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REVIEW PAPER

A bibliometric analysis of the effects of electronic waste on the environment

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ABSTRACT

The outcome of improper electronic waste management is an environmental and epidemiological catastrophe; therefore, its management has become crucial given the increase in e-waste generation. Global e-waste output eclipsed 52 million metric tonnes in 2020, growing at 3% per annum. The United Nations Sustainable Development Goal number 12 highlights that only 20% of the generated e-waste was properly recycled, with the remainder indiscriminately disposed of. There has been considerable growth in publications on e-waste and the environment over the past few decades. This study provides an overview of the research landscape on the impact of e-waste on the environment using bibliometric analysis. VOSviewer software is used to visualise the current trends and the recent hotspots. It is observed that the research hotspots in the field are: soil, health, environmental impact, recovery, electronic equipment, and waste electrical and electronic equipment. By tracing the evolutionary research pathway, it is clear that the research hotspots have shifted focus to e-waste generation, laser-induced breakdown spectroscopy, and circular economy. A total of 141 articles on e-waste and the environment published between 2003 and 2021 were selected for the study. The publication and citation analysis showed a steady increase in publications and citations. China dominates with a third of articles published by authors, followed by India and the United States. Developing countries contributed about 17% of total publications. The articles retrieved were cited 5290 times and had an h-index of 39. Finally, using network analysis techniques, four key themes are identified. The first theme relates to the strategies employed in recovering minerals from e-waste. The second theme focuses on the concentration levels of the heavy minerals found in e-waste. The third theme visualises the impact of e-waste on health, and finally, the fourth theme highlights the effects of e-waste on the environment. The study adds valuable insights to the body of literature in hazardous and toxic substances management. No studies were found chronicling the environmental effects of e-waste using bibliometric analysis. In light of the Sustainable Development Goals, further research needs to be undertaken, and these findings serve as a baseline for policymakers and scholars as more management strategies and policies are enacted.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
102	4	4

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INTRODUCTION

The fourth industrial revolution (4IR), urbanisation, and advances in information technology have radically transformed humanity in the past few decades. Information and communication technologies (ICTs) have permeated every aspect of human life, promoting and maintaining a higher standard of living, and have become the foundation for health, education, transport, security, and energy operations. Although this development has been transformational, irresponsible management of technological resources has raised environmental quandaries. Balancing technological advancements and environmental sustainability remains a challenge for current and future generations (Maphosa, 2021). The United Nation's Sustainable Development Goals (SDGs) foster sustainable economic, social and environmental development across the globe. The SDGs provide a framework for solving problems affecting humanity and the environment (Akon-Yamga, 2021). Rapid industrialisation and product innovations, population boom, shorter product lifespans and consumer demand and cheaper ICT products contribute to the growth of the electrical and electronic equipment (EEE) product market (Lin *et al.*, 2022). However, most of these developments do not promote environmental sustainability by lowering environmental degradation and reducing global warming (Sztumski, 2014). Computing activities contribute to global warming through carbon emissions released during the manufacture, use and recycling of the resultant e-waste through the release of harmful chemicals into the environment (Perkins *et al.*, 2014).

State of the art of e-waste management

The past decades have witnessed increased adoption of EEE; once this equipment is obsolete or unusable, it constitutes electronic waste (e-waste). E-waste is the fastest-growing solid waste stream at about 5% per annum (Amankwah-Amoah, 2016). Globally, e-waste output will rise to over 52.2 million metric tonnes in 2020, causing an environmental crisis (Baldé *et al.*, 2017). Only 17.4% of e-waste was collected and recycled, with 82.6% of the e-waste illegally exported to developing countries (Forti *et al.*, 2020). Developing countries have become an accessible channel for e-waste dumping. High unemployment rates have created employment opportunities where pervasive and informal processing is prominent in recovering rare earth minerals, but this is done at the expense of the environment and public health (Sthiannopkao and Wong, 2013). Although Africa is the largest recipient of e-waste, the International Telecommunications Union reports that only 0.1% of e-waste is formally recycled in Africa and has targeted a global collection and recycling rate of 30% by 2023 (Forti *et al.*, 2020). In most informal recycling areas, children are at risk due to exposure to Pb and PAHs, resulting in inflamed vascular endothelial (Zheng *et al.*, 2019).

Barriers to e-waste management

The manufacture of EEE is complex, with over 1000 substances used, including precious minerals such as platinum, palladium, gold, and copper, together with toxic elements such as lead, mercury, cadmium, arsenic, and many others (Maphosa and Maphosa, 2020). Deubzer *et al.* (2019) contended that it was challenging to manage e-waste. Some components had over 69 chemical elements composed of valuable and hazardous elements, which require complex processes and recycling technologies to recover the precious minerals. Over 50 tons of mercury were contained in e-waste produced in 2019, with brominated flame retardants accounting for 71-kilo tons, detrimental to the environment and human health if improperly handled (Sabra *et al.*, 2017). Developing countries lack the finances and infrastructure to set up formal e-waste processing. Informal management is unlicensed and unregulated, where individuals use primitive and rudimentary techniques such as burning, leaching, and heating, which negatively affect the environment and public health (Pathak *et al.*, 2019). Aimin *et al.* (2011) reported that pregnant women and children dwelling around e-waste dumpsites suffered perturbations of the fetus and neurodevelopment challenges. The precious materials found in e-waste are ten times purer than minerals found in mines, therefore, putting pressure on the environment through informal recycling (Vi and Matthew, 2014). Ardolino *et al.* (2021) report adverse environmental and public health outcomes in most developing countries, where e-waste is exported and improperly treated and managed.

E-waste recycling methods

Methods used to recycle and recover rare metals from e-waste should protect the environment and human health. E-waste recycling is highly informal in developing countries (Maphosa and Maphosa, 2020), with scholars estimating that 90% of recycling activities use rudimentary methods such as stones, hammers, and chisels to separate components (Pathak *et al.*, 2019). Cyanide has been used to extract gold from e-waste for centuries. Its use has been prohibited in many countries due to poisoning and contamination of the environment resulting in human and animal fatalities (Ghasem and Khoramnejadian, 2015). Material smelting has been used to recycle printed circuit boards, and the method has been condemned for being primitive and polluting the environment (Ye *et al.*, 2021). Hydrometallurgical techniques are used in recycling using leaching, purification, and electrowinning. This process uses many leaching reagents and is only applied to a few minerals, while the leachates contain heavy metals which are detrimental to the environment and human health (Wang and Xu, 2014). Recycling enterprises in developed countries have perfected e-waste recycling technologies using mechanical crushing, magnetic separation, and eddy current separation and have reached high levels of efficiency (Abdul *et al.*, 2014).

Movement of e-waste into developing countries

The United Nations (UN) SDG 12 specifically addresses e-waste management and highlights that only 22.9% of global e-waste is recycled, while the rest is improperly disposed of, affecting the environment (UN, 2021). Once labelled the dark continent, Africa has witnessed unprecedented growth in its cyberspace, leading to increased socio-economic development and sustained economic growth. Cheaper telecommunications equipment, computers, and mobile phones are being assembled and refurbished for low-income countries to bridge the digital divide and promote inclusive development (Chitotombe, 2013). Over 80% of the e-waste produced by developed countries is illegally exported to Africa, where primitive techniques are used to recover precious materials, thus harming the environment and public health (Grant *et al*., 2013). The demand for cheaper second-hand EEE is high in developing countries, and many communities survive by scavenging the resultant e-waste (Omobowale, 2013). Thus, most e-waste flows to the global south are illegal and disguised as genuine efforts to bridge the digital divide (Lambrechts, 2016). In a Kenyan study earlier, Mureithi and Waema (2008) reported that about 75% of second-hand EEE was exported illegally in the pretence that it was usable and repairable; beneficiaries such as schools reported that over 60% of the donated EEE was unusable and beyond repair. To manage e-waste without harming the environment and human health is costly. Therefore, in most developing countries, e-waste is indiscriminately disposed of, thereby posing a hazard to the environment.

E-waste management policies

Most of the global e-waste is produced by developed countries, which often view developing countries as an outlet for cheaper disposal due to the unavailability of environmental policies. Globally, 71% of the countries have crafted national e-waste policies for collection and management, although the majority still experience inefficient management due to lack of investment and partnerships, lack of compliance, and no harmonisation across countries (Lundgren, 2012). In 2019, only 13 African countries had an e-waste policy, legislation, or regulation (Avis, 2021). Thus, over 80% of the African countries do not have formal e-waste collection and recycling systems, and e-waste is mixed with municipal waste and dumped in landfills where informal workers salvage valuable materials through burning (Ongondo *et al.*, 2011). Lack of e-waste policies, laws, and legislation in most developing countries results in low awareness among those in the value chain from manufacturers to recyclers (Nwagwu and Okuneye, 2016). This remains the greatest threat to managing e-waste (Mutsau *et al.*, 2015).

Aim of the study

The study is motivated by Kiddee *et al.* (2013), who highlighted that the scientific community was concerned with the unsafe handling of e-waste in developing countries, threatening the environment. There is evidence of growth in studies focusing on e-waste, focussing on different aspects of e-waste. As early as 2014, Premalatha *et al.* (2014) opined that the e-waste problem was increasing at a much faster rate than the proposed solutions to contain it. A study by Hossain *et al.* (2015) showed that global e-waste management practices could prolong SDG achievement. Zeng and Li (2016) proposed a recyclability map that can serve as a guideline for establishing a feasible funding system for e-waste management. E-waste is a growing global concern, and a significant amount of e-waste is being added to the global waste inventory every year (Kumar *et al.*, 2017). Ikhlayel (2018) suggested implementing an integrated e-waste management system to prevent improper e-waste management in developing countries. Li and Xu (2019) compared supercritical fluid technology with traditional methods such as hydrometallurgy and pyrometallurgy. They found that supercritical fluid technology could recover valuable materials and remove hazardous components without secondary pollution. An aspect of e-waste management that has received attention is legislation. Patil and Ramakrishna (2020) compared different e-waste legislation enacted and proposed a generic e-waste management model for countries worldwide. The lack of proper technologies makes it difficult for many developing countries to formalise e-waste recycling (Rautela *et al.,* 2021). A few bibliometric studies on e-waste have been conducted. A study by Andrade *et al.* (2019) sought to assess recent research trends using the keyword e-waste from studies published between 1998 and 2018. Another study by Zhang *et al*. (2019) depicted the trends and features of WEEE-related studies. Gao et al. (2019) explored e-waste's status quo, hot topics, and future prospects. A study by Singh *et al*. (2021) provided an overview of e-waste and the circular economy using articles published between 2008 and 2020. The last study explored focus areas on e-waste and ascertained Brazil's ranking globally (de Albuquerque *et al.*, 2021). This study aims to use bibliometric indicators to review global research on e-waste and its effects on the environment in the past decade, compare publication trends over the years, and highlight the contributions of developing countries on e-waste research. This study is different from the studies discussed above in that it provides a bibliometric and visualisation of research on e-waste and its environmental impact in the past decade. The study explores the publication distribution by geography, journals, and citation trends. The study also assessed the frequency of keywords and H-index analysis and used bibliometric mapping tools to demonstrate developments in e-waste research covering environmental issues. No bibliometric studies published using the Web of Science database focusing on e-waste and the environment were found. This study aims to analyse and assess global research on e-waste and the environment, realising that issues to do with environmental sustainability are very urgent and topical. This study, therefore, provides a baseline for policymakers and researchers to plan and research on e-waste and climate change. This study was carried out between December 2021 and February 2022.

METHODS OF STUDY

The Web of Science database is one of the largest databases generally used for bibliometric analysis. One database is preferred when conducting bibliometric studies, as mapping indicators across several databases may be challenging (Sweileh, 2021). Accurate analysis of bibliometric studies is guaranteed by developing a comprehensive search query. The search query was identified and developed after conducting a literature review and identifying gaps in research covering e-waste and the environment. In December 2021 – January 2022, the Web of Science database was searched in the four indexes - Science Citation Index Expanded, Social Sciences Citation Index, Arts and Humanities Citation Index, and the Emerging Sources Citation Index. Multiple searches with multiple keywords search strings were used with the Boolean operators "AND" and "OR" to obtain relevant documents. The first search string retrieved articles related to climate, the environment, and sustainability. The search string TI = ("climate" OR "climate change" OR "environment" OR "sustainability" yielded 667 616 articles. The second search string TI = ("e-waste" OR "electronic waste" OR "electrical and electronic equipment" OR "EEE" yielded 2336 articles. The two search queries Were then combined to obtain articles appearing in both queries, and there were 166 articles. Articles published in 2022 were excluded, resulting in an exclusion of two publications leaving 164 articles. Filtered the papers by document types led to the exclusion of editorial materials, meeting abstracts, book reviews, corrections, letters, and news items, leaving 141 articles. The bibliometric analysis uses statistics and procedures to visually express general and dynamic patterns found in scientific publications (Ho, 2007). The Web of Science's database functionality to analyse search results were used to analyse results. The bibliometric data for analysis in text and excel file formats were exported. The text and excel data were imported to VOSViewer (van Eck and Waltman, 2010) to create the keyword occurrence network and density visualisation maps (Schulz and Schumann, 2006).

Publications and Citation Trends

Fig. 1 plots the publications and citation trends. The first article on e-waste and environment-related research was published in 2003. Between 2003 and 2013, less than ten were published per year. More authors started to research this field, leading to a steady increase in publications. The years 2016 to 2021 recorded more than ten publications except for 2019. In terms of citations, there were low citations between 2003 and 2009, with less than 100 citations per year. 2011 to 2020 saw citations in the hundreds between 113 in 2011 and 811 in 2020. The year 2021 saw more than 1000 citations. The last three years saw astronomical growth in citations, with 2019 having 790, 2020 having 811 and 2021 having 1049.

Table 1 shows the top 15 cited research articles in the field of e-waste and the environment. As shown, the study "E-waste: An assessment of global production and environmental impacts" published in 2009 is the most cited with 937 citations. This is followed by the article "Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste" published in 2013 with 214 citations and the article "Electrical and electronic waste: a global environmental problem" published in 2007 with 174 citations. Thus, the top 15 cited articles have been cited more than 100 times.

Distribution of articles by journal

The 141 articles analysed were published in 76 journals. Of these, 53 (69.7%) journals had a single publication each, 13 had two. The top ten journals published just over 40 (43.9%), as shown in Table 2. The journal with the most significant number of publications is the "Journal of Cleaner Production", with 11 publications. This is followed by "Science of

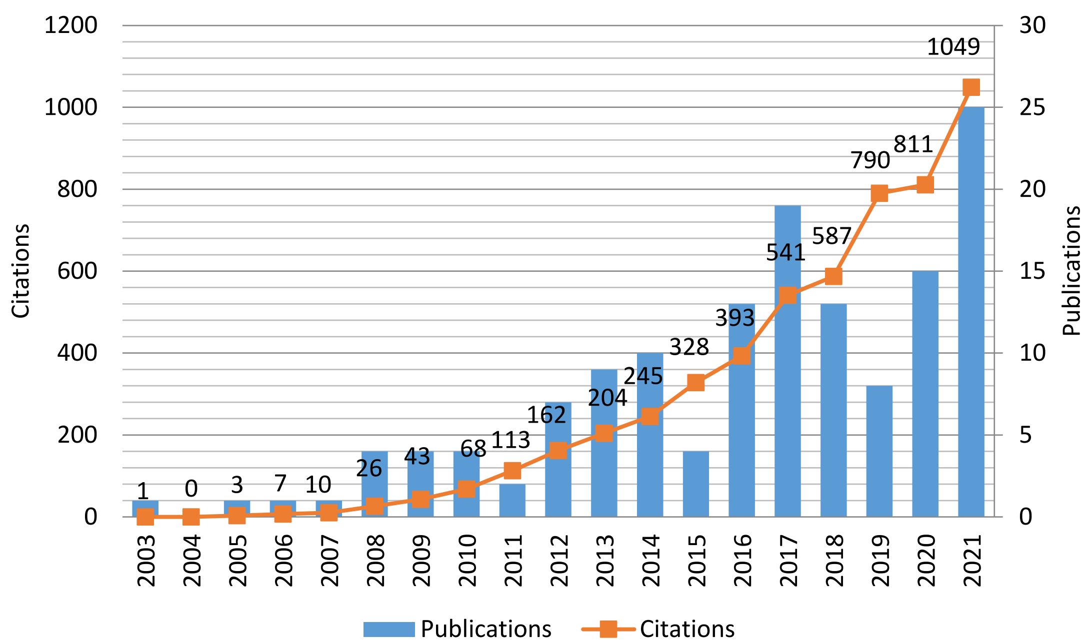

Fig. 1: Publication and citation index

Table 1: Top 15 cited articles

No.	Article	Year	Count	Reference
1	E-waste: An assessment of global production and environmental impacts	2009	937	(Robinson, 2009)
2	Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste	2013	214	(Kang *et al.*, 2013)
3	Electrical and electronic waste: a global environmental problem	2007	174	(Babu *et al.*, 2007)
4	Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE)	2005	170	(Hischier *et al.*, 2005)
5	Willingness to engage in a pro-environmental behavior: an analysis of e-waste recycling based on a national survey of U.S. households	2012	168	(Saphores *et al.*, 2012)
6	Environmental pollution of electronic waste recycling in India: a critical review	2016	151	(Awasthi *et al.*, 2016)
7	Sustainability in electrical and electronic equipment closed-loop supply chains: a system dynamics approach	2008	147	(Georgiadis and Besiou, 2008)
8	Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China	2009	136	(Xing *et al.*, 2009)
9	Environmental impacts of the Swiss collection and recovery systems for waste electrical and electronic equipment (WEEE): a follow-up	2011	134	(Wäger *et al.*, 2011)
10	Toward sustainability for recovery of critical metals from electronic waste: the hydrochemistry processes	2017	132	(Sun *et al.*, 2017)
11	Environmental effects of heavy metals derived from the e-waste recycling activities in China: a systematic review	2014	128	(Song and Li, 2014)
12	Electronic waste - an emerging threat to the environment of urban India	2014	118	(Needhidasan *et al.*, 2014)
13	Flame retardant emission from e-waste recycling operation in northern Vietnam: environmental occurrence of emerging organophosphorus esters used as alternatives for PBDEs	2015	115	(Matsukami *et al.*, 2015)
14	E-waste recycling induced polybrominated diphenyl ethers, polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins and dibenzo-furans pollution in the ambient environment	2007	108	(Liu *et al.*, 2008)
15	An analysis of some environmental consequences of European electrical and electronic waste regulation	2008	102	(Barba-Gutiérrez *et al.*, 2008)

Table 2: Top 10 journals

No.	Journal	Count	Percentage
1	Journal of Cleaner Production	11	7.8
2	Science of the Total Environment	10	7.1
3	Resources Conservation and Recycling	8	5.7
4	Environmental Science and Pollution Research	7	5
5	Waste Management	7	5
6	Environmental Science Technology	6	4.3
7	Environment International	4	2.8
8	Chemosphere	3	2.1
9	Environmental Pollution	3	2.1
10	International Journal of Environmental Research and Public Health	3	2.1

the Total Environment” with ten articles and then the “Resources Conservation and Recycling” with eight publications.

Geographical distribution of articles

Researchers from 48 countries authored the 141 articles analysed. Table 3 shows publications by country. As shown, China dominates with a third of articles published by authors in the country, followed by India with 19 articles (13.5%) and then the United States with 18 articles (12.8%). Developing countries contributed about 17% of total publications. Ghana and Pakistan are leading developing countries, contributing 3.5% of the research, while Nigeria, Bangladesh, Algeria contributed 1.7% each. Morocco, Benin, Iran and South Africa contributed 0.7% each.

Table 3: Geographical distribution of articles

No	Country	Count	Percentage
1	China	47	33.3
2	India	19	13.5
3	USA	18	12.8
4	Brazil	7	5.0
5	Italy	7	5.0
6	Japan	7	5.0
7	Australia	6	4.3
8	Canada	5	3.5
9	Ghana	5	3.5
10	Pakistan	5	3.5
11	Belgium	4	2.8
12	England	4	2.8
13	South Korea	4	2.8
14	Switzerland	4	2.8
15	Thailand	4	2.8
16	Germany	3	2.1
17	Greece	3	2.1
18	Netherlands	3	2.1
19	Portugal	3	2.1
20	Spain	3	2.1
21	Turkey	3	2.1
22	Vietnam	3	2.1
23	Algeria	2	1.4
24	Bangladesh	2	1.4
25	Denmark	2	1.4
26	France	2	1.4
27	Israel	2	1.4
28	Malaysia	2	1.4
29	Mexico	2	1.4
30	Nigeria	2	1.4
31	Norway	2	1.4
32	Romania	2	1.4
33	Saudi Arabia	2	1.4
34	Serbia	2	1.4
35	Sweden	2	1.4
36	Benin	1	0.7
37	Estonia	1	0.7
38	Iran	1	0.7
39	Ireland	1	0.7
40	Lithuania	1	0.7
41	Luxembourg	1	0.7
42	Morocco	1	0.7
43	New Zealand	1	0.7
44	Poland	1	0.7
45	Singapore	1	0.7
46	South Africa	1	0.7
47	Taiwan	1	0.7
48	United Arab Emirates	1	0.7

The citation and h-index analysis

The number of citations is the main factor to reflect the quality of a paper (Tahamtan *et al.*, 2016). According to the analysis of the data from Web of Science, all articles were cited 5290 times. These articles were cited in 110 countries, with four records not containing data in the field being analysed. The retrieved research studies have an h-index of 39. The h-index of 39 means that of the 141 research articles, 39 have received 39 citations. Based on

Table 4: Top 10 most occurring keywords

No.	Keyword	Occurrence	Link	Total link strength
1	Level	74	74	1085
2	Health	62	68	745
3	Soil	61	51	1274
4	Concentration	59	45	1353
5	Electronic equipment	57	57	872
6	Site	53	59	986
7	Sample	52	55	1120
8	Material	50	61	716
9	Area	48	64	742
10	System	45	61	644

the results of the citation report applied in the Web of Science database, the citation performance is summarised in the following indicators: citing articles – 4048; citing articles – 3959 (without self-citations); times cited – 5513; times cited – 5290 (without self-citations); and H-index – 39.

The keywords analysis of research hotspots

Analysis of e-waste and the environment research based on the frequency of the keywords used in the title and abstracts of the articles can achieve a conceptual image of the content of these studies and reflect research hotspots. A total of 4358 co-occurrence keywords were extracted from 141 articles. The minimum occurrence of each keyword was set to nine times, and 126 co-occurrence keywords were finally presented. The top three keywords ranked by the number of occurrences were as follows: level (n = 74), health (n = 68), and soil (n = 61). Table 4 shows the top ten most occurring keywords, links, and the total link strength. The link strength between two nodes refers to the frequency of co-occurrence. It can be used as a quantitative index to depict the relationship between two nodes (Pinto *et al.*, 2014).

Network visualisation graph

For each of the 126 keywords, VOSviewer calculated a relevance score and selected the 76 (60%) most relevant keywords that were mapped into four clusters representing four research themes. Fig. 2 shows the keyword co-occurrence network map. The distance between two nodes reflects their associative strength. A shorter distance generally reveals a more substantial relationship. The line between two keywords represents that they have appeared together. Nodes with a similar colour belong to the same cluster (Wiendartun *et al.*, 2022). Cluster 1 (red) is the largest cluster related to e-waste recycling, policies, strategies, technology, and environmental impact. Cluster 2 (green) shows the concentration levels of heavy metals and other chemicals in soil, water, plants and humans in the areas or region studied. Cluster 3 (blue) depicts the effect of e-waste management practices on health. Keywords include health, product, e-waste management, and information. The yellow cluster is the smallest, showing the level of knowledge on the generation of e-waste and its impact on the environment. The red cluster relates to e-waste recycling, policies, strategies, technology, and environmental impact.

Developed countries have the infrastructure and equipment to recycle electrical and electronic waste (WEEE) to recover valuable materials in an environmentally friendly manner (Maphosa and Maphosa, 2020). Developing countries lack policies, infrastructure and systems to recover precious materials, repair for reuse, and improper disposal of electronic equipment has a detrimental effect on the environment (Lebbie *et al.*, 2021). The green cluster shows the concentration levels of heavy metals and other chemicals in soil, water, plants and humans in the areas or regions studied. Studies reveal that a large area of farmland in China is contaminated with heavy metals such as pahs and phosphodiesterase (PDE) from e-waste recycling initiatives, thus reducing arable land, which has enormous consequences on sustainability (Wang *et al.*, 2020). Soil samples around e-waste dumpsites in Ghana have high levels of heavy metals, sometimes 50 times higher than the World Health Organisations' (WHO) threshold levels (Asante *et al.*, 2011). Crops and plants around dumpsites and

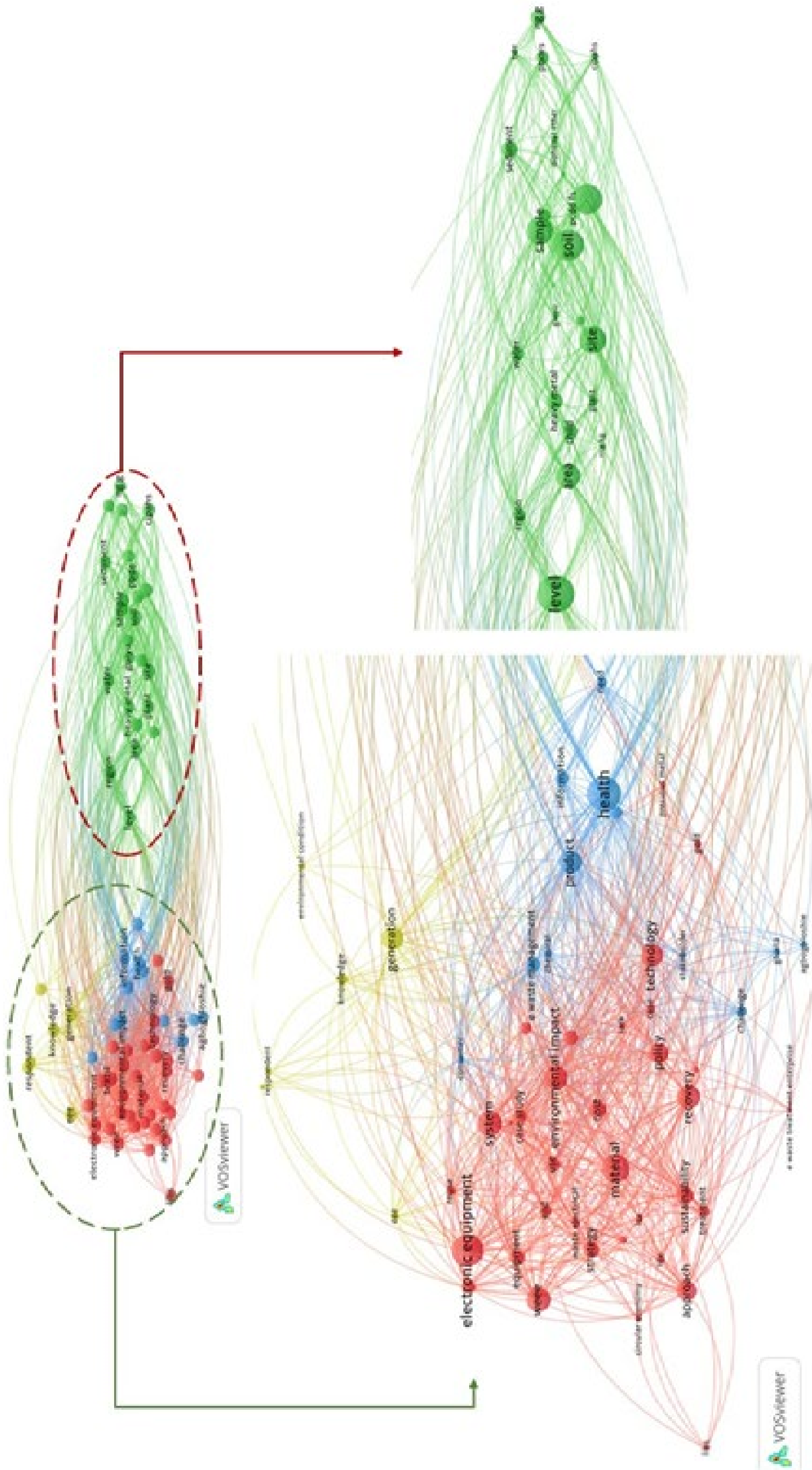

Fig. 2: The: Keywords co-occurrence network map

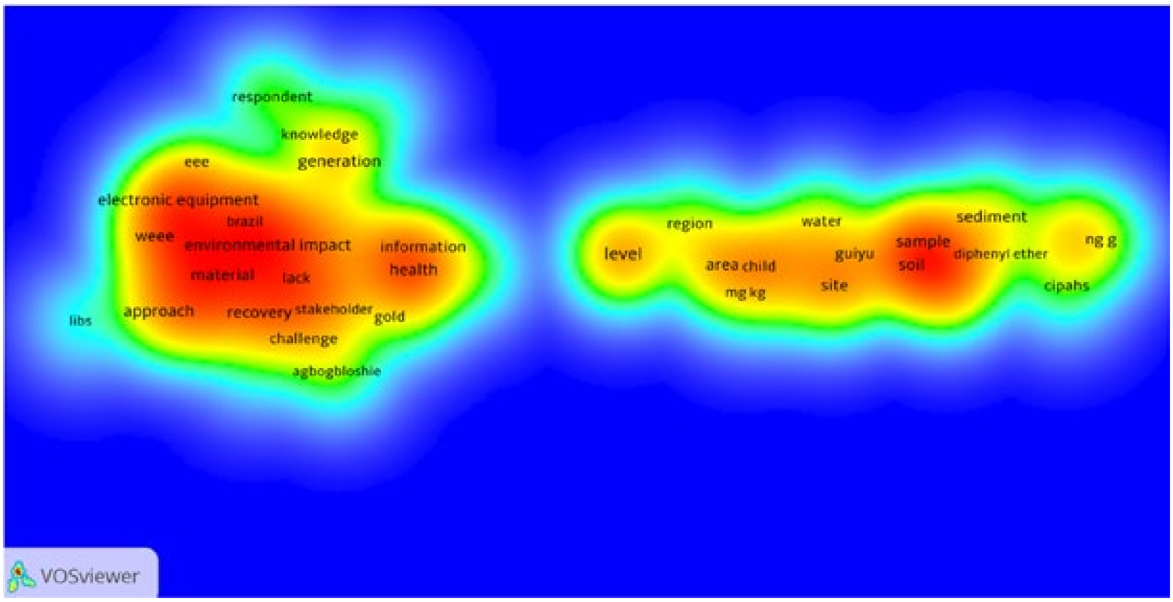

Fig. 3: Keywords density visualisation map

landfills are contaminated and toxic to humans and animals (Kiddee *et al.*, 2013). The blue cluster depicts the effect of e-waste management practices on health. Keywords include health, product, e-waste management, and information. The Agbogoloshie in Ghana is the largest landfill in Africa (Feldt *et al.*, 2014). Informal workers lack information on e-waste management and use rudimentary methods to extract rare earth metals through leaching, which causes health challenges (Huang *et al.*, 2014). The yellow cluster shows the level of knowledge on the generation of e-waste and its impact on the environment. The lack of e-waste policies, laws and legislation in most developing countries affects the awareness and knowledge levels of the community (Mutsau *et al.*, 2015). VOSviewer can make density visualisation (Fig. 3). Each node in the keyword's density visualisation map has a colour that relies on the density of items at that node. In other words, the colour of a node depends on the number of items in the node's neighbourhood.

The keywords in the red colour area appear more frequently; on the contrary, the keywords in the green colour area appear less frequently. From Fig. 3, we can see the core keywords in the e-waste and the environment field. These are: 'soil', 'sample', 'health', 'environmental impact', 'material', 'recovery', 'electronic equipment and 'WEEE'. In emerging economies, e-waste is collected together with municipal waste. Careless disposal and non-separation from solid waste lead to environmental pollution through illegal dumping and the recovery of precious minerals through rudimentary methods, polluting the air, soil, and water bodies (Kayes, 2019). Studies show that soils around e-waste dumpsites have high levels of toxic minerals such as lead, chromium, and cadmium. In some instances, these were 50 times higher than the permissible exposure levels set by WHO (Asante *et al.*, 2011). E-waste plants in Nigeria and China recorded high levels of lead, copper, manganese, cadmium in plants and the soils (Alabi *et al.*, 2012). Exposure to cadmium pollution during pregnancy may be a risk factor for shortened placental telomere length known to be related to cancer development and ageing (Lin *et al.*, 2013). The overlay network of keyword co-occurrence visualisation analysis is widely accepted to identify research hotspots (Chen, 2004). VOSviewer software was used to generate an overlay visualisation network of keyword co-occurrence to explore the changes of research hotspots over the last ten years. Fig. 4 shows the keywords overlay visualisation map. The results indicated that the keywords "LIBS" (laser-induced breakdown

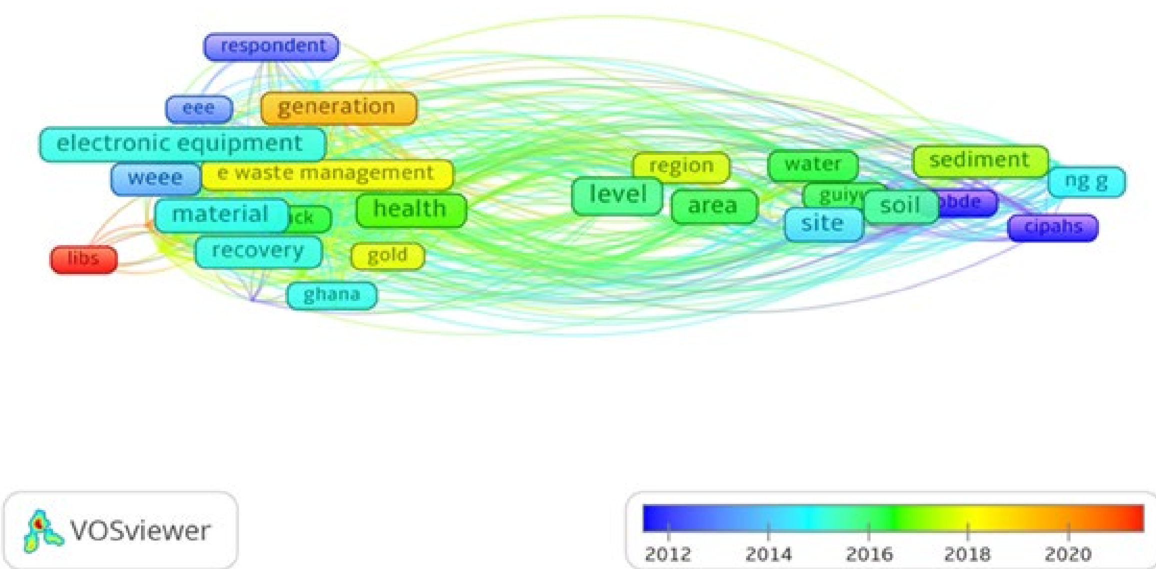

Fig. 4: Keywords overlay visualisation map (2012 – 2021)

spectroscopy) and "circular economy" emerged in 2021. LIBS is a tool for industrial process control that can be used to control the copper leaching process (Garcia *et al*., 2021). Besides e-waste, LIBS also analyses soil, rocks, sediments, waters, landfill leachates, lubricating oils, and aerosols (Gonçalves *et al*., 2021). A circular economy is an approach that avoids waste through the design of optimised cycles of products, components, and materials (Ellen MacArthur Foundation, 2013). More recently, the circular economy concept has been applied to e-waste. As a solution to the e-waste problem, a circular economy is an urban mining procedure of recovering and classifying mineral material (Xavier *et al.*, 2021). Gautam *et al.* (2021) explored how the disposal of solar photovoltaic e-waste could contribute to the circular economy in India. Islam *et al*. (2021) suggest a consumer-centric circular economy framework to advance knowledge and implementation strategies around e-waste.

The UN reported that e-waste recycling activities generated over USD 62.5 billion annually and reiterated the need to establish a circular economy based on e-waste management (IISD, 2019). Industry experts predict that e-waste revenue will surpass USD143 billion by 2028 (Allied Research Market, 2021). About 7% of the world's gold is contained in e-waste; low recycling rates have seen up to USD 22 billion worth of gold and platinum being dumped yearly (Globenewswire, 2018). Europe leads with about 40 collection and recycling rates, while less than 1% of e-waste generated in Africa is recycled (Forti *et al.*, 2020). China is currently recycling 30% of its generated e-waste (Chen *et al.*, 2019). Another study revealed that less than 1% of e-waste produced in Brazil was recycled in line with environmental and public health considerations (Caiado *et al*., 2017). Proper recycling can reduce the release of greenhouse gas emissions, and the recovery of precious and rare earth metals from e-waste minimises the demand for pure minerals (Foelster *et al*., 2016). Although informal e-waste recycling has created many jobs for the informal sector, rudimentary methods used to recover precious minerals are a threat to the environment and the health of the surrounding communities. The number of people dependent on e-waste activities continues to grow, and in 2010 over 200,000 people's livelihoods were supported by e-waste activities in Ghana (Prakash *et al*., 2010). Annual income from e-waste activities in Ghana is estimated to be USD268 million (Oteng-Ababio *et al.*, 2014). The government of Ghana has organised seminars and workshops for the public to raise awareness of the environmental and health impact of e-waste (Daum *et al.*, 2017). Based on the economic potential, e-waste management must be prioritised against other financial needs. The keywords such as "water", "soil", "health", "sediment", and "level" frequently appeared in the last six years, indicating that the impact of e-waste on the soil, water, and environment will continue to be researched hotspots in the near future. This is in line with findings of a study by Ackah (2017) that the major transport pathways in the e-waste recycling environment were: dust, air, water, soil, and biota. E-waste is dumped in landfills in most developing countries where informal workers attempt to recover precious materials using subsistence tools (Yohannessen *et al.*, 2019). Thus, hazardous chemicals contaminate water bodies, soils, and ozone-depleting gases are released into the atmosphere, contributing to climate change. Rare earth metals such as gold and copper, and other valuable materials are salvaged through burning and acid leaching, causing environmental damage and affecting the health of those living in the vicinity (Sun *et al.*, 2017; Tsydenova and Bengtsson, 2011). Informal workers in the e-waste value chain are often illiterate and cannot comprehend the environmental and health risks associated with their practices in recovering valuable materials (Singh *et al.*, 2020). An earlier study by Harayama and Rekacewicz (2004) revealed that only 50% of the computer components were recyclable. The remaining 505 contained about 2kg of lead and other harmful materials, often dumped in landfills. About 20% of the farmland in China is contaminated with polycyclic aromatic hydrocarbons (pahs) from e-waste recycling initiatives, thus reducing arable land, which has enormous consequences on sustainability (Sun *et al.*, 2018). Lakes, rivers and other water bodies in Guiyu, China, are contaminated with high lead levels due to indiscriminate burning and leaching of e-waste during the recovery of precious minerals (Li *et al.*, 2011). During recycling, released chemicals contaminate the dust, soils and water sources near dumpsites affecting the plants and fruits (Daum *et al.*, 2017). In a study in Japan, it was observed that rice and wheat irrigated with water from the Jinstu river were contaminated with cadmium and caused about 150 human deaths (Generowicz and Iwanejko, 2017). Research revealed that soils around informal e-waste recycling sites in Nigeria had high levels of zinc, nickel, chromium and cadmium compared to other sites (Isimekhai *et al.*, 2017). A study conducted in Ghana revealed that water bodies near dumpsites were contaminated as informal workers used leaching of acid to extract rare earth metals such as gold and copper from e-waste (Tue *et al.*, 2019). Thus toxic fumes, ashes, slag and harmful chemicals are released into the environment. E-waste recycling has contaminated large portions of underground water around landfills and dumpsites in Nigeria, making it unsuitable for human and animal consumption (Ewuim *et al.*, 2014;) explained that plants and crops are close to dumpsites are contaminated and are toxic to humans and animals. The UN's SDG 12 notes the rising e-waste problem and specifically addresses e-waste management. It highlights a recycling rate of 22.9%, while close to 80% of e-waste is unaccounted for and improperly disposed of, thereby polluting the environment (Ohajinwa *et al.,* 2017). Over 1000 substances are used in the manufacture of electronic equipment. These include precious minerals such as platinum, palladium, gold and copper, and toxic elements such as lead, mercury, cadmium, arsenic, etc. E-waste recycling is a lucrative industry; over USD 62.5 billion is realised annually, and over USD 22 billion worth of gold and platinum is dumped yearly. About 40% of e-waste generated in Europe is recycled, while less than 1% generated in Africa is recycled.

Looking forward

E-waste recycling is a lucrative industry; over USD 62.5 billion is realised annually, and over USD 22 billion worth of gold and platinum is dumped yearly. There is a need to establish a circular economy for the management of e-waste from the collection, separation, and recycling of e-waste. E-waste management will be improved by raising awareness of socio-economic and environmental benefits such as repairing, reusing, remanufacturing, and reducing. Funding is required to set up infrastructure that improves e-waste recycling and harnessing technology for e-waste management (Ellen Macarthur Foundation, 2021).

CONCLUSION

E-waste has become an environmental and epidemiological crisis requiring consented effort to protect the environment from improper disposal. Many emerging economies do not have e-waste policies to protect the environment and public health. Less than 20% of African countries have an e-waste policy, legislation or regulation. In most developing countries, e-waste is collected together with municipal waste. Its management is informal, and workers with no environmental awareness use rudimentary tools to recover precious materials and release toxic elements that contaminate water bodies, the soils, and the release of ozone-depleting gases. Countries such as China, Nigeria and Ghana revealed that up to 20% of farmland and grazing land is polluted due to e-waste recycling. Lakes, rivers and other water bodies near landfills and dumpsites are contaminated, affecting marine life and plants. Human fatalities are reported from consuming plants and aquatic animals near landfills and dumpsites. Bibliometric analysis and review of the environmental impact of e-waste were conducted. No studies were found chronicling the environmental effects of e-waste using bibliometric analysis. This study aims to provide a comprehensive insight into e-waste and the environment through bibliometric and network analysis. From the initial 667 661 articles, 141 articles on e-waste and the environment published between 2003 and 2021 were selected for the study. The results show considerable growth in publications on e-waste and the environment. The number of articles published increased from one in 2003 to 25 in 2021, and citations rose from zero to 1049. This study highlights publication trends, citation trends, and articles' distribution by journals and geography. A third of the articles were published by Chinese authors, followed by India 13.5% and the United States with 12.8%. Developing countries contributed about 17% of the publications. It is observed that the research hotspots in the field are: soil, health, environmental impact, recovery, electronic equipment and waste electrical and electronic equipment. By tracing the evolutionary research pathway, it is clear that the research hotspots have shifted focus to e-waste generation, laser-induced breakdown spectroscopy, and circular economy. The red cluster from the density maps shows the strategies employed in recovering minerals from e-waste. The green cluster shows the concentration levels of the heavy minerals found in e-waste. The blue cluster visualises the impact of e-waste on health, and finally, the yellow cluster highlights the effects of e-waste on the environment. The study adds valuable insights to the body of literature in hazardous and toxic substances management. Scholars from developing countries are being encouraged to contribute more research as their countries are affected by the environmental impact of improper e-waste management. The knowledge gained from this research serves as a baseline for policymakers and scholars as more policies need to be enacted, and further research needs to be undertaken in light of the sustainable development goals (SDGs).

AUTHOR CONTRIBUTIONS

M. Maphosa was responsible for defining the bibliographic search, searching the bibliography, selecting the relevant references, synthesising the manuscript, revising the final version. V. Maphosa was responsible for conceptualising the draft, analysing the references' coding, and reviewing the whole manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

PUBLISHER'S NOTE

ABBREVIATIONS

%	Per cent
4IR	Fourth Industrial Revolution
CIPAHs	Chlorinated polycyclic aromatic hydrocarbons
EEE	Electrical and electronic equipment
E-waste	Electronic waste
Fig.	Figure
h-Index	Hirsch index
LCA	Life Cycle Assessment
ICT	Information Communications Technology
LIBS	Laser-Induced Breakdown Spectroscopy
mg/kg	milligrams per kilogram
ng/ g	nanogram per gram
PAHs	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PCDD fs	Polychlorinated Dibenzo-p-Dioxins and Polychlorinated Dibenzofurans
PDE	Phosphodiesterase
SDG	Sustainable Development Goal
TI	Title
UN	United Nations
USD	United States Dollar
VOSviewer	A software tool for constructing and visualising bibliometric networks
WEEE	Waste Electrical and Electronic Equipment
WHO	World Health Organisation

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