ELECTRONIC WASTE (E-WASTE)/WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE): PROJECTING FUTURE RESEARCH TRENDS USING BIBLIOMETRIC ANALYSIS

[1]MD TASBIRUL ISLAM, [2]NAZMUL HUDA

[1] Ph.D. student, School of Engineering, Macquarie University, NSW 2109, Australia
[2] Senior Lecturer, School of Engineering, Macquarie University, NSW 2109, Australia

Abstract - This study performed a bibliometric analysis on the research topic of electronic waste (e-waste) or waste electrical and electronic equipment (WEEE) assessing global performance and international cooperation in scientific research over a 25-year timeframe from 1984 to 2019. A total of 3878 relevant publications were collected from the Web of Science (WoS) core collection database. The R-bibliometrix and Biblioshiny (in R-studio) application packages were utilized to conduct data analysis and network visualization. International performance in e-waste-related publications was assessed. The results showed that e-waste-related articles fell under three distinct research clusters, namely as sustainable e-waste management strategies as cluster 1, e-waste recycling, and material recovery techniques as cluster 2 and environmental pollution impact on soil and human health as cluster 3. Using keyword occurrences and text-mining approaches, potential future areas of research have been identified. This paper is particularly helpful for new researchers in the field.

Keywords - E-waste, WEEE, Bibliometric analysis, Research trends, Network visualization, Research policy

I. INTRODUCTION

An increased level of economic development, changes in customers' consumption patterns, and technological innovation are some of the significant contributors to the excessive use of modern electrical and electronic equipment (EEE)[1-3]. Due to a shorter product life span, the disposal rate of end-of-life (EoL) EEE has increased significantly over the years. "E-Waste is a term used to cover items of all types of EEE and its parts that have been discarded by the owner as waste without the intention of re-use" [4]. According to the latest "Global E-waste monitor report 2017" published by United Nations University (UNU) and The International Telecommunication Union (ITU), in 2016, globally, 44.7 million metric tonnes (Mt) of e-waste is generated and the final fate of 76% (34.1 Mt) of e-waste is unknown [5]. E-waste or waste electrical and electronic equipment (WEEE) has become an essential issue in holistic solid-waste management, not only because it contains valuable materials and rare earth elements (REEs)[6], but also due to the presence of toxic elements that create catastrophic environmental impacts, as 4% of the total quantity get mixed with general waste [7]. Developing countries are facing tremendous challenges managing this complex waste stream, as this is overburdened by domestic generation as well as by receiving e-waste from developed countries[8]. China, India, Pakistan in Asia and Ghana, South Africa in Africa are the major recipients of foreign e-waste [9-11]. Valuable materials such as gold, silver, aluminum, copper are recovered by crude recycling practices in Asia and Africa, thus creating environmental and health-quality degradation in terms of soil contamination and the existence of toxic elements in human blood [12, 13].As e-waste is a global environmental issue, researchers from all over the world are contributing to this field. International peer-reviewed publications are one of the measures that record the outcomes of that intellectual knowledge base[10, 14]. In this context, evaluation and quantification of the growth of literature in a particular research area is an essential task to identify research trends and critical issues of the field [15].

Bibliometric analysis is a statistical quantitative analysis method that has been conducted by many researchers in many different fields (e.g. carbon emission from transport sector by Tian, Geng [16]; solid-waste recycling and reuse by Li, Han [17]; science mapping by Aria and Cuccurullo [18]).In bibliometrics and scientometrics studies, the R-bibliometrix package provides a comprehensive tool for quantitative bibliometric analysis research. Research by Aria and Cuccurullo [18] implemented the tool.There has been an enormous number of published papers focused on e-waste. However, no other previously published work has used bibliometric analysis to investigate the progress and research trends in the academic publications and global performance in e-waste research using R-bibliometrix and "Biblioshiny". Besides that, the purpose of this paper is to provide a comprehensive compilation of research trends in e-waste that can serve as an invaluable resource for future researchers to understand the "big picture" of the research field. In this study, using these tools, e-waste related studies from 1993 to 2017 were analyzed to explore: 1) progressive development of the research field 2) leading contributor countries (in both international and domestic), influential authors, major journal outlets, emphasized subject categories and

international and national research-collaboration network; and finally 3) research trends, by analyzing authors' keyword co-occurrence and co-citation.

II. MATERIAL AND METHOD

The Web of Science (WoS) developed by Thomson Reuters Scientific, and currently being maintained by Clarivate Analytics (United States) is the most widely used scientific-research-article database in bibliometric-analysis studies. For a research topic, this database can provide a comprehensive and most up-to-date dataset that can be downloaded to a Bibtex-file (*.bib) format which later can be used in application package, such as Bibliometrix-R and its associated application "Biblioshiny". For the data collection of this study, all the associated indices of the WoS core collection databases were utilized. Based on the keywords string applied in the advanced search option in the core collection as follows: TS=("waste electrical and electronic equipment*") OR TS=("e-waste") OR TS=("E-waste") OR TS=("WEEE") OR TS=("waste electronics*") OR TS=("waste-electronics*") OR TS=("electronic scrap") OR TS=("electronics waste") OR TS=("obsolete electronics*") OR TS=("electronic-waste*") OR TS=("electronic waste") OR TS=("electrical waste") OR TS=("electrical wastes") OR TS=("electronic wastes") OR TS=("waste electrical") OR TS=("wastes electrical") OR TS=("waste electronic") OR TS=("wastes electronic") OR TS=("electronic rubbish") OR TS=("electronic garbage") OR TS=("electrical rubbish") OR TS=("electrical garbage"), a total of 3878 documents were identified for the time span from 1984 to 2019. In this process, publications containing the above-mentioned keywords found in their title, abstract and keywords were listed. The data retrieval date was 07 October 2019.

The annual scientific production, top manuscripts per number of citations, most productive authors, most productive countries, total citation per country, most relevant sources (journals) and most relevant keywords are the key criteria in a bibliometric analysis which are embedded in the previously downloadable file formats retrieved from WoS[19].

III. RESULT AND DISCUSSION

3.1 Annual Publication Trend

During the time period (1984 - 2019), a dramatic increase in publications in the field of e-waste research has been observed. In 1984, the total publications were only 1, which increased to 465 papers in the year 2019 (until October 2019). Although the highest number of papers published in 2018 was 569. At end of 2019, it is expected that a greater number of papers will be published from the previous year. The reason behind such a dramatic increase in publications may be because of the effect of the Basel convention that focused on the control of transboundary movements of hazardous wastes and their disposal from developed to developing countries. Furthermore, in 2002, the European Union (EU) parliament also passed the WEEE Directive 2002/96/EC that provided a regulatory framework for the member countries managing their e-waste (Islam, Huda, and Dias 2018). Besides this, financial support from various funding agencies, as well as research activities at the universities in both the developed and developing countries, also drove the dramatic growth in terms of publications between 2005 and 2019. Fig. 1 shows the annual publication output during the period on the topic. Overall, it is seen that the total 3878 articles published in 942 journals, books and in other sources in which total number of authors contributed was 8126. The total number of authors' keywords was 7696, and the average citations per article were 17.84. The number of authors in the single-authored article was 260 whereas number of authors in the multi-authors publications was recorded as 7866.The authors per document were 2.1 and documents per article was 0.477. Co-authors per documents were found 4.4.

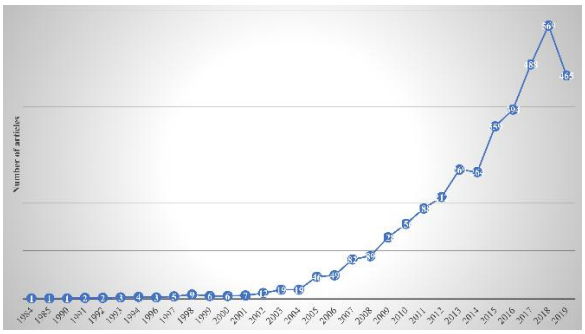


Fig. 1 Annual publication output in e-waste research

3.2 Publication Sources

As mentioned earlier, the 3878 articles were published in 942 different journal sources. The top 10 journals published approximately 40% of the total articles. The highest number of papers (268) was published in the Waste Management journal during the period. On the other hand, e-waste creates severe management and environmental challenges for nations in the world, and the Journal of Cleaner Production is one of the most innovative and progressive journals in which new and problem-oriented solutions are being proposed. The journal published 184 articles. Environmental Science & Technology of the American Chemical Society (ACS) published 145 papers while Science of the Total Environment and Resource Conservation and Recycling journal published 145 and 135 papers, respectively. Sustainability, industrial ecology-related approaches such as Life-cycle assessment (LCA), material flow analysis (MFA) and symbiosis among different actors and policy implications are the major thematic areas of the journal. Journal of Hazardous Materials publishes articles related to the hazardous

nature of e-waste components, while Resource Conservation and Recycling focuses mainly on material recovery, flow of e-waste materials within a region and/or country, recycling and reverse-logistics-related research. Fig 2. shows the top 20 journals in the e-waste research field.

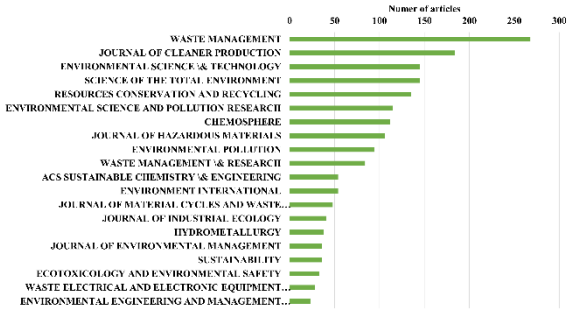


Fig. 2 Most product publication sources in the e-waste research field

3.3 Publication Distribution of Countries And Institutions

Based on the author's affiliation in the articles, the contribution of different countries and institutions across the globe can be analyzed. A total of 90 countries contributed to the e-waste research during the time period. Figure 3 shows the global progress in publishing e-waste research with respect to time-trend analysis during 1984 - 2019.

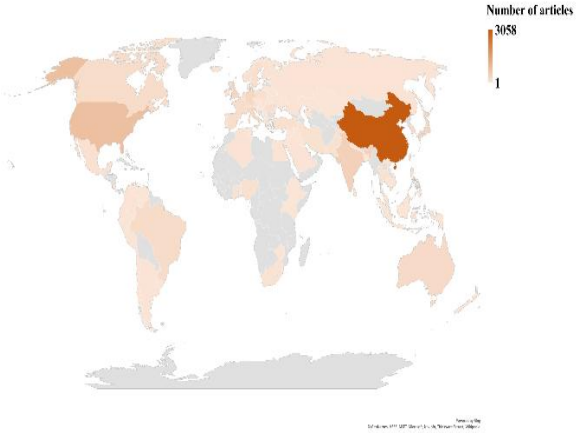


Fig. 3 Global production of e-waste research

In the top ten performing countries and regions, four countries, China secured the leading position (with 3058 articles) during the entire period with the total number of publications increasing rapidly after 2009.In 2004, a draft regulation "Take-Back and Recycling of Household Waste Electrical and Electronic Products" was proposed for controlling e-waste generation and initiating a policy approach in the e-waste area. After the enforcement of the "Regulations on Waste Electrical and Electronic Equipment, Order No. 551" in the year 2008, it is observed that publications in E-waste were increasing considerably compared to the previous years. Surprisingly, in the field of e-waste, the USA ranked second which is very different from other waste-related studies. Recently published bibliometric analysis studies by Wang et al. (2015) in Landfill research, Chen et al. (2015) in waste-management research, Reddy and H. (2016) in air-pollution research, Li, Han, and Lu (2018) in solid-waste reuse and recycling research showed that the USA ranked first in these areas of research. India and Japan two of the countries from Asia published 438 and 326 papers, respectively. UK (315 papers), Italy (276 articles), and Germany (270 papers) found as top paper producing countries from Europe. Australia from Oceania published 236 papers in the field while Brazil from South America published 203 articles. In the top 10 countries, South Korea stood 10th position publishing e-waste articles (with 182 articles). The country collaboration network is presented in Fig. 4 where it is seen that China is collaborating with different countries across the globe. The network diagram is developed with the VOSViewer application package.

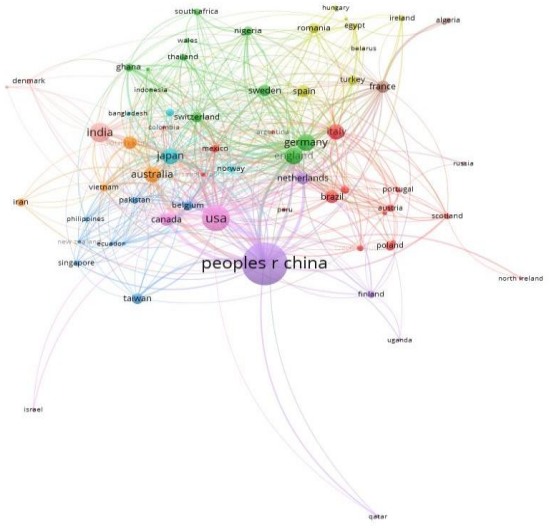


Fig. 4. Country collaboration network in e-waste research

Guangzhou Institute of Geochemistry of the Chinese Academy of Sciences from China published the highest number of papers (262) while Shantou University and Tsinghua University published 177 and 118 papers, respectively. Among the USA universities and research institutes, the University of California, Irvine was the most productive institution (50 papers).Delft University of Technology from the Netherlands andUniversity of Ghana from Ghana are the university in Europe, and Africa published 32 and 35 papers, respectively.Local environmental and pollution issues, informal-sector e-waste recycling, business opportunities, integrated waste-management policy development, connecting the ideas of sustainability, urban mining, the circular economy, and closed-loop supply chains are the major driving force for developing countries like China and India to give intense attention to this research field.

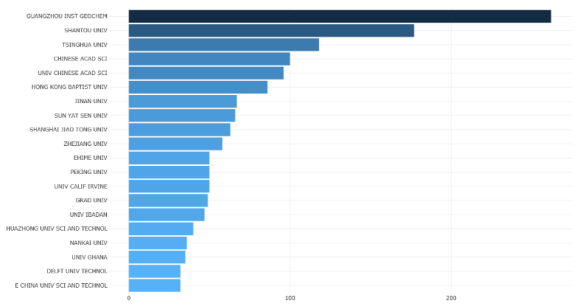


Fig. 5 Most productive institution in the e-waste research

3.4 Highly Cited Papers

Table 1 shows the top ten articles with the most highly cited articles, journal name, year of publication, the total number of citations and total citations per year. The most highly cited article was entitled "Global Perspective on E-waste" authored by Widmer, Oswald-Krapf [20]published in the Environmental Impact Assessment Reviews, with 678 total citations and 48.42 annual citations. "Mechanical recycling of waste electric and electronic equipment: a review" authored by Cui and Forssberg [21]and published in the Journal of Hazardous Materials, stood at second place in terms of both total citations (554) and annual citations (34.62). Of the articles presented in Table 1, six articles are from China, 2 articles from Europe and one from Eurasia region and one from USA. However, first, two highly cited articles are from Europe. Three of the papers were published in the Environmental Science & Technology journal, and the Journal of Hazardous Materials published two and one paper each at Resource conservation and Recycling and Mineral Engineering. Calculating the average annual citations of the articles, it is found that, even though some of the articles have a low total number of citations, due to the lag between the publication year and the subsequent citations, some of them have higher annual citations, for example, papers published by Luo, Liu [22] and Tuncuk, Stazi [23].In terms of research topics, environmental pollution by crude e-waste recycling practice and the human-health hazards incurred by this phenomenon, metal recovery by recycling techniques and critical issues in holistic e-waste management systems were the major concerns.

Paper	Total Citations (TC)	TC per Year
WIDMER R, 2005, ENVIRON IMPACT ASSESS REV	678	48.42
CUI JR, 2003, J HAZARD MATER	554	34.62
LEUNG AOW, 2007, ENVIRON SCI TECHNOL	391	32.58
FU J, 2008, CHEMOSPHERE	306	27.81
HUO X, 2007, ENVIRON HEALTH PERSPECT	296	24.66
LEUNG AOW, 2008, ENVIRON SCI TECHNOL	295	26.81
LUO C, 2011, J HAZARD MATER	294	36.75
TUNCUK A, 2012, MINER ENG	292	41.71
KANG HY, 2005, RESOUR CONSERV RECYCL	273	19.5
BI X, 2007, ENVIRON SCI TECHNOL	261	21.75

Table 1. The top 10 highly cited publications during 1984-2019; papers are written in the format author, year, journal

3.5 Dynamic Keyword Co-occurrence Analysis

The frequencies and co-occurrences of the author keywords of the 2463 articles were analyzed. Singular and plural forms of words, irrelevant and abbreviated keywords such as "method," "analysis," "electronics" were omitted from this analysis. Fig 6 shows the evolution of e-waste-related keywords in the publications.



Fig. 6. Word Cloud of e-waste research articles (with 110 most frequently used words)

Furthermore, the total number of occurrences of the words identified in the bibliometric analysis was 16931. The word "e-waste (657, 4%) was the most popular word among the researchers, followed by "recycling" (417, 2%). Although "hydrometallurgy" is a widely used recycling process of e-waste, it occurs only 22 times. "WEEE," which is an alternative to e-waste, also occurs 341 times while "waste electrical and electronic equipment" was found 76 times. "Printed circuit board" is one of the keywords that occurred 75 times. Almost all the electronics equipment includes this component, which contains both valuable metals such as gold, copper, silver and highly toxic metal such as arsenic, cadmium, lead, and others. Lead (64, 0.38%), "gold" (47, 0.27%), "copper" (69,0.41 %), "cadmium" (34,0.20%) and "indium" (23, 0.14%) are some of the metals that occurred in the author keywords. The word "heavy metals" and "PBDEs" appeared 107 and

96 times, respectively. Figure 7 shows the most frequent author keywords occurrence in e-waste research. As this research field is progressing much faster, some of the keywords that have been seen lately (from 2013 to 2019). "Polybrominated diphenyl ethers" (51, 0.30%) is a toxic material present in almost all the popular electronic devices such as a printer, rice cooker, computer monitor, TV, electric iron, and water dispenser as well as in the e-waste dismantling workshops [24]. "Bioleaching" (94, 0.56%) is a bio-hydrometallurgical process by which base metal, precious metal, and REEs can be recovered from e-waste shredding dust derived from the recycling process [25]. As the volume of e-waste is escalating exponentially, collection, recovery and transport of the waste from customer to recycling is a challenging task in a holistic e-waste management scenario. "Reverse logistics" (54, 0.32%) is the process by which this operation is done, and application of this concept in collection and recycling network design[26]has received tremendous attention among researchers.

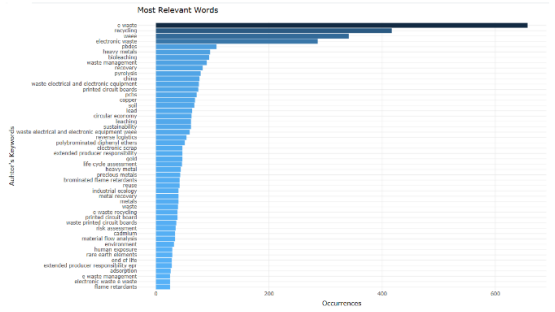


Fig. 7. Top 25 most frequent author's keyword occurred in the e-waste research

The toxic environment and human-health hazards of crude recycling processes due to the presence of such chemical components attracted most e-waste researchers."Life cycle assessment" (46, 0.27%), "Extended producer responsibility" (47,0.28%), "material flow analysis" (34, 0.20%) are the ecological evaluation tools for waste-management systems (including environmental impact assessment) which occurred significantly in recent articles. However, there are scopes to utilize combined LCA and MFA tools. "Mobile phones" (22, 0.13%) received considerable attention from researchers compared to other products. "CRT" (11 times) which is cathode-ray tubes coming from waste computer monitors and television receivers also found importance. All over the world, deployment of solar PV as a solar-energy-harvesting technology is increasing at an exponential rate [27-29]. After the 23-25 years of a typical lifetime, the equipment reaches its end of life (EOL) and it is expected that, by the year 2050, 4.5-7.5 million units of solar PV will be obsoleted[30]. In the future, it is expected that this sophisticated waste stream will create EOL management problems. The word "solar panel" occurred only three times within the collection of the keywords. Research published by Paiano [31] showed that developed countries such as Italy have started experiencing this overwhelming phenomenon. The EU revised the e-waste categories in the WEEE legislation lately, and solar PV is now being considered as one of the emerging waste streams in Europe[32]. Some concepts like "urban mining,""closed-loop supply chain," "green IT," "eco-design," "carbon foot-printing," "sustainable development" and "circular economy" are emerging in the field and it is expected that research on these concepts will be accessible in thecoming years. More interdisciplinary and cross-disciplinary solutions to specific e-waste problems can be found when these concepts are integrated. These concepts emphasize resource conservation, meaning that we recirculate the raw materials present in the waste stream for new-product development and/or secondary application for other industries [33].Based on the content of the articles within the cluster, key issues were identified that provide a set of directions for future e-waste research. Figure 16 shows the sub-topics of the three main research themes of the whole e-waste research domain.

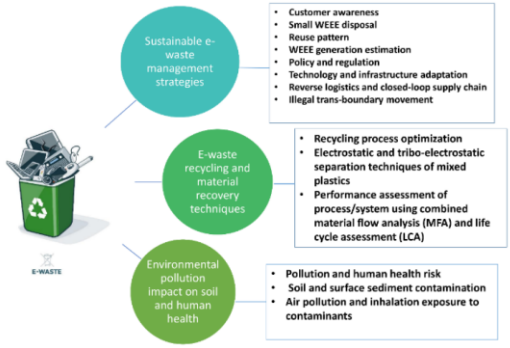


Fig. 8. Future perspectives of e-waste research

IV.CONCLUSION AND RECOMMENDATIONS

This paper performs a bibliometric analysis to assess the global effort in e-waste research in the years 1984 – 2020, based on the 3878 research articles retrieved from the Web of Science (WoS) core collectiondatabase. The analysis shows that China and the USA were leading contributors to international publications in e-waste research. Brazil and India are the two rising countries that will contribute more to e-waste research. The Chinese Academy of Science and Tsinghua University from China, followed by the University of California, Irvine from the USA are the three major institutions in producing e-waste publications. Simultaneously, the Chinese institutions are also vested with leading researchers in the field who are deeply involved in the multi-authored publications. In terms of single and multi-country publications, China's contribution is far more significant than any other country. Combinations of evolving concepts such as "urban

mining," "closed-loop supply chain," "green IT," "eco-design" "carbon foot-printing," "sustainable development" and "circular economy" will provide an interdisciplinary and cross-disciplinary solution to specific e-waste problems in future. Based on citation analysis, several future research issues need further investigation, such as customer awareness of e-waste disposal, e-wastegeneration estimation, implementation of IoT and big data in environmental monitoring, material characterization and property evaluation of different e-waste items, such as small IT and consumer electronics. Another important product soon will be waste solar PV panels. Long-term environmental and human health (workers and children) impact assessment (due to high concentrations of Polybrominated diphenyl ethers (PBDEs) and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs)) in the contaminated crude e-waste recycling sites in Asia (besides China) and Africa need attention.

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