analysis of global electronic waste management (EWM), with a focus on major challenges and issues, environmental and human implications, current and potential futures research trends worldwide. To achieve this, the study analysed a dataset comprising 342 publications that were published between 2014 and 2024, obtained from the Scopus database, using bibliometrics, content analysis, and network approach methods. The results analysed using VOSViewer, MS Excel, and Harzing's Publish or Perish software revealed that electronic waste management (EWM) is a crucial area of study. The analysis identified various themes and highlighted limitations in the literature's growth while offering suggestions for further research. The study employed a combination of bibliometric, content, and network analyses to investigate e-waste management disclosure.

Keywords: Bibliometric Analysis; Electronic Waste Management (EWM); e-waste; Management; Technology

1. INTRODUCTION

E-waste creation has increased significantly in recent years due to the growing global population and rapid urbanisation. Thus, it becomes a mini-catastrophe and a global hazard to the human ecosystem. Such inappropriate disposal and poor management pose a global risk to human health and the environment. It is the outcome of technological advancements, quick innovation cycles, and marketing strategies that shorten the lifespan of electronic equipment. E-waste is the world's fastest-growing trash source, increasing by 3 to 5 percent annually. Since the introduction of computers, the global consumer electronics industry has grown substantially, becoming a multibillion-dollar sector. During 2019, global e-waste generation reached 53.6 Mt. Based on a report released by the United Nations University along with the International Telecommunication Union (ITU) and the International Solid Waste Association (ISWA), waste electrical equipment would exceed 74 Mt by 2030, which is a worrisome statistic [1]. The vast amount of e-waste raises concerns about the way it affects the environment. Thus, inadequate waste management strategies may result in serious environmental and public health impacts.

Despite substantial improvements in EWM, some crucial points and challenges remain globally, with large efforts continuing to migrate from traditional linear models to circular economy (CE) frameworks to achieve environmental sustainability. Traditional EWM practices, which include insufficient disposal and restricted recycling, have led to significant harm to the environment and resource inefficiencies.

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E-waste and its improper disposal cause serious environmental and health risks. Inadequate management of electrical and electronic devices contributes to global warming, leading to increased scientific research and public policies to deal with the environmental impact of improper disposal. Several significant difficulties must be dealt with to improve EWM. Although most consumers are aware of e-waste recycling options, many keep using straightforward disposal techniques, such as dumping devices away with regular household trash. This approach is hindered by the absence of accessible recycling and disposal options and insufficient incentives for efficient EWM. There is a critical need for strict rules and guidance to manage domestic e-waste adequately. Current rules frequently fail to enforce proper disposal and recycling methods, resulting in considerable amounts of e-waste ending up in landfills or being burnt, which causes environmental harm.

This report highlights increased research on EWM over the past decade (2014 to 2024). Several research articles with peer review have been published in high-impact journals on EWM and related issues. However, there are few bibliometric research related to this issue [2]. Therefore, this study intended to map scientific research done on EWM using bibliometrics. This study used the Scopus database to rank authors, countries, journals, citations, and search areas as important concepts. By mapping the knowledge domain, this bibliometric analysis determined the key terms used in scientific production on the issue, identifying research networks, research flow, and significant subjects, forming the foundation for updated direction for future research in this field. The findings provide a comprehensive overview of research directions and various queries collected from publicly accessible information on the issue.

This study uses bibliometrics to analyse academic works on e-waste management, identifying trends and key contributions. It highlights the economic and environmental benefits of managing e-waste and the need for evidence-based policies. The study aims to guide decision-makers, researchers, and industry stakeholders towards sustainable e-waste solutions by exploring emerging research issues and significant factors. The following sections detail the methodology, findings, and implications for a sustainable economy and environment. The paper aims to identify major nations, publications, and research topics in EWM, as well as the authors, journals, and papers with the highest co-citation rates. Other goals include examining the evolution of EWM research from 2014 to 2024 and exploring the current research problems in the global EWM field. Aside from that, this paper intends to provide substantial insights into the complex landscape of e-waste research and its role in promoting sustainable economic development and environment by conducting thorough bibliometric studies of academic publications, citation networks, and co-authorship patterns.

This paper aims to map comprehensively and graphically analyse EWM from a bibliometric standpoint. It focuses on key topics, existing EWM research dynamics, and future research potentials. This bibliometric study also aimed to identify this field's publication patterns and intellectual framework. The research questions (RQs) that are addressed are as follows:

RQ1: What is the present state of electronic waste management?
RQ2: Which electronic waste management papers are the most important?
RQ3: What are the most popular themes in electronic waste management?
RQ4: Who are the most well-known electronic waste management scholars?
RQ5: How is the collaboration on electronic waste management research now progressing?
RQ6: Which aspects of electronic waste management require additional research in the future?

The rest of this paper is structured as follows. The first section concentrates on a literature review on electronic waste management (EWM), followed by the methodology used in the study. The analysis and findings are presented next, followed by the discussion and conclusion of this study.

1.1 Literature Review

The Global E-Waste Monitor 2020 reported that in 2019, the world generated 53.6 million metric tons (Mt), with just 17.4% being effectively collected and recycled. Since 2014, there has been a 1.8 Mt rise, although overall e-waste generation has increased by 9.2 Mt. Recycling efforts are falling behind the global increase in e-waste. Asia (24.9 Mt), the Americas (13.1 Mt), and Europe (12 Mt) generated the biggest amount of e-waste as a percent of total weight. Interestingly, despite being the world's second most populous continent, Africa produced some of the lowest levels of e-waste. A further study was conducted in 2019, and the Asia Pacific region also generated the highest amount of e-waste compared to America, Europe, Africa, and Oceania regions. The Asia Pacific region generated around 25 Mt, followed by America at 13.1 Mt and Europe at 12.1 Mt. The study also showed that Africa generated 2.9 Mt and Oceania generated 0.7 Mt of e-waste.

According to a report in Roundup.org [Figure 1], global electronic waste volume is expected to increase to 74.7 Mt by 2030, nearly doubling in just 16 years. Less than one-fifth gets recycled globally, though this varies by region [3]. Only about 17% of total worldwide e-waste has been collected and appropriately recycled. This figure has decreased as a percentage of overall waste generation during the last five years. Europe has the highest collection and recycling rate (42.5%). Asia ranked second with a rate of 11.7%. Africa has the lowest, with only 0.9%. 82.6% of electronic waste is not adequately recycled and thus not documented. Researchers are unable to trace its final location precisely. It is estimated that 8% of e-waste is tossed in the trash and then sent to a landfill or burnt. This consists primarily of tiny electrical and IT components. Up to 20% is expected to be exported, either as second-hand goods or pure junk.

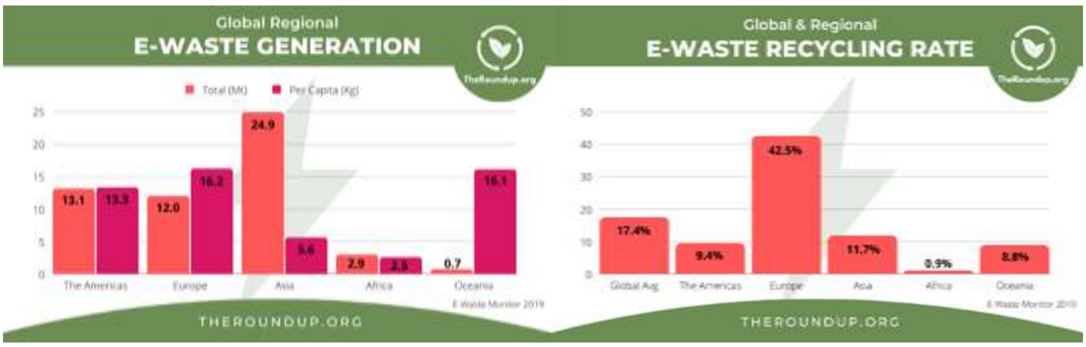

Figure 1: E-waste generation and recycling rate 2019.

Global E-Waste Monitor 2024 reported that the documented formal collection and recycling rates of e-waste vary significantly by region. In 2022, Europe produced the most e-waste (17.6 kg per capita) and had the highest reported collection and recycling rate (7.5 kg per capita), recycling 42.8% of the e-waste generated. African countries had the lowest rate, with less than 1% of e-waste being formally collected and recycled. According to data from June 2023, the growth rate of countries that have implemented e-waste policies, legislation, or regulations is declining. Worldwide, 81 countries (or 42%) currently have an e-waste policy, legislation, or regulation. This pertains to the ITU's target of 50% (97 nations) by 2023.

The Basel Convention, which regulates the movement and disposal of hazardous waste from industrialised to developing countries, may have contributed to the recent surge of publications. In 2002, the European Union (EU) parliament passed the WEEE Directive, establishing a legislative framework for member countries to manage their e-waste [4]. Post-consumption behaviours of electronic devices have a substantial impact on the health and safety of vulnerable groups, such as women and children in developing countries, demanding an assessment of electronic usage due to changing consumer preferences and shorter product lifespans [5]. Researchers have conducted numerous studies on electronic waste management [6–8], reverse logistics [4, 9, 10], and WEE production management [11]. Others are electronic waste recycling [12] and life cycle evaluation [13, 14], which highlight the problems and potential in a global context [15, 16].

1.1.1 EWM And Circular Economy (CE)

Governments, researchers, and industries have shifted their focus to effective EWM and Circular Economy (CE) strategies, such as extending product life cycles and recovering material and functional value from e-waste [11, 17]. Unlike the conventional economic model, which is based on the extraction, transformation, and disposal of basic materials, the CE encourages system innovation to reduce waste, improve resource efficiency, and keep materials useful. On a worldwide scale, a lack of efficient collection and recycling infrastructure, as well as gaps in policy development and legislative attempts to address the rate of e-waste generation, are considered major barriers to sustainable e-waste management. This gap causes the number of entrapped materials in e-waste to be understated. Users' awareness, behaviour, and demand growth are essential components of the e-waste problem, as it creates a circular economy [18]. Effective long-term strategic planning and infrastructure development for e-waste management requires a detailed assessment of e-waste's potential value, national volume, and material recovery. This method will contribute to a more efficient and sustainable EWM [12].

1.1.2 EWM And Consumer Behaviour

Researchers from several countries have looked into various aspects of e-waste recycling. Research has focused on recycling procedures in developing nations' manufacturing sectors [19, 20] and customer behaviour towards E-waste recycling [21]. More research studies on e-waste are needed to investigate current trends and future directions. Limited use of bibliometric analysis techniques hinders comprehensive field surveys. Several research studies on electronic consumer recycling behaviours have revealed that as ICT usage and utilisation increase, so does the level of WEEE because the majority of WEEE is generated by ICT-based items such as televisions, cell phones, and routers. Other research has found that data security, recycling convenience, availability and access to recycling facilities, education and awareness, and recycling cost are among the most important factors influencing consumers' recycling decisions [22]. Studies from various populations worldwide have frequently revealed that consumers are under-recycling their electronics for these reasons, although the impact of each element differs [23–25]. Socio-economic characteristics such as education and income have also been proven to be major predictors of recycling practices [26, 27]. It is believed that fundamentally improving residents' environmental awareness, standardised management of informal sectors, and improving e-waste recycling channels should be the focus of future work [28]. It is becoming more common in e-waste recycling literature to identify factors affecting consumer attitudes toward electronic waste [29–31].

1.1.3 EWM And Extended Producer Responsibility (EPR)

EPR is a mechanism for a policy that forces producers to manage their used or end-of-life (EoL) products both materially and financially. EPR regulations make producers handle product disposal, recycling, and take-back, which lessens the load on local governments and lessens environmental pollution [32]. EPR implementation in Europe has been the subject of research by researchers such as Huisman and Kahhat, who have demonstrated that these policies have significantly increased recycling rates and resource recovery. These measures are essential for environmental sustainability [33, 34]. Osibanjo and Nnorom emphasise the need for robust regulatory frameworks and public awareness to combat improper e-waste disposal while also highlighting the challenges in designing and implementing EPR schemes that effectively incentivise manufacturers to adopt eco-friendly practices and enhance product design for easier recycling. In Japan and Canada, EPR policies have successfully managed e-waste by ensuring formal collection and processing channels, thereby reducing illegal exports and harmful informal recycling practices [35, 36]. Another study indicates that the primary method of enhancing recycling in India is to implement EPR with WEEE directives and assign responsibility for e-waste collection to producers [37].

2. METHODS

This study uses bibliometric analysis to quantify and represent the management of electronic waste in environmental science research [6]. It employs several mathematical and statistical tools to investigate the literature features of a certain topic, assess the performance of authors, institutions, countries/regions, and journals, discover research hotspots, and forecast future research trends. These techniques include co-authorship, co-occurrence, citation, and co-citation analysis, as well as knowledge domain mapping. Essentially, critical reviews necessitate thorough debates based on bibliometric analysis results. Citation Analysis, as a specialised analytical tool, is a component of a bibliometric method based on citation graphs, which are effectively a network or graphical representation of citations in a document. However, bibliometric analysis is not a substitute for systematic manual reviews. Regarding research tools, the bibliometric analysis for this work was performed using VOSviewer. This specialised tool collects and displays bibliometric networks. It also provides text-mining algorithms for generating co-occurrence networks of significant labels extracted from scientific papers. Content analysis is a systematic approach to researching literature. Researchers use content analysis to learn about the objectives, messages, and impacts of communication content. They can also form opinions regarding the authors and the content and popularity of the works they examine. Content analysis can determine the frequency of specific words, phrases, subjects, or concepts in a historical or contemporary literature collection.

2.1 Procedure and Data Analysis

A data search was conducted on 25th June 2024 and involved the Scopus database. The search was restricted to the last ten years (2014-2024) to identify whether there were any changes in study patterns before and after the pandemic. The retrieved data was limited to article papers written in English only. The search excludes these subject areas: Immunology and Microbiology, Pharmacology, Toxicology and Pharmaceutics Biochemistry, Genetics and Molecular Biology Medicine, Physics and Astronomy, Neuroscience, Veterinary, and Nursing. The search was done based on all document types with titles containing words such as "electronic waste management" OR "e-waste management," OR "managing e-waste," OR "organising e-waste," OR "management of e-waste." The data search process is shown in Figure 2.

3. RESULTS AND DISCUSSION

3.1 Publication by Year

To address RQ1, the research trend by year of publication was monitored. Figure 3 depicts the research trend for EWM publications and citations. It is clear that there was a large increase in publications (39 papers) in 2023, which got 335 citations. The researchers are thought to have recognised the need for electronic waste management on a global scale. Furthermore, the Global E-Waste Monitor has been the primary source of reporting on this critical topic since 2014, with the goal of reducing e-waste mishandling. This might have encouraged researchers around the world to investigate EWM.

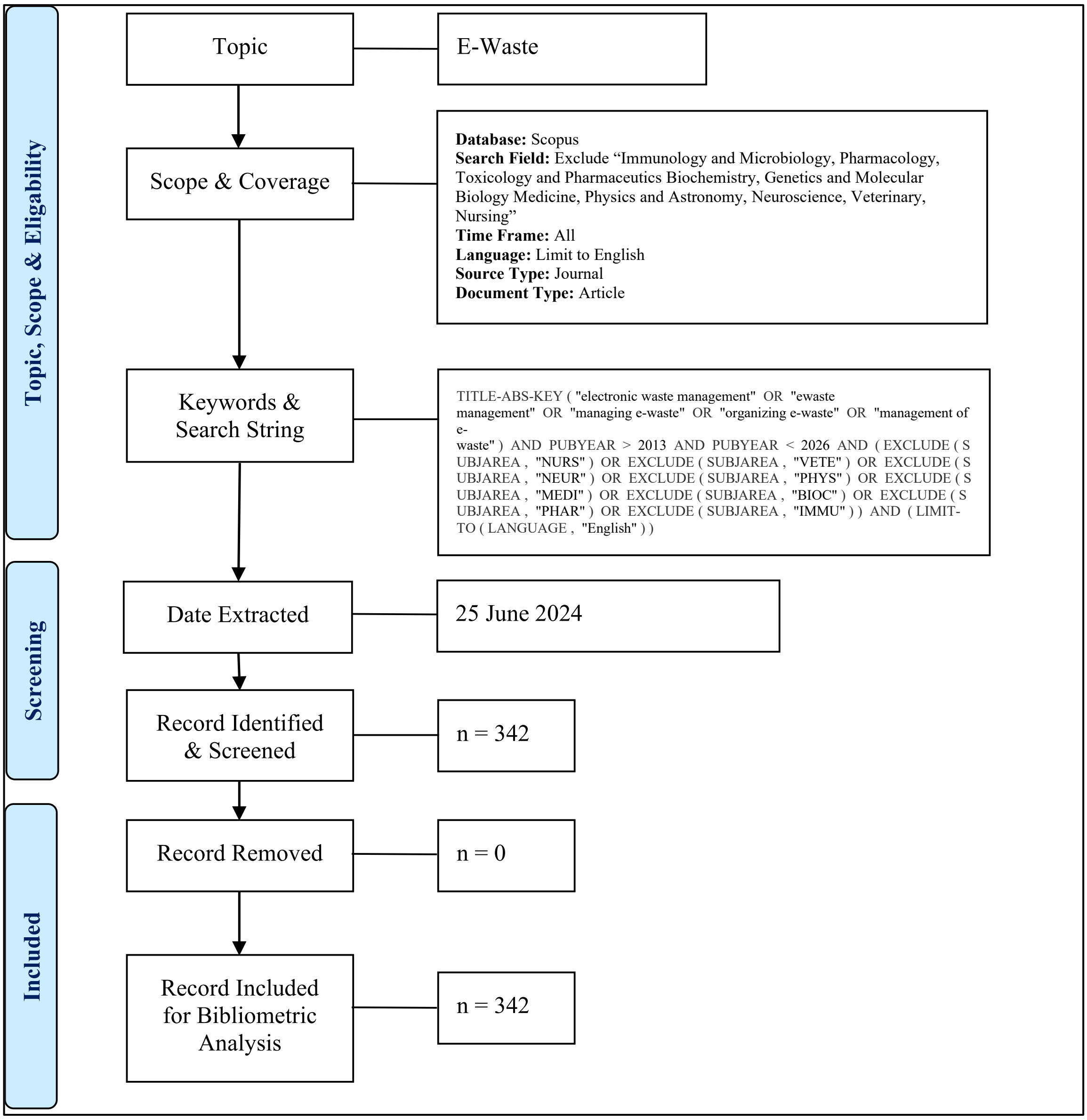

Figure 2: Flow diagram of the search strategy [38, 39].

According to Figure 3 above, EWM-related research has never stopped; it depicts a generally positive research movement in the area of EWM, and it will continue to be a significant subject worldwide. There is a modest decline in 2020 due to MCO globally. Meanwhile, 2022 indicates a tiny reduction due to researchers resetting their study after the post-Covid period. The graph for 2022 ascends quickly due to various variables, including a sharp increase in electronic goods consumption of up to 53.6 mt in 2019 [1], an increased degree of awareness and regulatory pressure, and technological and innovation advancements. The graph indicates an abrupt decrease after 2023 because the search is only completed until June 2024 [Table 1]. This EWM research statistic will inevitably rise in tandem with the growth in electrical and electronic product categories, such as electric vehicles and personal smart devices.

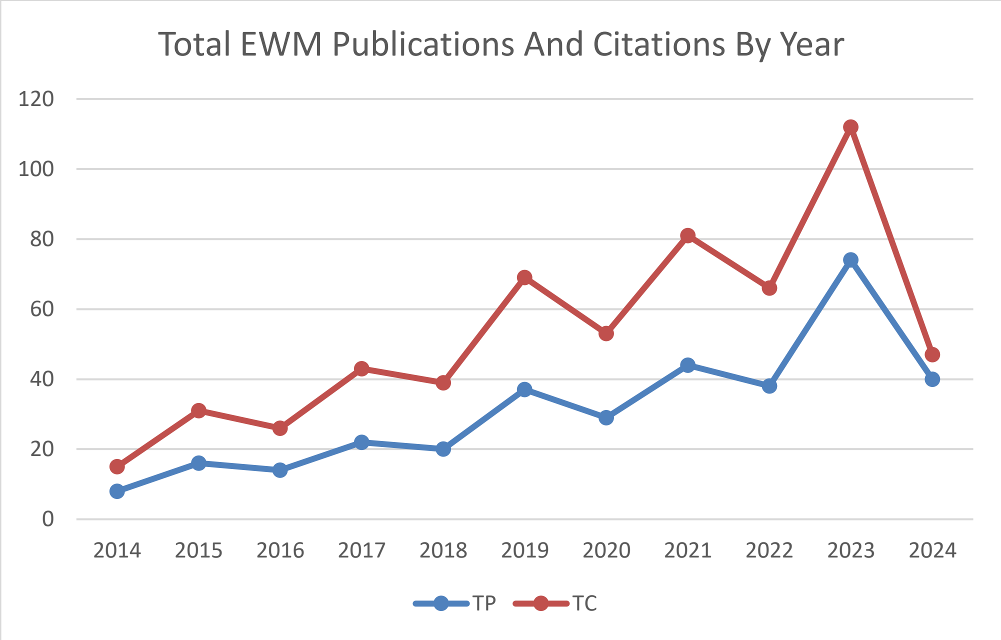

Figure 3: Total EWM documents published and cited in Scopus by year.

Table 1: Year of Publication.

Year	TP	NCP	TC	C/P	C/CP	*h*	*g*
2024	40	11.70%	7	30	0.75	4.29	2
2023	74	21.64%	38	332	4.49	8.74	11
2022	38	11.11%	28	393	10.34	14.04	11
2021	44	12.87%	37	757	17.20	20.46	13
2020	29	8.48%	24	586	20.21	24.42	10
2019	37	10.82%	32	751	20.30	23.47	16
2018	20	5.85%	19	450	22.50	23.68	11
2017	22	6.43%	21	679	30.86	32.33	12
2016	14	4.09%	12	262	18.71	21.83	8
2015	16	4.68%	15	301	18.81	20.07	9
2014	8	2.34%	7	170	21.25	24.29	5

Table 2 shows that half (about 51%) of all publications are classified as Article documents. Conference papers and review papers come next. Table 3 shows that journals account for about 63 percent of all source types, followed by books and proceedings. Table 4 shows that Environmental Science is the most preferred subject area with 187 TP, followed by Engineering (99 TP) and Computer Science (53 TP).

Table 2: Document Type.

Document Type	Total Publications (TP)	Percentage (%)
Article	174	50.88%
Conference Paper	61	17.84%
Review	61	17.84%
Book Chapter	34	9.94%
Conference Review	7	2.05%
Book	3	0.88%
Retracted	1	0.29%
Total	**342**	**100.00**

Table 3: Source Type.

Source Type	Total Publications (TP)	Percentage (%)
Journal	214	62.57%
Book	59	17.25%
Conference Proceeding	43	12.57%
Book Series	26	7.60%
Total	**342**	**100.00**

Table 4: Subject Area.

Subject Area	Total Publications (TP)	Percentage (%)
Environmental Science	187	54.68%
Engineering	99	28.95%
Computer Science	63	18.42%
Social Sciences	60	17.54%
Energy	53	15.50%
Business, Management and Accounting	43	12.57%
Chemical Engineering	31	9.06%
Chemistry	27	7.89%
Materials Science	26	7.60%
Decision Sciences	22	6.43%
Earth and Planetary Sciences	22	6.43%
Economics, Econometrics and Finance	21	6.14%
Agricultural and Biological Sciences	16	4.68%
Mathematics	13	3.80%
Multidisciplinary	4	1.17%
Arts and Humanities	2	0.58%
Psychology	1	0.29%
Total	**342**	**100.00%**

Notes: TP=total number of publications.

3.2 Publication by Country

This study also looked at countries that were actively involved in publications related to the research topic. 66 countries support the research on electronic waste management. The frequency data on nations engaged in the publication were computed using MS Excel, and the findings are shown in Table 5. Twenty countries that ranked highest in contributions to the research topic were collated. India supplied the most articles concerning research on electronic waste management (133:38.89%), followed by China (33:9.65%) publications and the United States and Malaysia (24:7.02%). The top 2 countries are in the Asia continent category. Based on the frequency data from MS Excel, total publications based on countries were mapped using the globe map, as shown in Figure 4. India's popularity as a major producer and consumer of electronics has resulted in enormous e-waste generation, driven by rapid technological advancement and a vast population, causing serious environmental and public health concerns [40]. India's e-waste dilemma has its own specific characteristics and calls for adequate addressing from the research and policy community [41].

Furthermore, the potential for resource recovery from valuable elements in e-waste makes it economically and environmentally vital to investigate sustainable recycling methods [42]. The country's informal recycling sector, which is characterized by harmful practices and a lack of robust regulatory frameworks, highlights the importance of research in developing efficient management methods [43]. China is an issue of concern in e-waste study because of its prominence as the world's largest producer of electronic goods and a significant destination for global e-waste. China's rapid industrialization and urbanization have resulted in significant e-waste generation, posing serious environmental and public health risks [44].

Table 5: Top 20 countries contributed to the publications.

Country	TP	%	Continent
India	133	38.89%	Asia
China	33	9.65%	Asia
United States	24	7.02%	North America
Malaysia	24	7.02%	Asia
United Kingdom	17	4.97%	Europe
Australia	16	4.68%	Oceania
Indonesia	16	4.68%	Asia
South Africa	12	3.51%	Africa
Brazil	10	2.92%	South America
Germany	10	2.92%	Europe
Bangladesh	8	2.34%	Asia
South Korea	8	2.34%	Asia
Canada	7	2.05%	North America
Japan	6	1.75%	Asia
Nigeria	6	1.75%	Africa
Saudi Arabia	6	1.75%	Asia
Sri Lanka	6	1.75%	Asia
Sweden	6	1.75%	Europe
Italy	5	1.46%	Europe
Philippines	5	1.46%	Asia

Notes: TP=total number of publications.

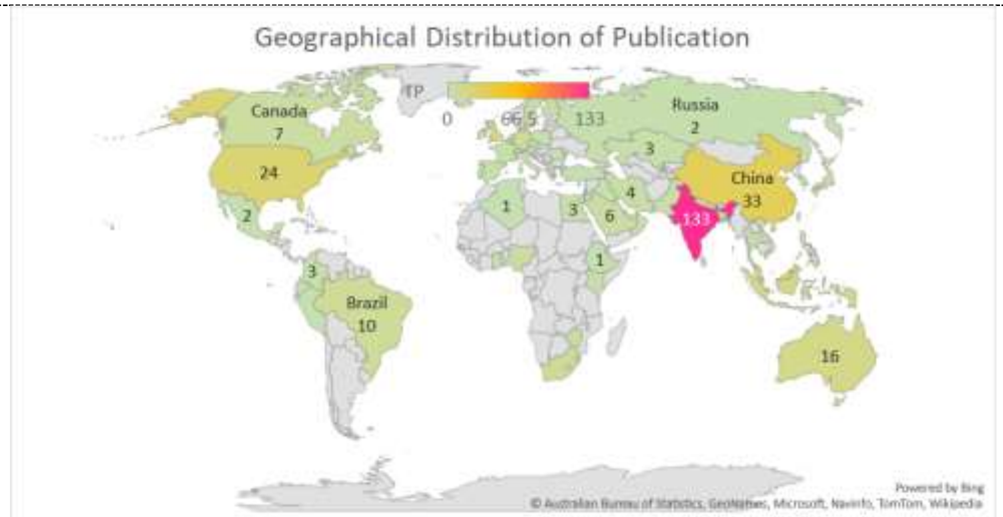

Figure 4: Geographical distribution of publication.

3.3 Publishing Activity by Author and Organization

Data show that 160 organizations were involved in publications concerning the study topic. To answer the RQ2, MS Excel was used to calculate the frequencies and the list of the most influential institutions, as shown in Table 6. The Indian Institute of Technology Delhi is the most significant contributor to the research field, with 9 (2.63%) publications over 10 years, followed by both the Vellore Institute of Technology and the University of Delhi (7:2.05%), also located in India. Table 7 lists the top ten authors in terms of output. According to the data, the most productive author is Borthakur, A. of Jawaharlal Nehru University, India, who authored eight publications (2.34%). Jadhao of the Indian Institute of Technology Delhi and Pant of Central University of Himachal Pradesh, both from India, contributed 6 (1.75%) papers to the research topic. These findings relevantly answered RQ4.

Table 6: Most influential institutions with a minimum of five publications.

Affiliation	Country	TP	%
Indian Institute of Technology Delhi	India	9	2.63%
Vellore Institute of Technology	India	7	2.05%
University of Delhi	India	7	2.05%
National Environmental Engineering Research Institute India	India	6	1.75%
Jawaharlal Nehru University	India	6	1.75%
Academy of Scientific and Innovative Research AcSIR	India	6	1.75%
Council of Scientific and Industrial Research India	India	5	1.46%
Chinese Academy of Sciences	China	5	1.46%
Tsinghua University	China	5	1.46%
Universitas Diponegoro	Indonesia	5	1.46%

Notes: TP=total number of publications.

Table 7: Most Productive Authors.

Author's Name	Affiliation	TP	%
Borthakur, A.	Jawaharlal Nehru University, India	8	2.34%
Jadhao, P.R.	Indian Institute of Technology Delhi, India	6	1.75%
Pant, K.K.	Central University of Himachal Pradesh, India	6	1.75%
Rautela, R.	CSIR- National Environmental Engineering Research Institute (NEERI), India	5	1.46%
Dutta, D.	SRM University—AP, Amaravati, India	4	1.17%
Govind, M.	Jawaharlal Nehru University, India	4	1.17%
Kumar, S.	CSIR- National Environmental Engineering Research Institute (NEERI), India	4	1.17%
Li, J.	Tsinghua University, Beijing, China	4	1.17%
Maphosa, V.	National University of Science and Technology, Zimbabwe	4	1.17%
Mohammad, R.	UTM Razak School of Engineering and Advanced Technology Universiti Teknologi Malaysia	4	1.17%

Notes: TP=total number of publications.

The 342 articles gathered from the Scopus database were published in 32 publications. According to the frequency statistics as shown in Table 8, the Journal of Sustainability Switzerland was the most active in publishing electronic waste management articles, publishing 15 (4.39%) articles between 2014 and 2024. Following that is Environmental Science and Pollution Research, which has published 11 (3.22%) articles, and Iop Conference Series Earth and Environmental Science and Journal of Cleaner Production, which both have 10 (2.92%) publications.

Table 8: Most Active Source Title

Source Title	TP	%	Publisher
Sustainability Switzerland	15	4.39%	Multidisciplinary Digital Publishing Institute (MDPI)
Environmental Science and Pollution Research	11	3.22%	Springer Nature
Iop Conference Series Earth and Environmental Science	10	2.92%	IoP Publishing
Journal Of Cleaner Production	10	2.92%	Elsevier
Handbook Of Electronic Waste Management International Best Practices and Case Studies	7	2.05%	Elsevier
Waste Management	6	1.75%	Elsevier
Electronic Waste Management and Treatment Technology	5	1.46%	Elsevier
Handbook Of Solid Waste Management Sustainability Through Circular Economy	5	1.46%	Springer Nature
Issues In Environmental Science and Technology	7	492	Royal Society of Chemistry
Science Of the Total Environment	7	43	Elsevier

Notes: TP=total number of publications.

3.4 Citation Network Analysis

This study is expected to identify the most significant publication based on RQ2 (Which are the most influential articles on electronic waste management?). Thus, to answer the RQ, citation networks of 342 publications were examined. To perform the centrality analysis of citations and construct a network visualisation map of the article's citations, the Harzing Publish or Perish and VOSViewer tools were used. Table 9 shows the citation metrics data for the publications. As for the 342 articles on electronic waste management, there were 4714 citations. The typical number of citations per year is 471.4, with each document receiving an average of 13.8.

Table 9:
Citations Metric.

Citation metrics	Data
Papers	342
Citations	4714
Years	10
Annual Citations	471.4
Citations per paper	13.78
Citations per author	1667.22
h-index	35
g-index	57

Figure 5 depicts the network visualisation map for document citations by country. The minimum number of articles and citations for a country was set at five. There are 66 countries active in research-related publications. However, only 20 countries were linked and organised into 7 clusters. On the network visualisation map, India is marked with the largest circle, demonstrating that articles published by Indian writers are the most cited in publications concerning the study topic. According to the network visualisation map, other articles on electronic waste management consistently cited 179 documents produced by Indian authors with 68 links. Hence, by referring to the other significant circles on the network visualisation map, this study found papers written by authors from China (33, 13 links), Malaysia (24, 7 links) and the United States (24, 11 links) that were frequently cited.

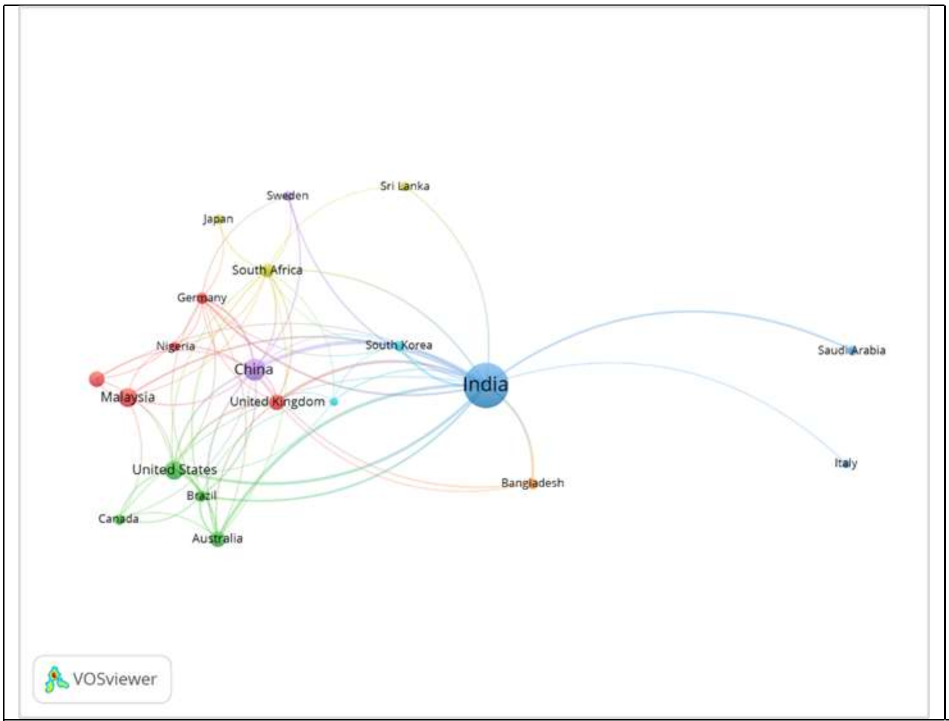

Figure 5: Network visualisation map of the citation by countries.

This study found papers that had received the most references using information from the Scopus database. The list of highly referenced publications on the research topic is shown in Table 10. A. Borthakur, M. Govind wrote the most cited article entitled "Emerging Trends in Consumers' E-waste Disposal Behaviour and Awareness: A Worldwide Overview with special focus on India," which was published in 2017 and had 175 citations. Next was the paper entitled "E-waste Management and its Effects on the Environment and Human Health" by R. Rautela, S. Arya, S. Vishwakarma, J. Lee, K.-H. Kim, S. Kumar, with 168 citations. Followed by K. Parajuly, C.

Fitzpatrick, O. Muldoon, R. Kuehr with 144 citations, paper entitled "Behavioural change for the circular economy: A review with a focus on electronic waste management in the EU."

Table 10: Top 20 highly cited articles.

No.	Authors	Title	Year Publication	Publisher	Citations
1	A. Borthakur, MGovind	Emerging trends in consumers' e-waste disposal behaviour and awareness: A worldwide overview with special focus on India	2017	Resources, Conservation and Recycling	175
2	R. Rautela, S. Arya, S. Vishwakarma, J. Lee, K.-H. Kim, S. Kumar	E-waste management and its effects on the environment and human health	2021	Science of the Total Environment	164
3	K. Parajuly, C. Fitzpatrick, O. Muldoon, R. Kuehr	Behavioural change for the circular economy: A review with a focus on electronic waste management in the EU	2020	Resources, Conservation and Recycling: X	144
4	G. Nagaraju, S.C. Sekhar, J.S. Yu	Utilising Waste Cable Wires for High-Performance Fiber-Based Hybrid Supercapacitors: An Effective Approach to Electronic-Waste Management	2018	Advanced Energy Materials	143
5	X. Zeng, H. Duan, F. Wang, J. Li	Examining environmental management of e-waste: China's experience and lessons	2017	Renewable and Sustainable Energy Reviews	142
6	K.D. Kang, H. Kang, I.M.S.K. Ilankoon, C.Y. Chong	Electronic waste collection systems using Internet of Things (IoT): Household electronic waste management in Malaysia	2020	Journal of Cleaner Production	101
7	C.P. Garg	Modelling the e-waste mitigation strategies using grey theory and DEMATEL framework	2021	Journal of Cleaner Production	98
8	M. Premalatha, T. Abbasi, S.A. Abbasi	The generation, impact, and management of e-waste: State of the art	2014	Critical Reviews in Environmental Science and Technology	88
9	H. Duan, J. Hu, Q. Tan, L. Liu, Y. Wang, J. Li	Systematic characterisation of generation and management of e-waste in China	2016	Environmental Science and Pollution Research	84
10	A. Król, P. Nowakowski, B. Mrówczyńska	How to improve WEEE management? The novel approach in mobile collection with an application of artificial intelligence	2016	Waste Management	76
11	P.R. Jadhao, E. Ahmad, K.K. Pant, K.D.P. Nigam	Environmentally friendly approach for the recovery of metallic fraction from waste printed circuit boards using pyrolysis and ultrasonication	2020	Waste Management	71
12	A. Islam, A.M. Swaraz, S.H. Teo, Y.H. Taufiq-Yap, D.-V.N. Vo, M.L. Ibrahim, G. Abdulkreem-Alsultan, U. Rashid, M.R. Awual	Advances in physiochemical and biotechnological approaches for sustainable metal recovery from e-waste: A critical review	2021	Journal of Cleaner Production	71
13	Y.S. Yong, Y.A. Lim, I.M.S.K. Ilankoon	An analysis of electronic waste management strategies and recycling operations in Malaysia: Challenges and future prospects	2019	Journal of Cleaner Production	70
14	C. Cau Dit Coumes, M. Dhoury, J.-B. Champenois, C. Mercier, D. Damidot	Combined effects of lithium and borate ions on the hydration of calcium sulfoaluminate cement	2017	Cement and Concrete Research	68
15	S. Nandy, E. Fortunato, R. Martins	Green economy and waste management: An inevitable plan for materials science	2022	Progress in Natural Science: Materials International	67
16	M. Xue, A. Kendall, Z. Xu, J.M. Schoenung	Waste management of printed wiring boards: A life cycle assessment of the metals recycling chain from liberation through refining	2015	Environmental Science and Technology	66
17	N. Gupta, P. Bedi	E-waste Management Using Blockchain-based Smart Contracts	2018	2018 International Conference on Advances in Computing, Communications and Informatics, ICACCI 2018	63

No.	Authors	Title	Year Publication	Publisher	Citations
18	N. Safdar, R. Khalid, W. Ahmed, M. Imran	Reverse logistics network design of e-waste management under the triple-bottom-line approach	2020	Journal of Cleaner Production	63
19	R. Heeks, L. Subramanian, C. Jones	Understanding e-waste Management in Developing Countries: Strategies, Determinants, and Policy Implications in the Indian ICT Sector	2015	Information Technology for Development	61
20	N. Singh, H. Duan, O.A. Ogunseitan, J. Li, Y. Tang	Toxicity trends in e-waste: A comparative analysis of metals in discarded mobile phones	2019	Journal of Hazardous Materials	59

3.5 Keywords and Co-occurrence Analysis

According to Kent Baker *et al.* [45], co-occurring keywords are those that suggest popular themes, appear in an article and indicate that two thoughts are connected. In response to RQ3 (What are the most common academic electronic waste management topics?), this current study aimed to determine the most frequently used keywords by researchers investigating electronic waste management (EWM). Data frequencies of keywords employed in the research topic were calculated using MS Excel, and the results are displayed in Table 11. “Electronic waste” is the most frequently used keyword in EWM (198: 57.89%), followed by “E-waste” with (134: 39.18%) and “Recycling” with (133: 38.89%). This study also ran the keyword co-occurrence analysis using the VOSViewer software to build a network visualisation map. Fractional counting was used, and the minimum number of occurrences was set at five per publication. Of the 2341 keywords, only 137 were related. Therefore, it was decided to create a network visualisation map that only showed the keywords related to each other. Figure 6 depicts a network visualisation map for the co-occurrence of the author’s keywords. The largest circle identified “electronic waste” (198 occurrences) as the most often used keyword by writers in publications related to the research topic. Other primary keywords discovered were “e-waste” (146 occurrences), “recycling” (133 occurrences), and “waste” (119 occurrences). The phrases "e-waste" and "e-waste" have distinct meanings, which can be utilised to tailor search tactics to specific research objectives. The term "e-waste" is commonly used to refer to a wide range of studies on electronic waste management and policy. In contrast, "e-waste" frequently focuses on specific categories or occurrences of electronic waste, providing more comprehensive and targeted results.

Table 11: Top Keywords.

Author Keywords	Total Publications (TP)	Percentage (%)
Electronic Waste	198	57.89%
E-waste	134	39.18%
Recycling	133	38.89%
Wastes	119	34.80%
Waste Management	99	28.95%
Electronic Equipment	60	17.54%
Waste Disposal	59	17.25%
E-wastes	55	16.08%
Sustainable Development	44	12.87%
E-waste Management	40	11.70%
Electronic Waste Management	38	11.11%
Electronics Wastes	38	11.11%
Oscillators (electronic)	38	11.11%
Sustainability	31	9.06%
Environmental Management	28	8.19%

Notes: TP=total number of publications.

This study analysed the term co-occurrences of the title and abstract fields while reviewing the content of publications focused on electronic waste management using the VOSViewer software. Binary counting was used, and the requirement was that a term should appear at least ten times in the title and abstract of articles. As a result, 5738 terms met the criterion out of 13,320 total terms. By default, the software considered 43% of the criterion noteworthy, resulting in 129 terms being declared relevant. Using the titles and abstracts of the 342 Scopus papers as a basis, Figure 7 shows a network visualisation map of term co-occurrences of the title and abstract field. It shows the network visualisation map with five clusters. The largest circle of each colour was used to symbolise the content of each cluster. The Red theme (Cluster 1) focused on researching electronic waste resource recovery with 40 items, whereas the Green theme (Cluster 2) highlighted the study of factors of consumer awareness and sustainability (32 items). The Blue theme (Cluster 3) depicts the policy, regulations, and legislation of the government study with 28 items, and the Yellow theme (Cluster 4) describes the pollution and health study. In contrast, the Purple theme (Cluster 5) depicts the study on WEEE and EEE methodology.

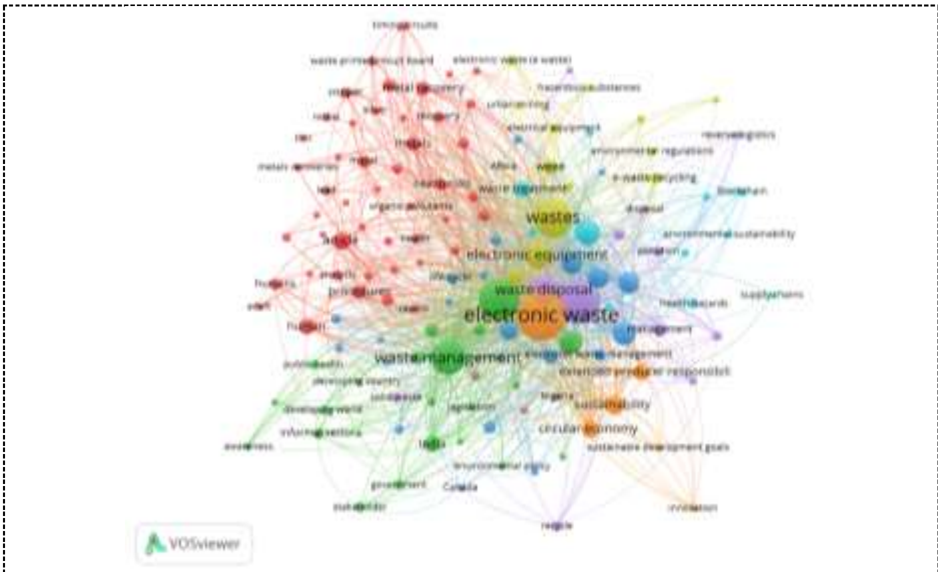

Figure 6: Network visualisation map of the co-occurrence of keywords.

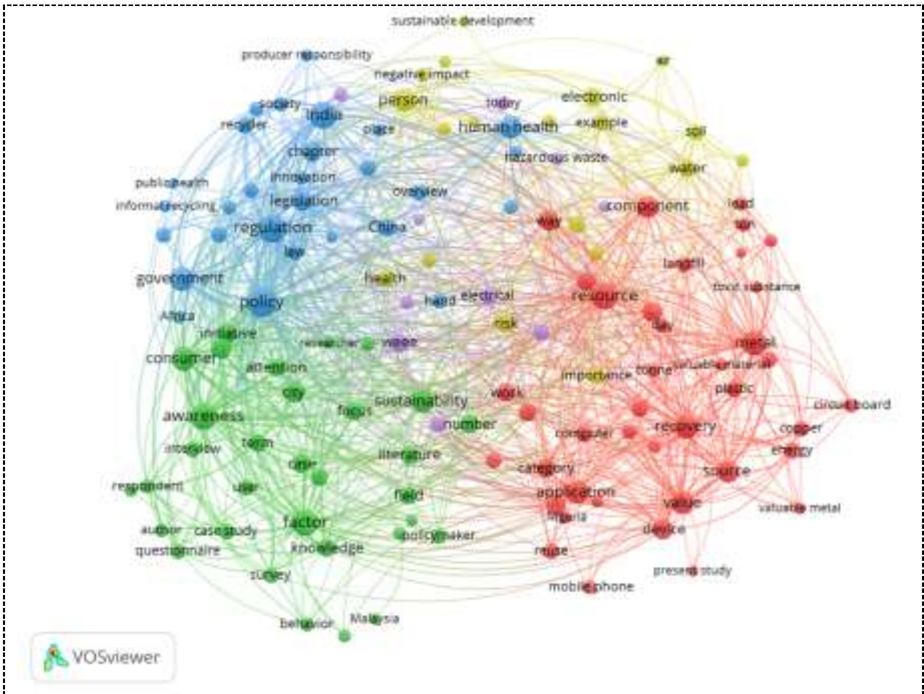

Figure 7: VOSviewer visualisation of a term co-occurrence on title and abstract fields.

3.6 Co-authorship Analysis

To answer the RQ, this study undertook a co-authorship study using the VOSViewer software to analyse the current relationship between writers. According to the data subset, 1025 writers contributed to 342 papers on electronic waste management.

3.6.1 Centrality analysis of the co-authorship network

Figure 8 depicts a network visualisation map of co-authorship by authors in electronic waste management articles. Fractional counting was employed, and the minimum number of papers and citations was set at one. One hundred sixty papers are connected as indicated in the 8 clusters shown on the network visualisation map. This answered RQ5, and it demonstrates the collaboration among writers in their respective areas of research.

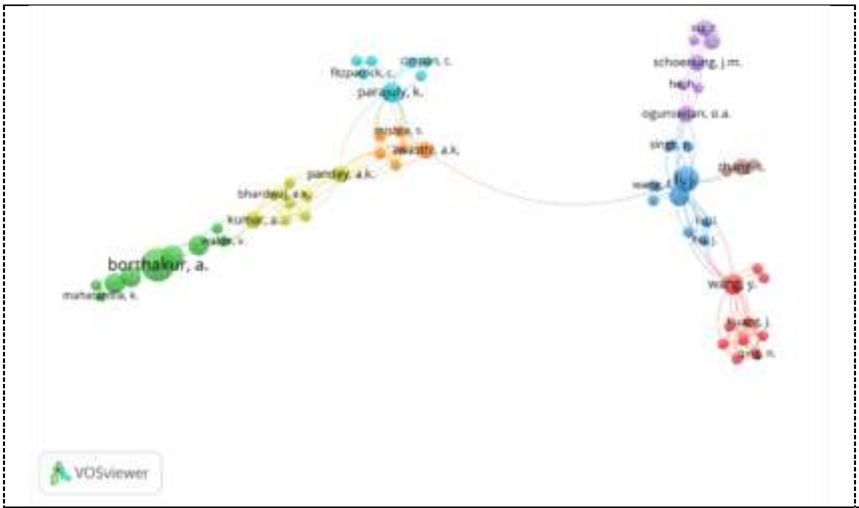

Figure 8: Network visualisation map of co-authorship by authors.

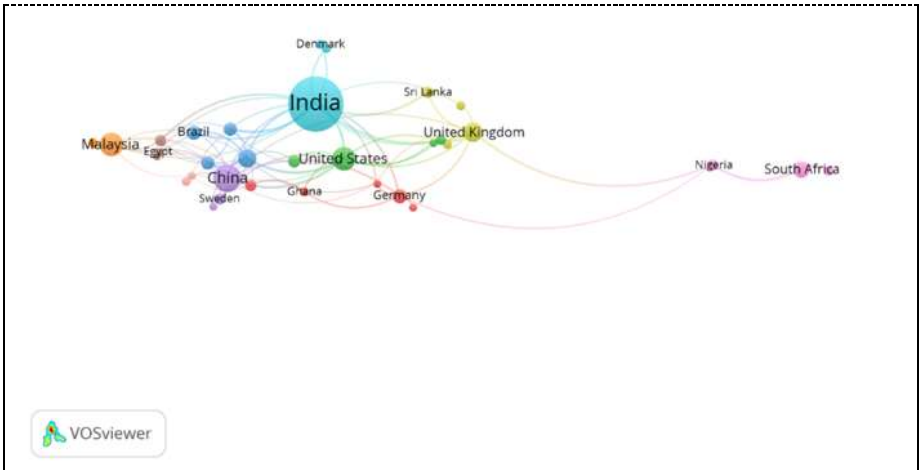

Figure 9: The network visualisation map for co-authorship by country.

Additionally, this study produced a network visualization map based on country co-authorship. Fractional counting was used, and a country needed to have a minimum of three documents and one citation. Only 38 out of 65 nations participating in electronic waste management publications met the threshold. Figure 9 shows the network visualization map for co-authorship by country with 10 clusters. Based on the largest circle in the network visualization map, it was found that authors from India, China, the United States of America, Malaysia, and the United Kingdom collaborated with other countries on the research topic. Furthermore, the network visualization map shows that authors from India (17:23 link strength) and China (13:14 link strength) have a significant co-author link with authors from other nations, including Malaysia, the United States of America, and the United Kingdom.

3.7 Co-citation Analysis

Co-citation analysis helps researchers understand the conceptual structure of science and foresee future developments. It focuses on the intellectual development and organisation of scientific disciplines [46]. According to Liu, it is also beneficial to highlight the direction, structure, and advances in a study domain [47]. Using co-citation analysis, this study focused on understanding the intellectual framework of the study's issue to answer the RQ.

A network visualisation map was created using the VOSViewer software to observe the co-citation network among the cited authors in publications related to the study topic. Fractional counting was used, and a minimum requirement of ten author citations was set. Figure 10 depicts the co-citation network based on cited authors. Out of the 22272 authors who submitted their papers, 704 met the threshold. There are five clusters shown in the network visualisation map. Authors in the same cluster are thought to have referenced one another in their papers. Each cluster usually represents a different discussion point on electronic waste management.

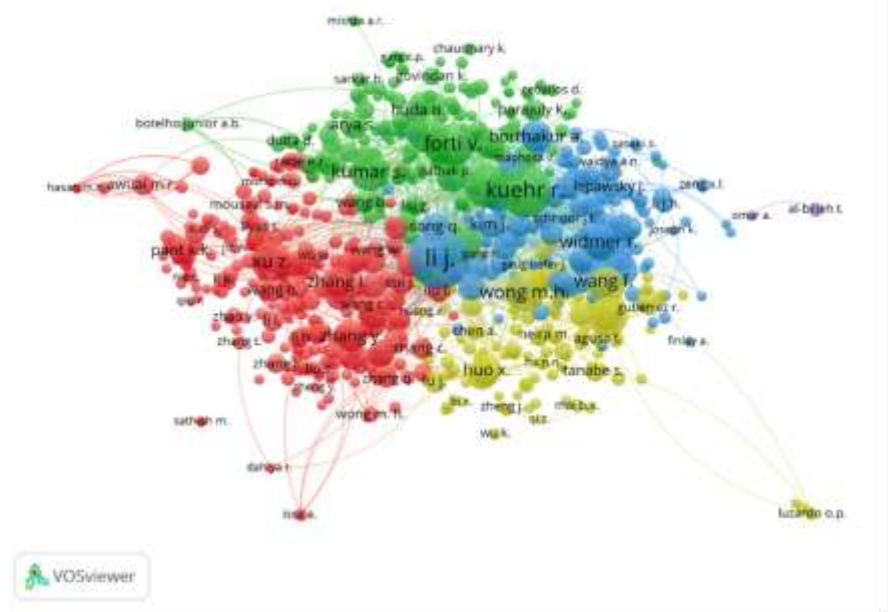

Figure 10: Network visualisation map of the co-citation network among the cited authors.

3.7.1 Literature Classification

According to Xu *et al.* [48], data clustering can be used in a co-citation analysis to identify patterns of collaboration and interrelationship [48]. This current study conducted a co-citation analysis of cited references using the VOSViewer software. Fractional counting was selected, and the minimum number of cited references was set at 5. Out of 15554 cited references, 53 met the threshold, with only 364 cited references connected. Figure 11 shows the four clusters that were assigned with different colors each. Cluster 1 (Red) listed 16 cited references based on the co-citation of the cited references' network visualization map. The most cited reference (10 citations, 17 links) in Cluster 1 is an article entitled "E-Waste: An overview on generation, collection, legislation and recycling practices ” by Kumar *et al.* [49]. Cluster 2 (Green) shows 13 cited references. An article by Forti *et al.* [1] entitled “The Global E-Waste Monitor 2020: Quantities, flows, and the circular economy potential” (24 citations) is the most cited article in Cluster 2. Cluster 3 (Blue) shows 13 cited references, and Robinson's article entitled “E-Waste: An Assessment of Global Production and Environmental Impacts” contained the most cited references. Cluster 4 (Yellow) presents 11 cited references. The most cited reference in Cluster 4 is “Global Perspective on e-waste” by Widmer *et al.* [50].

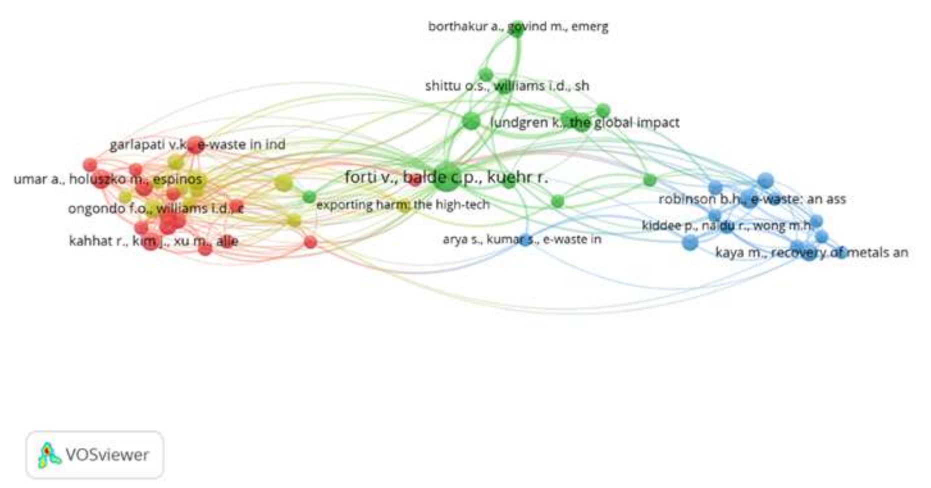

Figure 11: Network visualisation map of co-citations of cited references.

3.7.2 Cluster 1 (Red): E-waste Recycling

Many studies' findings indicate statistics on global e-waste generation and the sales of new electrical equipment and electronics in general. Studies found that there is a direct link between a country’s gross domestic product (GDP) and its e-waste generation. However, the population of the country doesn’t have a significant impact. Red clusters briefly highlight the importance and benefits of recycling and discuss the current techniques used in recycling facilities. New technologies for collecting, recycling, and reusing electronic e-waste are vital for global management. This is a critical issue for sustainability, both domestically and worldwide. To address e-waste challenges, an affordable and environmentally friendly recycling system must be designed, with valuable and dangerous components separated. Effective ways for managing e-waste include EPR and CE initiatives, legislative measures, and public education. To get everyone in the community to engage well in e-waste recycling, future initiatives should include rigorous rules, innovative technologies, and enhanced community awareness.

3.7.3 Cluster 2 (Green): Global E-waste Management

Cluster Green generally discusses global e-waste issues. Effective e-waste management requires collaboration between local governments and recycling operators, community participation and national, regional, and global initiatives. Pilot programs in the e-waste recycling sector can promote green jobs, create organizational capacity, and foster public-private partnerships while addressing poverty reduction. It can exchange information by launching an e-waste code of practice, publishing best practices, collaborating with other organizations, and promoting green jobs. As discussed in most papers, there are issues to address in all elements of e-waste. Several factors contribute to e-waste issues, including consumer unwillingness to return and pay for disposal, uncoordinated importation of e-waste disguised as secondhand devices, a lack of awareness among consumers and collectors, a lack of funds and investment to improve e-waste recycling, a lack of recycling infrastructure, and inadequate management of e-waste. In addition to these difficulties, there is an increase in cybersecurity risks, as discarded devices may contain sensitive data.

3.7.4 Cluster 3 (Blue): Environmental Impact and Health Issues

Electronic waste is a significant environmental and health issue caused by inappropriate disposal and recycling of electronic devices. Cluster 3 discusses more about how the accumulation of e-waste causes the release of harmful compounds such as lead, mercury, and cadmium, which contaminate soil and water sources and harm ecosystems and human health. Proper management and recycling procedures are critical for reducing these hazards and fostering a sustainable future. Unfortunately, a huge portion of e-waste is not effectively recycled, resulting in significant environmental damage [51]. The World Health Organization's [52] thorough report emphasised the urgent need for effective measures to protect children and other vulnerable groups from the dangers of e-waste. Research focused on the carcinogenic risks associated with e-waste, particularly noting the presence of harmful substances like polycyclic aromatic hydrocarbons in affected areas [53]**.** Robinson [54] provides a comprehensive assessment of global e-waste production and its environmental impacts. He highlights that e-waste contains hazardous materials that pose severe health risks. For instance, exposure to e-waste can lead to respiratory problems, skin diseases, and other health issues due to releasing toxic chemicals during the informal recycling process. Research by Grant [55] found that people living in e-waste recycling towns or working in e-waste recycling had evidence of greater DNA damage than those living in control towns [55].

4. DISCUSSION

The citation analysis revealed the most prominent article on electronic waste management written by Borthakur and Govind [41] from India, with 175 citations. Followed by Rautela et al. [56] in 2021 with 164 citations, and Parajuly et al. [57] with 144 citations. Effective e-waste management needs the integration of behavioural science insights to encourage environmentally friendly consumption and pro-environmental behaviours. A conclusion to these papers analyses behavioural theories and emphasises the necessity of understanding consumer disposal behaviour and awareness, pointing out major variances both globally and within countries. By utilising global expertise and applying systematic management approaches, particularly in developing regions, countries can improve e-waste management practices, promote a circular economy, and reduce negative environmental impacts. Furthermore, the keyword and occurrences analysis showed that “electronic waste”, “e-waste,” and “recycling” are the most popular keywords used by authors in publications on the research topic. The co-occurrences of the title and abstract field show that the highest content focused on electronic waste resource recovery, followed by the study of factors of consumer awareness and sustainability, the policy, regulations, legislation of the government, the pollution and health study, and the smallest cluster circle is on the study of WEEE and EEE methodology.

Analyses of co-authored works and their citations have indicated global collaboration and networking among researchers, as well as citations in their publications. Both analyses helped this study undertake a content analysis of the data collected. The content analysis indicates that EWM has four dimensions of enablers: social and policy, economy, technology, and environment. More concerns are raised about resource recovery, the environmental impact of e-waste, and the policies and procedures utilised to develop comprehensive and long-term e-waste management solutions. This is critical for successfully handling the ever-increasing and limitless volume of electronic waste.

Further research should be conducted into effective public policies and international collaboration to promote sustainable e-waste management, focusing on consumer behaviour and awareness, and the integration of informal recycling sectors. Consequently, additional studies should concentrate on important areas such as technological advancements, cost-effective methods for efficient e-waste processing, and material recovery, with a special emphasis on scalable worldwide solutions. Furthermore, comparative examinations of worldwide practices might assist in finding effective ways, particularly for integrating informal sectors into formal systems. Research should also improve circular economy methods for e-waste management, promoting durable and recyclable products. More research should be conducted to determine the long-term effects of harmful e-waste, as well as preventative measures, particularly in economically deprived communities. Finally, while many studies have been conducted on various aspects of e-waste, such as technology, policy instruments, management, and recycling techniques, few have taken a sustainability-focused approach to studying the issue. This research has limitations. We exclusively used the Scopus database for this research. Second, we only considered publications from the previous ten years. Third, a few search fields are excluded, including immunology and microbiology, pharmacology, toxicology, and others. To conduct a thorough analysis, it's recommended to check multiple databases.

5. CONCLUSION

The Scopus database was used to undertake a comprehensive bibliometric analysis of scientific production related to waste electrical and electronic equipment (WEEE) throughout the last decade (2014-2024). Overall, the study of electronic waste continues to grow year after year. Although the publication of e-waste-related articles decreased during the pandemic from 2019 to 2021, an abrupt spike occurred afterward. These studies made major contributions to the field by evaluating factors influencing e-waste management in many nations and identifying crucial research that has worldwide influenced future citations, despite its sometimes-small contribution. Through content analysis, this study categorized previous research into five clusters, highlighting the popular keywords used by researchers in this field. The key research themes highlighted were electronic waste recycling, environmental implications, sustainability, circular economy, and efficient e-waste management systems. The Asian continents contributed significantly to research production. The study discovers that increasing amounts of WEEE require additional scientific research and the development of robust public regulations to mitigate the negative environmental and health consequences of improper disposal. This research has crucial management and policy implications, highlighting the need for sustainable practices and effective recycling technology to address the worldwide e-waste situation. The presented approach aims to provide a complete overview of the current state of e-waste management and to map the direction for future research and policy development to solve this rising global challenge. However, the data in this study are limited to the Scopus database, and future studies can expand by collecting data from other databases. Future research could also look into how the evolution of electronic waste through different paradigms can assist in solving the current challenges in this field.

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