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Bibliometric review of electro-electronic waste (WEEE) in the Web of Science database: groups' production and main themes

Revisão bibliométrica de resíduos eletroeletrônicos (REEE) no banco de dados da Web of Science: produção de grupos e principais temas

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ABSTRACT

The waste of electrical and electronic equipment (WEEE) has been one of the largest and growing wastes generated in the world, turning into a great challenge for humanity. The objective of the article was to map the scientific production on WEEE in the last decade (2012–2022), adopting a bibliometric analysis as a research method based on the survey of documents obtained from the Web of Science database. A total of 278 research and review articles were selected for analysis, with the use of Vosviewer and RStudio software. As a result, there was a significant increase in the number of publications in the last decade, with 86% of articles published between 2015 and 2022. In addition, it was possible to obtain the ranking of the most important authors, and the journals most used for publication of articles; it was found that the Asian, European and American continents had the greatest contribution. In the analysis of document coupling, combined with that of keywords, the main areas connected to WEEE currently researched were found: electronic waste recycling; environmental impacts; sustainability; circular economy; efficient e-waste management and e-waste recycling technologies; in addition, the keywords "e-waste" and "polybrominated diphenyl ethers" were the most frequent words used by the authors to represent the theme. It can be concluded that the theme has stood out over the last few years, with several publications providing managerial and political implications for researchers and professionals.

Keywords: bibliometric analysis; circular economy; environmental Impact; electronic waste; sustainability.

RESUMO

Os resíduos de equipamentos elétricos e eletrônicos (REEE) têm sido dos maiores e crescentes resíduos gerados em todo o mundo, tornando-se um dos grandes desafios da humanidade. O objetivo do artigo foi mapear a produção cientifica sobre REEE na última década (2012–2022), adotando como método de pesquisa uma análise bibliométrica com base no levantamento de documentos obtidos da base de dados Web of Science. O total de 278 artigos de pesquisa e revisão foi selecionado para análise utilizando o *software* Vosviewer e RStudio. Obteve-se, como resultado, um aumento significativo nos números de publicações na última década, com 86% dos artigos publicados entre 2015 e 2022. Além disso, foi possível obter o *ranking* dos autores mais importantes e revistas mais utilizadas para publicação dos artigos; constatou-se que o continente asiático, europeu e americano foram os que tiveram maior contribuição. Na análise de acoplamento de documentos, combinada com a de palavras-chaves, constataram-se as principais áreas pesquisadas atualmente em relação ao REEE: reciclagem de lixo eletrônico; impactos ambientais; sustentabilidade; economia circular; gestão eficiente lixo eletrônico e tecnologias para reciclagem lixo eletrônico. além disso, as palavras-chave "e-waste" e "polybrominated diphenyl ethers" foram as com maior frequência utilizadas pelos autores para representar a temática. Pode-se concluir que a temática tem se destacado ao longo dos últimos anos com diversas publicações, fornecendo implicações gerenciais e políticas para pesquisadores e profissionais.

Palavras-chave: análise bibliométrica; cconomia circular; impacto ambiental; lixo eletrônico; sustentabilidade.

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Introduction

The strong inclusion of electronic equipment in our lives and the speed at which such equipment become technologically outdated has led to an unprecedented increase in the waste of electrical and electronic equipment (WEEE) (Perkins et al., 2014). Emerging technologies (e.g., 5G technology and virtual reality) compound the accelerating rate of electronic obsolescence, generating new e-waste streams (Shittu et al., 2021).

The electronics industry produces different types of WEEE, which contain toxic and hazardous substances that significantly threaten the environment and human health (Bressanelli et al., 2019). On the other hand, e-waste contains precious metals and raw materials that, if recycled, could be useful for long-term economic and environmental sustainability.

According to the 2020 global e-waste monitoring report (Forti et al., 2020), e-waste production in 2019 was around 53.6 million tons, of which 17.4% were duly collected and recycled, preventing the equivalent of up to 15 million tons of carbon dioxide from being released into the environment. The remaining 82.6% did not reach processing units for this type of waste, indicating they were inappropriately disposed of, mostly in the ecosystem. This data becomes more alarming when estimates indicate that global electronic waste should reach 74.7 million metric tons by 2030 (Forti et al., 2020), with 80% being generated in developed countries in Europe and North America.

Southeast Asia and Africa are now some of the largest recipients of e-waste in the world (Lepawsky, 2015). However, this data goes against sustainability; according to a report by the International Telecommunication Union, only 0.1% of e-waste is formally recycled in Africa, which is targeting a global collection and recycling rate of 30% by 2023 (Forti et al., 2020).

Therefore, the increasing levels of electronic waste, as well as the inappropriate and unsafe treatment and disposal, represent significant challenges for the environment and human health. Their inadequate management contributes significantly to global warming, which makes the intensification of scientific studies to find a better use for this waste necessary, as much as sustaining public policies to properly dispose of WEEE and mitigate the environmental impacts caused by incorrect disposal.

In the literature, several authors reported different reviews on electronic waste that support this research. Among them are studies on its management (Li et al., 2013; Pérez-Belis et al., 2015; Tsai et al., 2020; Shittu et al., 2021); reverse logistic (Govindan and Soleimani, 2017; Islam and Huda, 2018; Türkeli et al., 2018); the production of WEE (Ismail and Hanafiah, 2020); its recycling (Zhang and Xu, 2016); life cycle evaluation (Ismail and Hanafiah, 2019; Corrêa Nunes et al., 2021), emphasising the challenges and opportunities in a global context (Sharma et al., 2010; Ilankoon et al., 2018; Goodship et al., 2019; Gollakota et al., 2020); or a case study of one particular country (de Oliveira Neto et al., 2019).

In the last 10 years, the research on WEEE has been increasing, as demonstrated in this study. Several peer-reviewed articles have been published in high-impact journals focusing on WEEE and its subtopics. However, there are few bibliometric studies aligned with this theme (Zhang et al., 2019). Therefore, the purpose of this work was to map the scientific production on WEEE using bibliometrics.

This article used the Web of Science (WoS) database to retrieve publication data in the form of ranking authors, countries, journals, citations, and search fields as important keywords.

By mapping the domain of knowledge, this bibliometric analysis accounted for the main terms used in scientific production on the subject, identifying research networks, research flow and relevant topics, becoming a basis for updated guidance for future research in this area. The results present a panoramic view of research directions and several questions derived from documents published on the subject.

Methodology

The data was analyzed through bibliometric indicators, which took into account both the quantitative and qualitative aspects of scientific production, and scientometric indicators, which were used to analyze the quantitative aspects of science. This allowed for the analysis of the scientific productions that were included in the database (Kücher and Feldbauer-Durstmüller, 2019).

The bibliometric analysis for this study was carried out gathering information through the WoS database, and the following filters were applied: period (2012 to 2022), type of document (article review), category (environmental science) and language (English); on the subject of electronic waste, reverse logistics and environmental impacts. The platform was chosen because it provides access to the main citation databases in the world.

The demarcation of the articles using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Prisma) method was conducted through the systematization of four steps: identification, selection, eligibility and inclusion (Moher et al., 2009). This method is widely used to analyze studies published in different areas of science, thus allowing a systematic and integrated analysis of published scientific data.

A brief description of the steps followed for analysis can be seen in Figure 1.

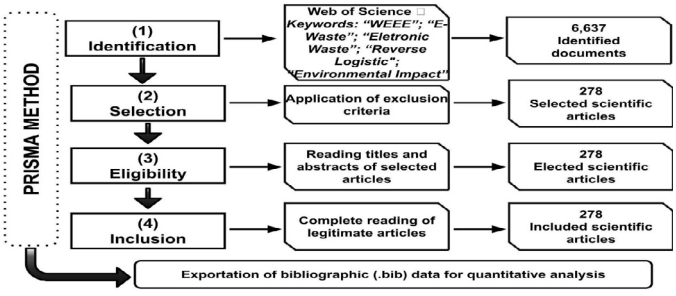

Figure 1 – Systematic flowchart search in the database.
Source: adapted from Guedes et al. (2022).

In the identification stage, a survey was applied to the Web of Science database — Main Collection (CLARIVATE ANALYTICS) platform through "all fields", with the simultaneous application of the terms ("WEEE" OR "e-waste" OR "electronic waste" AND "reverse logistic" AND "environmental impact"), in order to try to reach a greater scope. Then, in the selection stage, the initial search was carried out in April 2022, and the following filters were applied: period (2012 to 2022), type of document (article review); category (environmental science); language (English). Afterwards, in the eligibility stage, the titles and abstracts of the articles were read to confirm their relationship with the addressed theme. Finally, in the inclusion stage, the articles were read in full to leave only those that matched the focus of this study.

As a result, 278 articles filled the selection criteria and were used as the final sample for analysis. Then, the data containing information about the articles were exported in .bib and .csv excel format to be submitted to bibliometric analysis using the Vosviewer software (1.6.17 version) and RStudio.

The Vosviewer software was used to map the bibliometric networks, enabling the quantitative analysis of data regarding the behavior of scientific production on WEEE in the analyzed period. This method made it possible to conduct the research in a more assertive and uniform way on specific groups (author citation, author co-citation, journal citation, country citation, bibliographic coupling of documents and keyword co-occurrence), confirming the study hypotheses.

In the bibliographic coupling analysis of documents, the links indicate the number of shared cited references (Van Eck and Waltman, 2010), that is, when two documents cite the same document, showing the strength of a particular publication compared to other ones (Mulet-Forteza et al., 2018; Cavalcante et al., 2021).

The bibliometric analysis was conducted using the R software (Bibliometrix package). For this stage, the impact factor (IF) of total citations, index H, and the number of articles published by the researcher were considered, which obtain citations greater than or equal to this number, following the methodology described by Almeida et al. (2018).

Finally, the result of the different bibliometric parameters data mapped the bibliometric information of scientific publications in the last decade on the proposed theme.

Results and Discussion

Evolution of publications over time

From the Web of Science database, a total of 6,637 articles participated in the research on electronic waste and produced, after choosing the filters, a total of 278 articles for the bibliometric analysis.

There was an increase in the number of publications on WEEE and its aspects in the last decade (Figure 2). Within the evaluated period, most of the articles on the subject were published in the last seven years (2015–2022). Of the total sample, 36 articles were published before 2015, while 232 articles were published from 2015 onwards. The peak number of articles was published in 2022 (44 articles).

The results establish an equivalence between this study and the ones conducted by Zhang et al. (2019), Singh et al. (2021) and Concari et al. (2022) in which this topic is considered to be of global interest.

There was a notable growth in the amount of research published from 2015 to 2022. The increase in publications in the sample period can be attributed to the international agreements and directives of the United Nations (UN) and public policies on WEEE (ONU, 1992, 2000, 2015; Brasil, 2010, 2020), to restrict the use of certain hazardous substances in WEEE, aiming to reduce its environmental impact at the end of its life cycle.

Overall, the average number of citations per document was 56.3, or about 5 citations per year per document. The observed trend showed a decrease in the number of citations in the last two years of the study, but the prevailing phenomenon did not indicate distancing from the scientific community over time. Therefore, the drop in 2021 and 2022 citations does not mean a drop in reader interest, but only a brief gap between publication and citation conversion. The number of publications and academic involvement in the subject increased between 2015 to 2022.

Main productive authors and citations

The analysis accounted for a total of 1,024 authors, with a minimum of four published documents (Figure 3). The most outstanding authors in the theme (cluster 1 — red) were: Li jinhui, with 23 publications and 1,791 citations, followed by Zeng, Xianlai, with ten publications and 886 citations; Awasthi, Abhishek Kumar with seven publications; and Song, Quingbin with six publications; the primary authors of these clusters are from Tsinghua University in China. It must be highlighted that the members of Chinese universities together, with a minimum of five published documents, represent the majority of the total number of authors in the sample (80%).

Figure 2 – Annual distribution, citations and average citations per year of published articles on e-waste compiled in the Web of Science database (2012–2022), using RStudio.

Research by Zhang et al. (2019) also showed a correlation with this analysis, where out of a total of 6,601 authors, 14 published more than 30 articles. The most productive authors according to the study are the Chinese, further indicating that Chinese researchers have paid more attention to this field.

In cluster 2 — green (right side, Figure 3), the most outstanding author was: Xu, Zhenming (Jiao Tong University, China); with ten publications and 1,103 citations; followed by He, Wenzhi (University of Science and Technology, China), who contributed with four publications and 233 citations of the used sample.

Bibliometric analysis of co-citation between authors

A total of 14,623 authors were obtained with a co-citation relationship, with a minimum of 20 citations per author, totaling 171 collaborating and cooperating authors (Figure 4).

In Figure 4, the lines between authors represent their cooperation links through citations, while the different colors represent the four collaboration clusters. The main researchers in the network were "Song, Qb" (cluster 3 — blue); Li (cluster 2 — green); Leung, Aow (cluster 1 — red) and Awual, Mr (cluster 4 — yellow). Of these authors, "Song, Qb" has the highest link and total link strength (166/4,046 and 115 citations). Other authors were linked to one of these main authors.

It was observed that, although some authors have a relatively lower link, their articles were more cited and contributed significantly to scientific knowledge on the WEEE theme. The authors were "Zeng, Xl" (127 citations); "Cui, Jr" (90 citations); "Unep" (84 citations) and "Islam", with 46 citations. It is important to mention that most of these publications focus on the environmental impact caused by the improper disposal of WEEE. In recent years, researchers have focused their attention on this topic due to its potential economic and environmental benefits. Another prominent author was Li Jinhui (104 citations), with publications that focus on the theme of metal pollution and waste recycling.

Main sources and its citations

The primary sources analysis indicates the predominance of journal publications in environmental science and pollution, environment and sustainability.

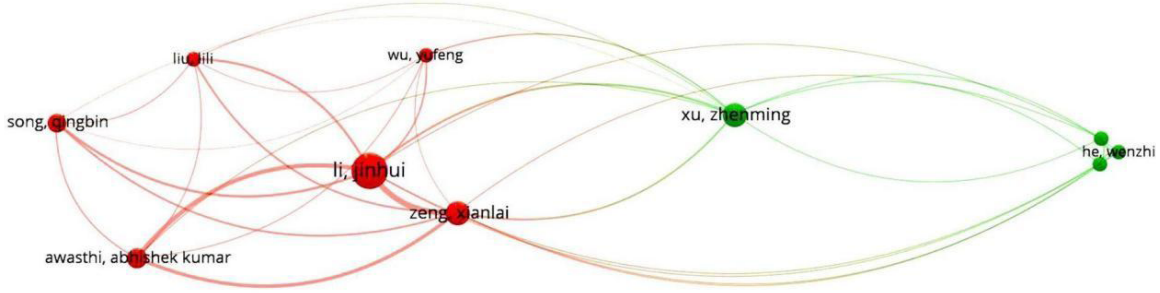

Figure 3 – Map of network with the ten most influential and productive authors in waste electrical and electronic equipment research.

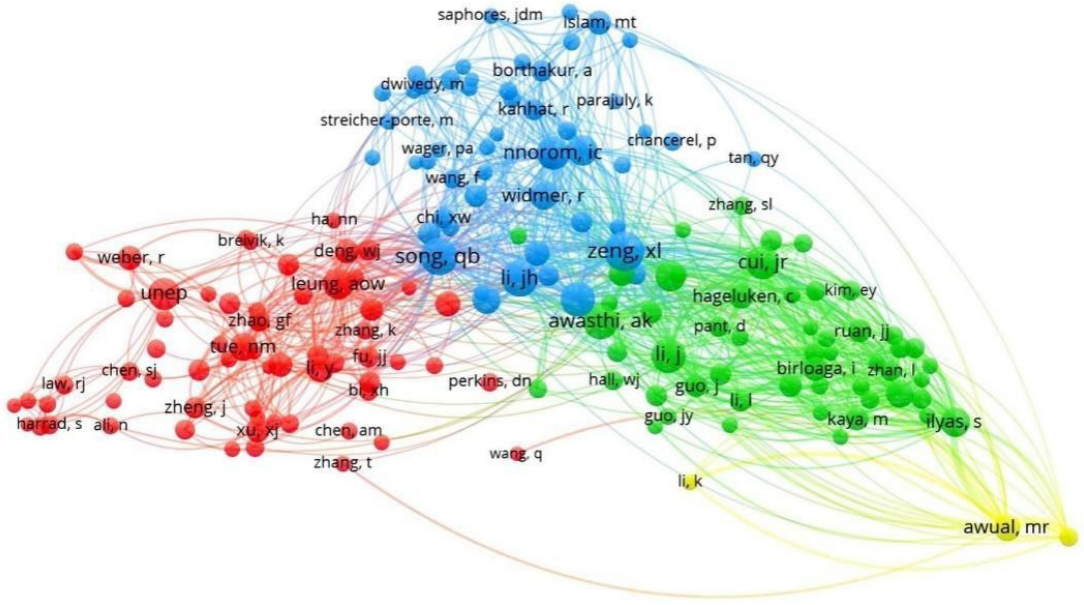

Figure 4 – Main authors — co-citation network map.

A total of 51 major journals that published 229 documents on the subject (2012–2022) were analyzed. The main ten journals account for approximately 75.9% of the selected articles in the database, indicating that the topic interests many journals (Figure 5).

In Figure 5, the size of the circles represents the number of publications in a journal; the wider circles imply more journal contributions for the subject. The color of the circles shows the year of publications on electronic waste.

The bibliometric analysis shows that the *Journal of Cleaner Production and Environmental Science and Pollution* is that which plays the most dominant and influential role on the subject, with 58 (25%) of the publications, followed by *Resources Conservation and Recycling*, *Waste Management*, *Waste Management & Research*, *Science of the Environment*, *Environmental International*, *Environmental Pollution* and *Critical Environmental Reviews* with 23 (10%), 23 (10%), 16 (7%), 14 (6.1%), 10 (4.3%), 10 (4.3%), and 9 (3.9%) articles, respectively.

The *Journal of Cleaner Production* collaborated with 30 (13.1%) published documents and 1,691 citations, currently occupying the rank of the journal that published the most articles on the subject. Regarding the *Waste Management Journal*, with its 23 (10%) published documents and 2,914 citations, it is the most cited journal globally, ranking first in citations, containing 154 link strengths.

It is opportune to verify the results of research carried out by Zhang et al. (2019) and Singh et al. (2021), where the most productive journals on the subject were *Waste Management* (8.54%), *Journal of Cleaner Production* (5.20%), *Environmental Science & Technology* (4.43%) and *Resources Conservation and Recycling*, demonstrating that this field of research attracted several scientific journals globally.

It could be noticed that the journals that published the most on the subject were not necessarily the most cited. The *Journal of Cleaner Production* (IF — 11.072) was considered one of the most important journals using the bibliometric method of evaluating scientific journals, based on received citations and articles published by the journal, its high impact factor and academic prestige. Next are the *Journal Waste Management* (IF — 8.816) and *Environmental Science and Pollution Research* (IF — 5.8).

Collaboration analysis

Ranking of contribution per countries/regions of the world

Figure 6 ranks the leading nations and their evolution in terms of scientific contribution concerning WEEE during the study.

In this analysis, the larger each circle is, the greater the number of documents that the corresponding country has. Furthermore, the thicker the link between circles, the more they collaborated. The distance between the clusters indicates the strength between them and how much these authors publish in co-authorship. It appears that China and the USA have great cooperative relationships in studies on the subject.

Figure 6, cluster (5) — lilac shows that China, USA, Pakistan and the Netherlands are in evidence, since together they represent 38.7% of publications.

The bibliometric network shows that the Asian continent (China, India, Malaysia and Japan) had the greatest contribution, with 163 (41.5%) publications, followed by the European continent (Italy, England, Germany and the Netherlands), with 77 (19.6%) publications, and the American continent (USA, Canada and Brazil), with 54 (13.7%). The other continents and countries contributed with 98 (25%) publications, highlighting a worldwide interest in the subject.

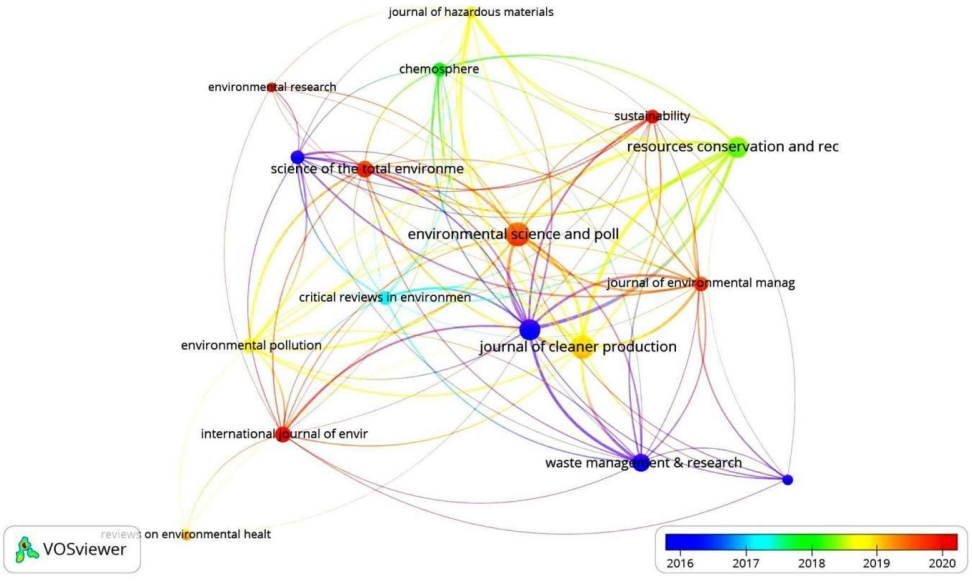

Figure 5 – Map of main journals that publish papers concerning the waste of electrical and electronic equipment.

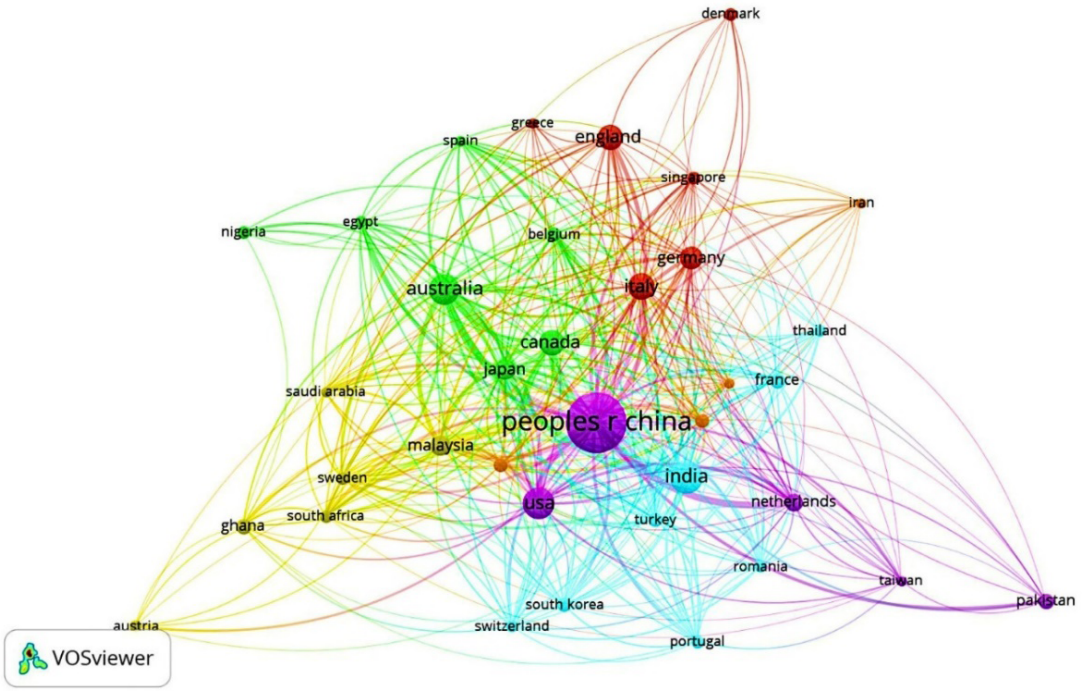

Figure 6 – Map of citations per country in waste of electrical and electronic equipment research during the period of 2012 to 2022 (sample 66 countries, minimum 3 articles per country, 392 documents — VOSviewer).

China, India, Australia, USA and Italy are leaders in research and publications on the subject, with 106 (27%), 33 (8.4%), 28 (7.1%), 29 (7.3%) and 21 (5.3%) articles, respectively.

The developing countries contributed to this sample with a significant number of publications. China (106 publications; 27%), Malaysia (12 publications; 3%) and Brazil (6 publications; 1.5%) contributing to 31.6% of the research, while Pakistan (7 publications; 1.8%); Turkey (6 publications; 1.5%); Singapore (5 publications; 1.3%); Bangladesh (6 publications; 1.5%) and Ghana (7 publications; 1.8%) contributed with 7.9% of this research. The other developing countries in the analyzed bibliometric network contributed with less than five publications (16.6%).

Based on the bibliometric results of this study, in the last decade, countries around the world have studied ways to properly dispose of WEEE, especially developed countries (USA, Japan and Russia), the main producers of WEE, and the developing countries (China, India, Brazil) (Forti et al., 2020).

The research conducted by Concari et al. (2022) corroborates this study by confirming the expansion of academic influence in several countries on the subject and the prominence of China in this field, due to its various works on WEEE.

Bibliometric analysis: bibliographic coupling of documents

A total of 278 articles were identified as the most relevant in the WEEE theme in the Web of Science database. The analysis results generated five article clusters, with 15,807 links in total (Figure 7).

Figure 7 – Bibliographic coupling network of research data (VOSVIEWER).

The obtained bibliographic couplings and their influential articles are essential to perform the qualitative content analysis and discover the main themes and research directions.

Analysis of the most cited articles reveals several groupings indicated by the names of the authors, as shown in Figure 7. The red cluster shows the perspective of studies on "electronic waste recycling". The most cited article is that by Hahladakis et al. (2018), with an overview of chemical plastic additives and their environmental impacts. This analysis also includes Tansel's (2017) article on consumer electronics and e-waste.

The green cluster is characterized by numerous quotes from Kumar et al. (2017), who address an overview of electronic waste, generation, collection, legislation and recycling practices in his article. This set of articles addresses some issues related to waste management using a broader approach. For example, Islam and Huda (2018) address both the reverse logistics of electronics, the management of this waste and the implications of the circular economy on sustainable development.

The blue cluster shows that the authors worry constantly about the environmental sustainability theme. This topic has been effusively addressed in recent articles linked to subareas of interest. The main articles on the electronic waste management approach are from Kiddee et al. (2013), and, on environmental pollution and electronics recycling, by Awasthi et al. (2016).

The yellow agglomerate is characterized by articles concerned with the recycling of metals from electronic waste. The main articles are by Kaya (2016), on the recovery of metals and non-metals from electronic waste, Zhang and Xu (2016), on the analysis of recycling technologies for waste from electronic equipment. The most cited article was Ilankoon et al. (2018), which analyzed electronic waste in the international context, a review of the dangers and management strategies.

A smaller cluster (lilac) focuses on environmental concerns with the impacts and treatment of electronic waste in the local and spatial dimension of recycling behavior; the main works are Premalatha et al. (2014), on "The generation, impact and management of electronic waste", and Tembhare et al. (2022), on e-waste recycling practices.

The qualitative analysis shows that Premalatha et al. (2014), Pérez-Belis et al. (2015), Al-Salem et al. (2022) and Tembhare et al. (2022) are significant, because although they still have few citations in their articles, the strength of intensity and cooperation of their links is revealing, demonstrating the importance of coupling data with other clusters.

The bibliometric analysis proves that articles characterized by numerous references have greater influence on bibliographic coupling, and that the five analyzed clusters have interconnections with each other and with the subtopics presented in the keywords.

According to Zhang et al. (2019) and Singh et al. (2021), WEEE research hotspots focused mainly on recycling technologies, environmental impacts and WEEE policies, closed loop and reverse logistics; in addition to this study, this analysis found that, over time, the frontiers of research on WEEE followed an evolutionary path, including dominant themes such as sustainability and circular economy.

Keywords analysis

In the analyzed documents, a list of predominant words and their frequency in scientific articles were detected (1,795, minimum 5 occurrences), and those more prominent in the textual analysis are highlighted in the central area and are more extensive (Figure 8).

Figure 8 also shows that the themes with the highest occurrence in the keywords were "e-waste" and "polybrominated diphenyl ethers", appearing with a 107 and 61 times frequency, respectively, and being the keywords most used as an index for the analyzed articles. The distance between these two main keywords demonstrates the relative strength and similarity of the topics. The circle in the same grouping color suggested a similar topic among these publications. The size of the circles represents the occurrence of the keywords; that is, the number of times the keyword was co-selected in publications on WEEE.

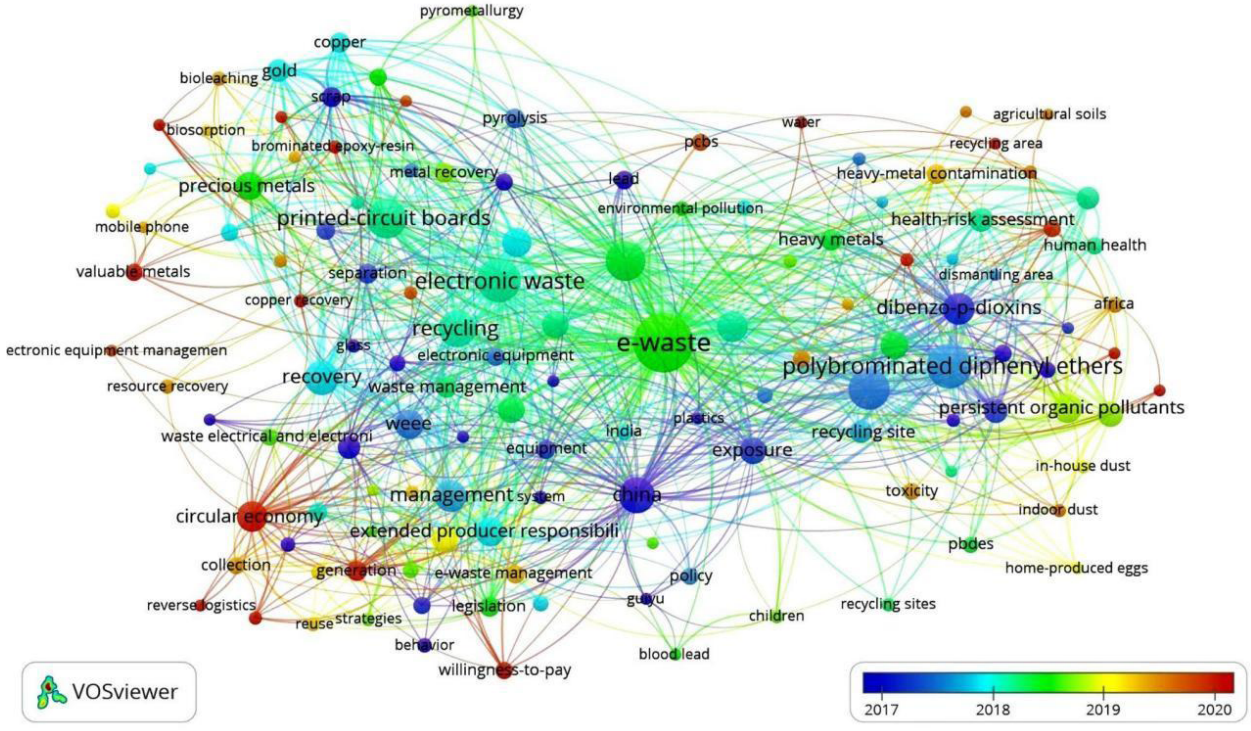

Figure 8 – Chain of connectivity about the co-occurrence of keywords in articles about waste of electrical and electronic equipment (visualization based on occurrence and periodicity).

Regarding the statistical analysis of the titles and abstracts of the articles in the sample, it was verified through the cloud of words (Figure 9) that the words that stood out the most were, in order of frequency: "review", "e-waste", "polybrominated diphenyl ethers" and "electronic waste", clearly showing trends in research on electronic waste.

In the word cloud of the abstracts, the words "e-waste" (793), "waste" (532), "recycling" (454), "management" (316) and "environmental" (277) are highlighted. Among the keywords that make up the cloud of titles in our sample, the most significant are "review" (147), "waste" (95), "recycling" (58), "electronic" (54) and "management" (51).

Figure 9 – Title keyword cloud (RStudio — bibliometrix package).

Figure 10 – Abstract keywords cloud (RStudio — bibliometrix package).

On the networks by the co-occurrence of terms located in the titles and abstracts (Figure 10) analysis, it is observed that the synergy between the words occurs around the words "recycling" and "e-waste", which are interconnected with all the other highlighted keywords.

Identifying the most recent active keywords in all these WEEE analyses can provide researchers with the most attractive research frontiers and areas of investigation within the explored field. The results demonstrate that the search criteria in the databases are well aligned with the purpose of the research.

Conclusions

The bibliometric analysis of published articles on electronic waste has grown significantly in the last ten years, revealing various themes and perspectives.

Of the 278 articles obtained from the Web of Science database, 40% had at least fifty citations. Among these, the five documents with the highest number of citations were Kiddee et al. (2013), Kaya (2016), Zhang and Xu (2016), Kumar et al. (2017) and, Hahladakis et al. (2018).

The results show that the *Journal of Cleaner Production* and *Environmental Science and Pollution* are the most dominant journals in number of publications, with approximately 25% of the total. The *Journal of Cleaner Production* tends to be more influential than others, with a higher impact factor and h-index. Scientific research on the subject is concentrated in about 66 countries. The nations with the highest volume of scientific contributions are from the Asian continent. China is the most productive country, followed by India. "E-waste" and "polybrominated diphenyl ethers" were the keywords with the highest frequency to represent the central theme of the study. The scientific mapping indicates that the main research themes on WEEE are recycling, environmental impacts, sustainability, circular economy, efficient management and technologies for recycling electronic waste.

This research is not without limitations. First, we considered only peer-reviewed publications and excluded books and other types of documents. Second, we only considered the WoS database in this study. Extracting data from other scientific databases such as Scopus and Google Scholar, academic document types (e.g. book chapters and conference papers), as well as non-English papers may provide further information for future bibliometric analyses. In addition, for a more detailed analysis, a domain review would be desirable.

Contribution of authors:

BIZERRA, M. G. C.: Conceptualization, Methodology, Data curation, Investigation; Formal Analysis; Data curation; Writing — Original Draft. SANTOS, L. A.: Formal Analysis; Writing — Review & Editing. CORDEIRO, L. F. A.: Writing — Review & Editing. SALES, A. T.: Supervision; Writing — Review & Editing.

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