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Using the Circular Economy to Mitigate the Global Electronic Waste Challenge: A Systematic Literature Review Approach

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Abstract

The global electronic waste (e-waste) output is increasing at an alarming pace, albeit with limited management practices, resulting in the release of toxic anthropogenic elements that threaten the environment and public health. The linear economic model, which follows the take-make-consume-dispose has shaped the global economy. In contrast, the circular economy reduces wastage, recirculates raw materials, and extends the lifespan of products through repairing, refurbishing and remanufacturing. This reduces supply chain risks and product supply disruptions and creates formal jobs. This systematic literature review evaluates how the knowledge economy and modernisation growth have contributed to the e-waste burden, and how the circular economy can mitigate environmental and health effects. The study evaluates the impact of the circular economy and the e-waste problem. It identifies the research landscape, the key research clusters, relevant topics, and research hotspots from research output from the 949 publications selected from the Scopus database published from 2014 to 2023. The analysis involved quantitative descriptions of several metrics related to the research outputs. The analysis also involved creating network and density graphs using VoSViewer and generating the ten key topics and a word cloud using Provalis WordStat. The study also highlights the conceptual developments and current and future research trends. The findings show that research outputs increased substantially from two in 2014 to 257 in 2023 and citations grew astronomically, from one in 2014 to 8409 in 2023. The analysis reveals five research clusters: material management and resource recovery, business practices and circular economy strategies, technology integration and sustainability, recycling challenges, and environmental health and sustainable practices. The study recommends that emerging economies should embrace the circular economy and integrate the informal sector for e-waste collection, sorting, and less complex recycling, while the formal sector conducts high-end recycling.

Keywords: Circular Economy, Electronic Waste, Electrical and Electronic Equipment, Sustainable Development, Supply Chain, Extended Producer Responsibility

1. Introduction

The growth of the global economy has been fueled by the linear economic model which follows the take-make-consume-dispose approach (Zeng & Li, 2018). In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development. This agenda outlines 17 goals and 169 targets structured around five pillars (people, planet, prosperity, peace, and partnership) to promote sustainable, resilient development and ensure no one is left behind (United Nations, 2015). Sustainable development requires a move from a linear-based economy to a circular economy that follows the made-to-be-made-again policy.

Electrical and electronic equipment (EEE) is central to socio-economic development and improving the lives of billions across the globe. The COVID-19 pandemic transformed most of our activities and increased our reliance on EEE, resulting in unprecedented adoption, especially in developing countries. Businesses depend on EEE to remain competitive despite changing consumer patterns and globalisation. Businesses have to manage supply chain risks to eliminate product supply disruptions (Althaf & Babbitt, 2021). The Fourth Industrial Revolution (4IR), the rise of the knowledge economy and artificial intelligence, the Internet of Things (IoT), the miniaturisation of EEE, and declining prices have resulted in multiple device ownership (Bachér et al., 2017).

Most recently, the internet, social media and smartphones have become part of our daily lives. Electronic waste (e-waste) refers to EEE whose owner has discarded it, whether working or at the end of its useful life (Forti et al., 2020; Maphosa & Maphosa, 2022). This includes information technology, telecommunications equipment, medical equipment, office and home appliances, batteries and solar panels. Over time, the lifespan of desktop computers diminished from ten years to three years, fuelling rapid e-waste accumulation (Agamuthu et al., 2015); thereby threatening the people and planet pillars in the United Nations' Agenda for Sustainable Development (United Nations, 2015).

The global demand for EEE has surged, and poor recycling initiatives strain the supply of raw materials used to manufacture this equipment. IoT devices will reach 75 billion by 2025 (Statista, 2016), fuelling e-waste. Global e-waste output rose from 9.2 metric tonnes (Mt) in 2014 to 54 Mt in 2019 and is expected to reach 74.7 Mt by 2030 (Kumar et al., 2022). Of the 57.4 Mt of e-waste produced in 2021, only 17.4% was formally recycled, with about 47 Mt dumped into landfills and dumpsites in developing countries (Forti et al., 2020), leaving a toxic legacy. Improper recycling releases toxic anthropogenic elements such as cadmium, mercury, lead and nickel, and organic compounds such as flame retardants, chlorofluorocarbons, polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, that threaten the environment and public health (Parvez et al., 2021).

Following the circular economy approach reduces the need for exploiting virgin resources and encourages rethinking resource and waste management, product redesign for cost efficiency, job creation, innovative technologies, and environmental friendliness. It also promotes reuse, sharing, repair, refurbishment, remanufacturing, and recycling in a closed-loop system (Zeng & Li, 2018). Thus, the circular economy aims to reduce wastage and pollution, recirculate raw materials, improve product design and extend the lifespan of EEE through repairing, refurbishing and remanufacturing (Lazar, 2021).

The study aims to highlight the ever-growing e-waste burden and explore how the circular economy can improve e-waste management for sustainable development. This study aimed to achieve the following objectives:

- Examine the current state of research on the circular economy and its implications for e-waste management.
- Identify and analyse the central themes and research clusters in the circular economy and e-waste management research outputs.
- Explore existing research gaps and propose future directions for investigation in the fields of circular economy and e-waste management.

This study explores how the knowledge economy contributes to the e-waste burden and examines how the circular economy can mitigate its environmental and health effects. The study analyses research outputs to identify key clusters, topics, and trends in e-waste and circular economy research. Using Provalis WordStat and VOSviewer, the research combined quantitative methods with text mining, topic modelling, and visualisation techniques to provide an understanding of the field. Network and density graphs highlight research clusters and hotspots, while word clouds and topic modelling identify the most relevant topics in the literature. The findings reveal key research clusters namely material management, circular economy strategies, sustainability practices, and recycling challenges. The study underscores the importance of adopting circular economy principles globally, recommending that emerging economies integrate the informal sector for e-waste collection and basic recycling, with the formal sector focusing on advanced recycling processes.

2. Literature Review

2.1 The circular economy

The dominant traditional linear economic model does not achieve equilibrium as it results in the depletion of natural resources, biodiversity loss and drastic climate change (PwC, 2021). In contrast, the circular economy is a generative system premised on natural evolution, where materials are preserved at their optimal value, with toxic materials and waste designed out of the system (WEF, 2019). Industry experts note that adopting a circular economy improves productivity and efficiency and reduces environmental and health impacts for communities around landfills (UNIDO, 2019; Mwaijande, 2024). This perspective highlights the potential for circular practices to not only benefit industries but also to protect vulnerable populations from the detrimental effects of waste accumulation. Furthermore, scholars pointed out that the circular economy reduces supply chain risks, which can result in product supply disruptions (Pan et al., 2022). Other essential models of the circular economy include product-as-a-service, extending the useful life of EEE through green designs, repair and reuse, and ultimately recycling (WEF, 2019).

The application of the circular economy aims to decelerate, bridge and regenerate resource cycles, thereby minimising extraction of virgin materials and waste production (Arpin et al., 2024). Central to the circular economy are the “7 R’s”: redesign, reduce, reuse, refuse, rethink, recover, and recycle. These principles serve as foundational guidelines that collectively promote sustainable development while safeguarding environmental integrity and public health (Meloni et al., 2018). The emphasis on these principles highlights the necessity for a holistic approach to resource management that transcends traditional linear models. Scholars have further emphasised that the circular economy optimises product design and policy frameworks to eliminate waste, thereby facilitating the adoption of cleaner and renewable technologies (Lin & Wei, 2023). This process allows for the extraction of valuable materials from e-waste, which can then be reused in the manufacturing of EEE and other products (de Oliveira Neto et al., 2023). These materials can be redirected back into the manufacturing process, thereby reducing the need for virgin resources and minimising environmental impact (Lazar, 2021).

In developed countries, the extended producer responsibility (EPR) scheme supports the circular economy model through take-back mechanisms, sending e-waste back to the manufacturer for recycling and proper disposal. The EPR is one of the most

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viable e-waste management strategies, where precious minerals are recovered using environmentally friendly and economically viable methods that protect public health and the environment (Thakur & Kumar, 2022). By integrating the EPR into the circular economy, developed countries are better positioned to manage e-waste effectively, reduce resource depletion, and enhance recycling rates. In contrast, 99% of e-waste recycling in developing countries, is handled by the informal sector, with no protective clothing, such as gloves and nose masks. To extract precious minerals, workers employ hammers, stones, and screwdrivers to dismantle, burn, and apply acid leaching techniques on EEE, thereby threatening environmental integrity and public health (Maphosa & Maphosa, 2020).

Nevertheless, obstacles that hinder the operation of circular economies in Africa include the lack of policies and finance, an unknowledgeable informal sector, and weak collection and transportation systems (Moyen Massa & Archodoulaki, 2023). Unlike developed countries, reports show that in most developing countries there are no defined e-waste collection points and transportation systems (Maphosa, 2021; Dias et al., 2022); hence, most individuals and institutions illegally dispose of their e-waste with municipal garbage. As noted by the United Nations (United Nations, 2015), sustainable development is critical to sustaining economic growth for a growing population with finite resources. The circular economy model does not only represent an important area in the management of e-waste but also covers sustainable development.

2.2 Electronic-waste

Differing definitions of e-waste and lack of policies have resulted in a booming toxic waste trade against the spirit and mission of the Basel Convention, which aims to end the transboundary movement and trade of poisonous waste (Forti et al., 2020). Developing countries are adopting digital technologies to leapfrog into the knowledge economy and, thus, have enacted policies to bridge the digital divide (Ohemeng & Ofosu-Adarkwa, 2014), albeit with minimum consideration of the epidemiological and environmental effects.

The unidirectional flow of e-waste from the Global North to the Global South has been critically described as a form of neo-colonialism, highlighting a significant decarbonisation divide (Maphosa, 2022). This phenomenon reflects a systemic issue where the burden of e-waste management is disproportionately transferred to developing countries that often lack the necessary infrastructure and capacity to handle such waste effectively. Research indicates that over 80% of second-hand electrical and electronic equipment (EEE) is illegally exported from the Global North to developing nations (Agamuthu et al., 2015; Mihai et al., 2022). This illegal trade not only exacerbates the e-waste crisis in these regions but also raises ethical concerns regarding environmental justice and accountability. Furthermore, reports reveal that more than 75% of the imported second-hand and donated EEE in developing countries are deemed unusable and unrepairable (Osibanjo & Nnorom, 2007). This statistic underscores the detrimental impact of such exports, as they contribute to environmental degradation and undermine local economies that are ill-equipped to manage the influx of non-functional equipment.

The composition of e-waste reveals significant deposits of minerals; for instance, a ton of mobile phones contains mineral deposits that are 50 times more valuable than a ton of mineral ore extracted from even the richest mines (Chatterjee, 2015). This highlights the economic potential inherent in e-waste, suggesting that effective recycling practices could yield substantial

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financial benefits. EEE is produced using some of the world's rare earth metals, including indium, lithium, and cobalt, as well as precious metals such as gold, silver, aluminium, and copper (Chancerel et al., 2015). The recovery of these minerals from e-waste not only presents an opportunity to mitigate environmental damage caused by over-mining but also addresses the exploitation of virgin and finite natural resources (Maphosa, 2022). Such recovery processes are critical in promoting sustainable practices within the industry. Moreover, research indicates that unrecycled e-waste accounts for over 7% of the world's gold output (United Nations, 2019). This statistic underscores the substantial economic loss that occurs when e-waste is not properly managed and recycled.

Extending the lifespan of EEE and reusing components from broken down EEE has more economic and environmental benefits. Reusable components are salvaged to rebuild EEE, while non-reusable components are recycled and disposed of in a formal way that does not endanger public health and the environment. Thus, conserving virgin minerals, protecting the environment and creating formal and sustainable jobs. Recycling e-waste releases fewer carbon emissions compared to conventional mining. Lack of policies, low recycling, lack of knowledge and infrastructure and unavailability of the EPR schemes in most African countries result in the loss of scarce resources and precious metals (Maphosa & Mashau, 2023).

3. Methodology

The study adopted a systematic literature review allowing for the gathering of relevant literature that meets specific eligibility criteria to address research questions (Moher et al., 2015). In this study, bibliometric analysis and text mining are integrated together. Bibliometric analysis provides a quantitative method for mapping literature, revealing influential publications and research trends (Secinaro et al., 2020). The focus on the last decade is driven by the recent surge in academic interest in circular economy and e-waste, as earlier publications were limited. Text mining techniques, such as information retrieval and data mining, complement this by uncovering direct and indirect relationships between pieces of information, yielding deeper insights (Ferreira-Mello et al., 2019; Thomas et al., 2011). The combination of topic modelling and text mining is especially effective in this review, as it uncovers patterns and trends within a vast body of literature, leading to an efficient synthesis of findings. Together, these methods help identify conceptual developments, current research, and future trends in the field.

3.1 Inclusion criteria

The inclusion criteria help to define the conditions for the inclusion of research outputs for review. Based on the requirements for this study, we used the following criteria:

- The research output must be a journal article, review paper, conference paper, book, or book chapter written in English. These formats were selected because they are peer-reviewed, and the language criterion ensures consistent analysis using VoSViewer and Provalis WordStat.
- The article should have been published in the past decade, from January 2014 to December 2023. This allows us to trace the research landscape in that decade.
- The research output had to include both constructs of interest (circular economy and e-waste).

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3.2 Literature Research Strategy

The research outputs were identified by searching the Scopus databases in January and February 2024. The search was updated in September 2024 to include articles that were published in 2023 but were in press and could not be accessed in January and February 2024. We searched for all available records using the following combination of keywords in the title or abstract of the research output: “circular economy” AND “e-waste” OR “electronic waste” OR “WEEE” OR “waste electrical and electronic equipment”. The initial query retained 1.257 records. We then removed all non-English research outputs as specified in the inclusion criteria and remained with 1.239 research outputs. Next, we filtered to the last decade – 2014 to 2023, as indicated in the inclusion criteria, leaving 970 research outputs. We then filtered by document types as stated in the inclusion criteria, leaving 949 research outputs. We then downloaded the research outputs as an MS Excel CSV file for analysis using VoSViewer and Provalis WordStat (Luo et al., 2018). The downloaded file contained information about the authors, the publication title, the year of publication, citation count, abstract, author keywords and the index keywords.

3.3 Data analysis

The research outputs were analysed using quantitative methods to address the research objectives. The Scopus database was used to extract information about the types of research outputs, their distribution in terms of the subject areas, publication and citation trends and the h-index. To process and analyse the data, we used Provalis WordStat a text mining tool that employs tokenisation, stop-word removal, and stemming to clean and standardise text for analysis. This step is crucial to enhance the quality of the data for subsequent analysis. Provalis WordStat uses Latent Dirichlet Allocation to perform topic modelling, enabling the identification of key topics within the research outputs. The optimal number of topics was determined using coherence score evaluation, ensuring that the model captured meaningful patterns and relationships in the data.

Once the key topics were identified, we used Provalis WordStat to generate a ranked list of the top ten key topics. Additionally, we created a word cloud to provide a visual representation of the most frequently used terms, making it easier to discern prominent themes and terminology within the dataset. To complement the text mining and topic modelling results, we employed VOSviewer to create a network graph that depicted the relationships between research clusters and showed the interconnected areas of study. We also used VOSviewer to generate a density graph. The density graph shows the research hotspots, highlighting insights into areas of concentrated research activity.

4. Results

4.1 Descriptive analysis

Table I provides the distribution of the document types analysed. Journal articles dominate, accounting for almost two-thirds of the research outputs; review articles represent almost 15%; followed by conference papers just above 13%; book chapters contribute just over 8% and books make up less than 1%. The dominance of journal articles bodes well and signifies a mature and topical research focus that attracts the attention of publishers.

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Table I. Distribution of the document types

Type	Number of research outputs	Percentage
Journal articles	600	63.2%
Review articles	140	14.8%
Conference paper	124	13.1%
Book chapter	78	8.2%
Book	7	0.7%
Total	949	100%

Source: Authors' elaboration

In terms of the geographical distribution of the producers of research outputs, a total of 75 countries are represented. Research publications are generated by countries across the world, reflecting a truly global interest in the circular economy and e-waste research. Table II presents the top 10 most productive countries in research outputs, showing Italy in the lead with 112 research publications. Italy is followed closely by India with 105 outputs, and then China and the United Kingdom simultaneously, each with 98 publications. The United States follows with 81 outputs, then Germany with 68. Spain, Australia, Brazil and France make the last four contributions with 55, 54, 49 and 39 outputs respectively.

Table II. Top 10 Most Productive Countries

Country	Number of research outputs
Italy	112
India	105
China	98
United Kingdom	98
United States	81
Germany	68
Spain	55
Australia	54
Brazil	49
France	39

Source: Authors' elaboration

Figure 1 presents the distribution of the research outputs by the Scopus database subject areas. It is necessary to note that a research output can be indexed in more than one subject area. As shown in the figure, "Environmental Science" is the most represented with 588 research outputs, followed by "Engineering" (304) and "Energy" (275). "Materials Science", "Social Sciences" and "Business Management and Accounting" have 124, 123, and 115 research outputs, respectively. "Chemistry", "Economics, Econometrics and Finance", and "Chemical Engineering" command substantial representation, each with over 80

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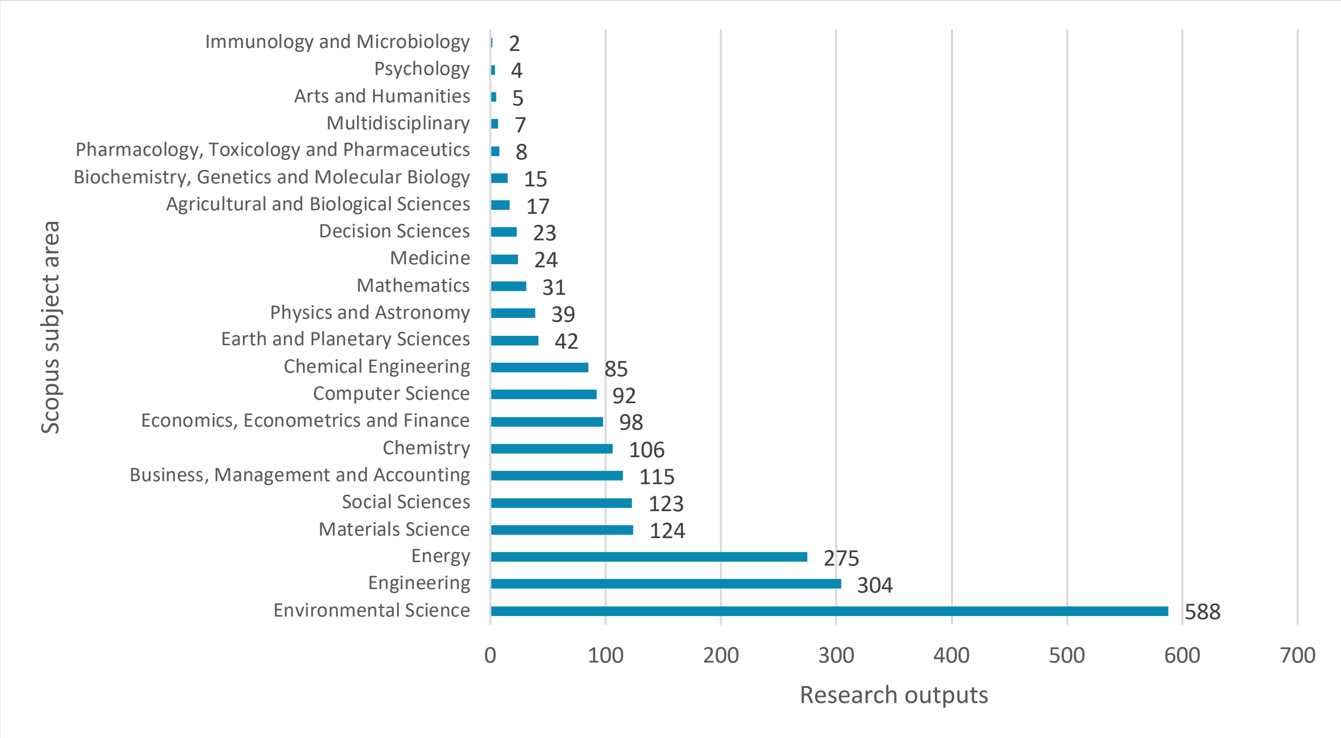
research outputs. "Psychology" and "Immunology and Microbiology" have much lower representation, each having less than five research outputs. Although environmental science is dominant, the presence of 22 more subject areas underscores the interdisciplinary and transdisciplinary nature of the circular economy and e-waste research.

Figure 1. Distribution of the research outputs using the Scopus database subject area



Source: Authors' elaboration

4.2 Publication and Citation Analysis

Figure 2 shows the publication trends for the research outputs analysed. There was a notable increase in research outputs between 2014 and 2023. The number of research outputs steadily increased from two in 2014, seven in 2015 and then 22 in 2016, reflecting a growing recognition of the importance of these topics. By 2017, the number of research outputs reached 32, indicating a growth in research activity and a growing body of knowledge on the circular economy and e-waste. There were 56 research outputs in 2018, 86 in 2019, 107 in 2020 and 179 in 2021. The years 2022 and 2023 saw a further increase in research outputs, with each year producing 201 and 257 research outputs respectively. This surge denotes a growing interest in research on e-waste management and the circular economy, amplifying the importance of the topics.

The citation trends for research outputs analysed in the study are shown in Figure 3. In 2014, there were two citations. In the following two years, the number of citations began to increase monumentally, with 15 citations in 2015, 66 in 2016, and 174 in 2017. The number of citations more than doubled from the year 2018 to 2020, reaching 1.626 by 2020. In 2021, citations

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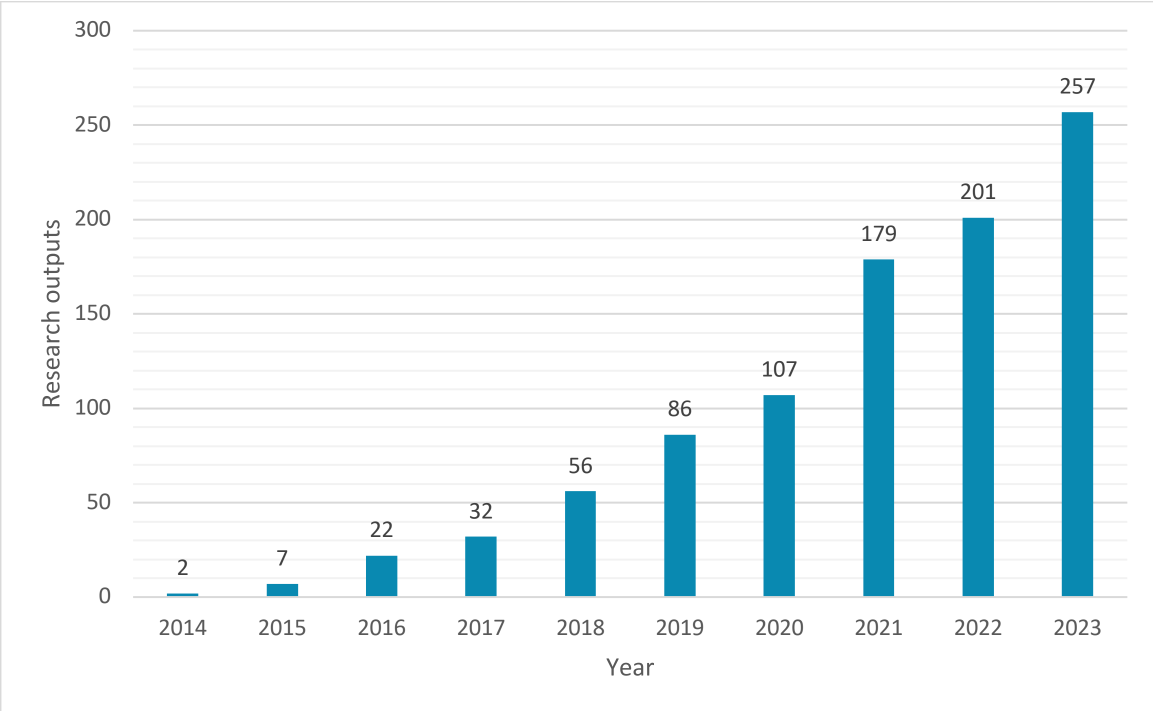
increased to 3 391, and the trend continued with citations reaching 5.628 and 8.409, in 2022 and 2023 respectively, indicating growing interest, increased impact and visibility of research on the circular economy and e-waste over the last ten years.

Figure 2. Publication trends of the 949 research outputs analysed



Source: Authors' elaboration

Table III shows the top 10 most cited research outputs in the circular economy and sustainability field showing that the most influential papers are not necessarily the oldest. The highest-cited paper, by Schroeder, Anggraeni, and Weber (2019), explores the relevance of circular economy practices to the Sustainable Development Goals and has amassed 893 citations. This significant citation count highlights the growing importance of linking sustainability efforts with global development frameworks. Another highly cited work from 2019 by Nascimento et al. (2019), examines how Industry 4.0 technologies can support the circular economy practices in manufacturing, has garnered 601 citations. Cucchiella et al. (2015), assess the economic aspects of WEEE recycling. Despite its earlier publication date, it has accumulated 619 citations. This shows that while newer research is quickly gaining attention, older studies remain critical in shaping the field. The blend of older and newer studies in the top 10 reflects how ongoing technological advancements and sustainability challenges maintain long-term relevance for researchers and policymakers.

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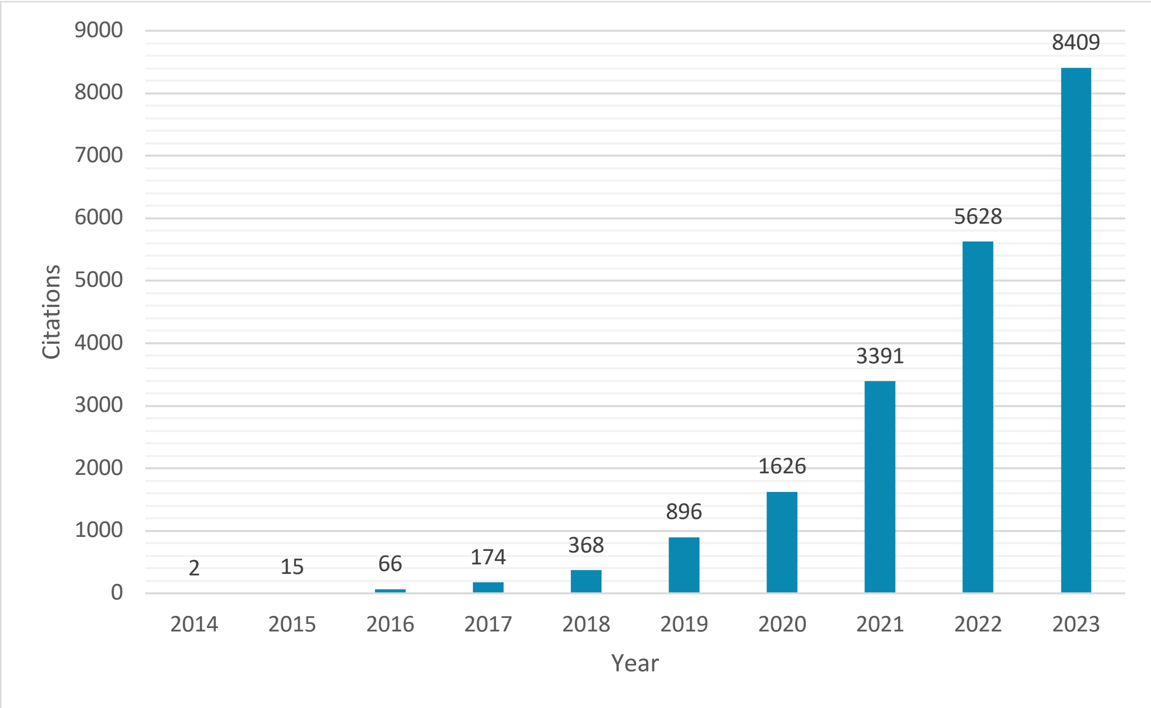
Figure 3. Citation trends for research outputs analysed



Source: Authors' elaboration

In addition to these influential works, several recent publications on lithium-ion battery recycling are rapidly gaining citations. For example, papers by Yang et al. (2021) and Makuza et al. (2021) on the sustainability and recycling options for lithium-ion batteries have already garnered 525 and 477 citations, respectively. These numbers highlight the urgent focus on battery recycling in the context of the circular economy, particularly with the rise of electric vehicles and renewable energy storage. This trend underscores that impactful research in this domain is not limited to older studies; newer contributions that address emerging sustainability challenges are quickly becoming central to the conversation.

The h-graph is a tool for visualising and comparing the productivity and impact of research outputs, institutions or authors. It uses the h-index, a metric developed by Hirsch (Hirsch, 2005) to achieve this. The h-index is determined by the highest number of articles that have received at least the same number of citations. The h-index was calculated using the Scopus database analysis feature. Of these 949 research outputs, only 846 have at least one citation. These research outputs have been cited 29,238 times. The research outputs have an h-index of 81, meaning that 81 articles have been cited at least 81 times.

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Table III. Top 10 most cited research outputs

Research output	References	Citations
The relevance of circular economy practices to the sustainable development goals	(Schroeder, Anggraeni, & Weber, 2019)	893
Recycling of WEEEs: An economic assessment of present and future e-waste streams	(Cucchiella, D'Adamo, Koh, & Rosa, 2015)	619
Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal	(Nascimento et al., 2019)	601
On the sustainability of lithium-ion battery industry – A review and perspective	(Yang et al., 2021)	525
Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review	(Makuza, Tian, Guo, Chattopadhyay, & Yu, 2021)	477
Recycling of lithium-ion batteries—current state of the art, circular economy, and next generation recycling	(Neumann et al., 2022)	354
A critical review of lithium-ion battery recycling processes from a circular economy perspective	(Velázquez-Martínez, Valio, Santasalo-Aarnio, Reuter, & Serna-Guerrero, 2019)	336
Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments	(Mossali et al., 2020)	325
The future of waste management in smart and sustainable cities: A review and concept paper	(Esmaeilian et al., 2018)	308
Circular economy strategies for electric vehicle batteries reduce reliance on raw materials	(Baars, Domenech, Bleischwitz, Melin, & Heidrich, 2021)	294

Source: Authors' elaboration

4.3 Keyword analysis

We created the network graph using VoSViewer by analysing the co-occurrence of all the author keywords in the 949 research outputs. Co-occurrence analysis calculates the relatedness of the keywords based on the number of research outputs in which they occur together. We used fractional counting, meaning the link's weight between two keywords is fractionalised. We set the minimum number of occurrences of the keywords to five. Out of the 2.435 keywords in the 949 research outputs, 107 met the threshold. We then removed keywords that appeared in singular and plural. This resulted in 72 keywords, shown in Figure 4. The figure shows research clusters that represent five key themes that the research on the 949 research outputs is centred around. In the figure, the nodes represent the keywords, those with a larger node represent the prominence of the keyword and the joining lines represent relationships between the keywords.

The red cluster is the largest of the groups, consisting of 25 terms highlighting the technical processes involved in material recovery and recycling, particularly within the domain of electronic waste. The cluster is centred around critical and precious metals, such as gold and copper, and processes like hydrometallurgy and pyrometallurgy, which are essential for metal recovery from mobile phones, printed circuit boards and other devices. Concepts like urban mining, industrial ecology, and green

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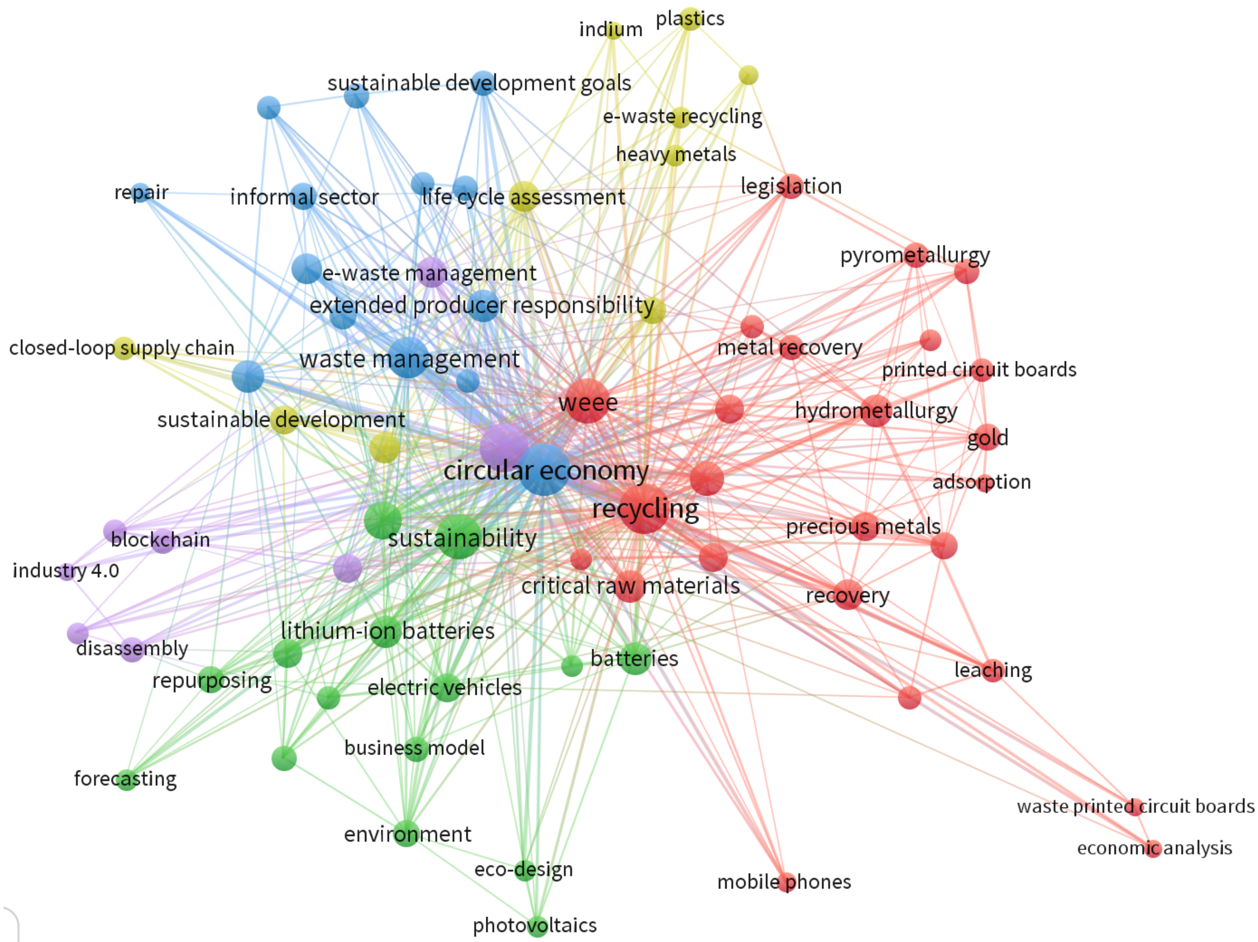
chemistry also feature prominently, illustrating the cluster's focus on sustainable extraction techniques. This cluster also touches upon the regulatory and policy frameworks surrounding the recycling of electronic waste, emphasising the need for legislation and economic analysis to support the circular economy.

Figure 4. Network graph of the keywords from the author keywords (VoSViewer)



Source: Authors' elaboration using VoSViewer

The green cluster comprises 15 terms and focuses primarily on sustainability within electronic products, particularly around electric vehicles and batteries. This cluster covers the lifecycle management of electronic devices, with a focus on eco-design, resource efficiency, and second-life applications, such as the repurposing of lithium-ion batteries and photovoltaics (Song et al., 2023). The terms reflect an interest in forecasting environmental impacts, emphasising the role of business models that integrate end-of-life strategies, reuse, and repurposing. Sustainability is the core theme, where resource efficiency and circular practices for electronic equipment are key drivers.

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Next is the blue cluster, with 14 terms, integrating broader sustainability themes, such as the circular economy, climate change, and sustainable consumption. The cluster brings attention to consumer behaviour and policy mechanisms like the extended producer responsibility, which regulates the roles of manufacturers in managing the end-of-life phase of their products. This cluster also explores the challenges posed by the informal sector and its role in waste management, particularly in municipal solid waste. Furthermore, it touches on global objectives like the Sustainable Development Goals, linking circular economy practices to broader environmental and societal outcomes. The terms emphasise the importance of remanufacturing, repair, and reverse logistics as part of sustainable consumption practices.

The yellow cluster, consisting of 10 terms, focuses on the recycling and management of hazardous materials in electronic waste. It highlights substances like brominated flame retardants and heavy metals, alongside key methodologies such as life cycle assessment and materials flow analysis, which are used to track and evaluate material flows and environmental impacts. The cluster emphasises resource recovery through closed-loop supply chains, especially in plastics recycling and the sustainable management of e-waste. The terms indicate a concern with mitigating the harmful environmental effects of materials used in electronics while promoting resource recovery.

Finally, the purple cluster includes eight terms but focuses on the intersection of advanced technologies and e-waste management. It features terms related to emerging technologies such as artificial intelligence, blockchain, and the Internet of Things, which are being integrated into the management and disassembly of e-waste. The cluster emphasises Industry 4.0 technologies and their potential to optimise supply chains and enhance sustainability within e-waste management processes. This blend of technology and environmental management positions the cluster as forward-looking, addressing future challenges in the context of the circular economy.

Figure 5 shows the density map generated by VoSViewer, revealing the research hotspots. As shown, the highest density represented by the red and pale yellow are in the middle of the figure focusing on the circular economy and recycling. This hotspot also includes research focused on the circular economy, WEEE, recycling, critical raw materials and waste management. Research areas that are growing are in yellow – represented by terms – EPR, e-waste management, life cycle assessments (LCA), remanufacturing, supply chain and lithium-ion batteries (Ragossnig & Schneider, 2019). The next prominent research hotspot is represented by chartreuse on the map. This hotspot covers research on hydrometallurgy, gold, precious metals, industry 4.0, blockchain, disassembly, repurposing, waste printed circuit boards, metal recovery, recovery, and the informal sector. The light blue indicates emerging research hotspots. These include – repair, forecasting, mobile phones, economic analysis, eco-design, closed-loop supply chain, indium, photovoltaics and plastics.

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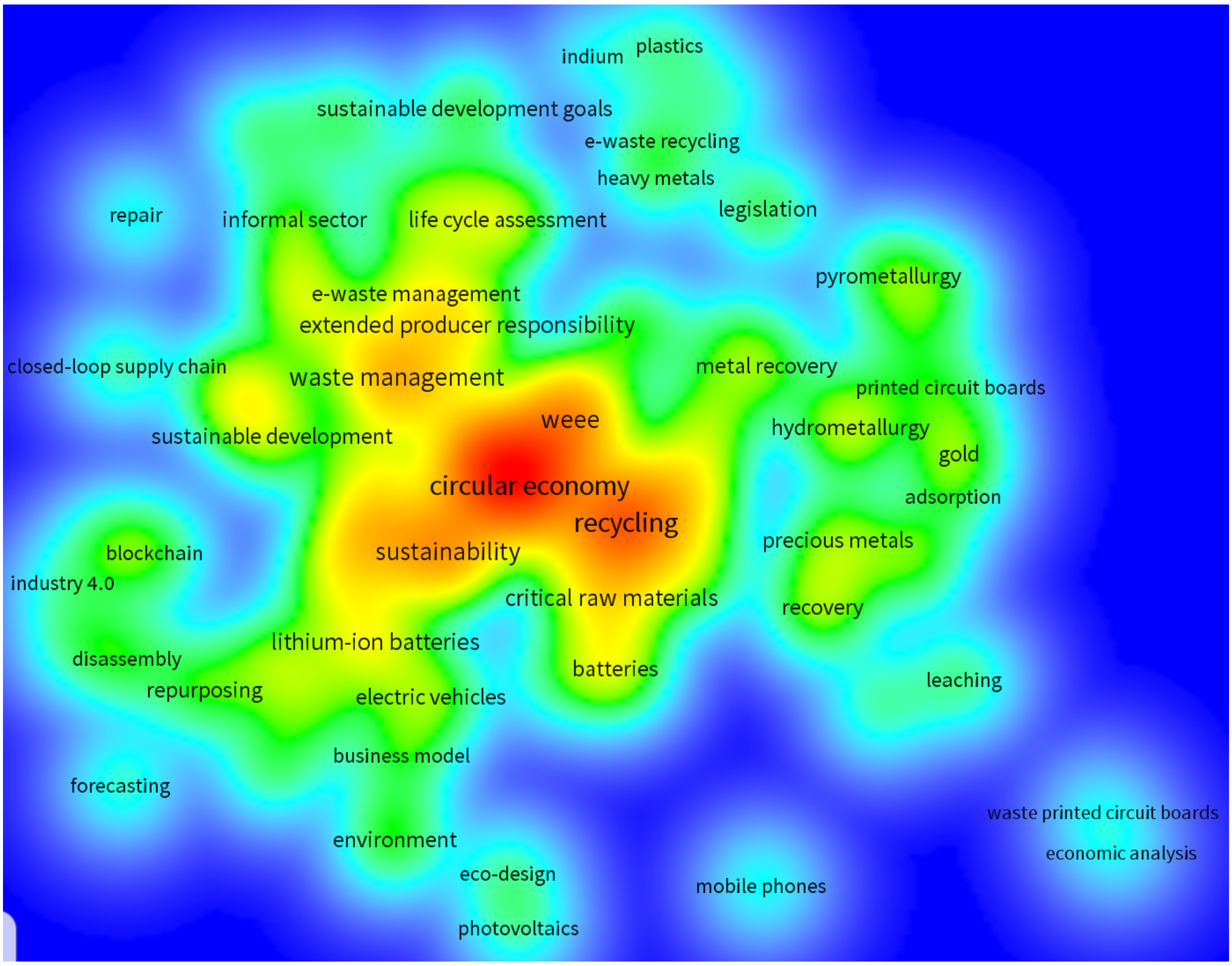
Figure 5. A density map of the keywords from the authors' keywords



Source: Authors' elaboration using VoSViewer

4.4 Topic Analysis

The topic analysis was done using Provalis WordStat (version 2023.2). Provalis WordStat is a text analysis software that facilitates fast extraction of themes and trends and quantitative content analysis, suitable for analysing large data (Provalis, 2024). Table IV shows the top 10 topics extracted from the authors' keywords of the 949 research outputs analysed. The description of the table headers is given below:

- Topic is the topic generated by WordStat using an algorithm that assigns a label to the extracted topic.
- Keywords are the words meeting the factor loading cutoff criteria. These keywords are ordered by descending factor loading, along with associated phrases.
- Coherence refers to the weighted average of the correlations among words associated with the topic.
- Eigenvalue indicates the eigenvalue of each factor.

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- Freq represents the total frequency of all items listed in the keywords column.
- Cases show the number of research outputs containing at least one of the items listed in the keywords column.
- % cases show the percentage of cases with at least one of the items listed in the keywords column (Provalis, 2022).

Coherence scores and eigenvalues provide insights into the consistency and significance of the top ten topics generated by Provalis WordStat. Higher coherence scores indicate more cohesive themes within a particular topic, aiding in the interpretation of extracted topics. At the same time, eigenvalues quantify the importance of each topic, with higher values suggesting greater prevalence and influence. Frequency and case counts offer additional context by revealing the prevalence and distribution of topics across the analysed data. Higher frequencies and case counts denote more prominent themes, and case percentages offer insight into each theme's overall coverage (Provalis, 2022).

The topic of electrical and electronic equipment, with a coherence score of 0.177 and an eigenvalue of 2.42, represents almost 20% of the cases studied. Key terms associated with this topic include equipment, electrical, electronic, WEEE, responsibility, producer, and management. This reflects a growing interest in the EPR within the context of business and product lifecycle management. The focus is primarily on how producers can be held accountable for the environmental impact of their products, especially in the context of waste management and sustainable production (Campbell-Johnston et al., 2021; Andersen, 2022).

Producer responsibility (extended) is a more specific subset of the EPR concept, with a coherence score of 0.155 and an eigenvalue of 3.39. Representing almost 4% of the cases, this topic focuses on producers and their responsibility to manage waste generated by their products. The research in this area highlights the significance of holding producers accountable for their products from manufacturing to disposal (Andersen, 2022). This approach is critical in fostering sustainable practices and reducing environmental harm caused by electronic waste (Campbell-Johnston et al., 2021).

The lithium-ion batteries topic, with a coherence score of 0.127 and an eigenvalue of 2.89, accounts for almost 10% of the cases. This topic focuses on the development and impact of lithium-ion batteries in the context of electric vehicles and energy storage systems. Keywords such as lithium, batteries, electric vehicles, and energy indicate a growing body of research dedicated to improving battery technology and addressing the challenges related to recycling lithium-ion batteries (Sheth et al., 2023; Silva et al., 2023). As the demand for electric vehicles increases, so does the need for sustainable recycling practices for these batteries. Another topic covers raw materials (critical metals), with a coherence score of 0.107 and an eigenvalue of 2.59, represents just over 4.44% of the cases. This topic revolves around raw materials, critical metals, and the end-of-life stage of resources. It emphasises the importance of managing critical raw materials and reducing the reliance on primary sources through the circular economy framework (Smol et al., 2020). The research in this area also focuses on finding alternatives to scarce materials and promoting recycling to support sustainable resource management (Favot & Massarutto, 2019).

With a coherence score of 0.091 and an eigenvalue of 1.72, rare earth elements represent almost 4% of the cases. Keywords such as rare earth, metals, and leaching indicate that the research focused on the challenges posed by the extraction, recycling, and management of rare earth elements. These materials are critical for many modern technologies but are challenging to recycle, posing significant environmental concerns (Chatterjee, 2015). As such, research on rare earth elements plays a key role

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in the circular economy and e-waste management (Pan et al., 2022). The topic of material flow analysis (MFA) has a coherence score of 0.087 and an eigenvalue of 1.90, also representing almost 4% of the cases. This topic focuses on tracking the movement and use of materials within industrial systems to optimise resource management and minimise waste. Keywords include flow, material, and analysis, with research centred around understanding the lifecycle of materials and improving waste management through efficient recycling and recovery processes (Tembhare et al., 2022).

The next topic, reverse logistics has a coherence score of 0.084 and an eigenvalue of 1.58, representing almost 3% of the cases. This topic deals with the management of products after they have been used, particularly in the collection and recycling of electronic waste. Keywords such as reverse logistics and collection highlight the importance of developing systems that facilitate the return and recovery of products to ensure their proper disposal or reuse (Mishra et al., 2023). The end-of-life cycle topic has a coherence score of 0.073 and an eigenvalue of 2.68, appearing in almost 10% of the cases. Keywords include LCA and end of life, with a focus on evaluating the environmental impact of products at their final stage. This topic also explores economic evaluations of recycling and disposal practices, promoting the importance of responsible product design and sustainable waste management (Kwok et al., 2024; Ismail & Hanafiah, 2021).

Table IV. Top ten topics extracted with Provalis WordStat

Topic	**Keywords**	**Coherence (Npmi)**	**Eigenvalue**	**Freq**	**Cases**	**% Cases**
Electrical and electronic equipment	Equipment; electrical; electronic; waste; WEEE; responsibility; producer; extended; business; management; product	0.177	2.42	300	183	19.83%
Producer responsibility Extended	Producer; Responsibility; Extended	0,155	3,39	39	35	3.79%
Ion batteries lithium	Ion; Lithium; Batteries; Battery; Electric; Vehicles; Energy	0,127	2,89	174	91	9,86%
Raw materials critical metals	Raw; Materials; Critical; End; Resource; Rare	0,107	2,59	61	41	4,44%
Rare earth	Earth; Rare; Metals; Leaching; Critical	0,091	1,72	44	34	3,68%
Material flow	Flow; Material; Analysis	0,087	1,90	54	35	3,79%
Reverse logistics	Reverse; Logistics; Collection	0,084	1,58	27	25	2,71%
End of life cycle	Life; Cycle; Assessment; End	0,073	2,68	138	91	9,86%

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Supply chain closed loop	Supply; Chain; Management; Reverse	0,058	2,08	51	36	3,90%
Sustainable development Circular	Circular; Economy; Development; Sustainable	0,038	1,94	692	620	67,17%

Source: Authors' elaboration from Provalis WordStat

The supply chain (closed-loop) topic, with a coherence score of 0.058 and an eigenvalue of 2.08, represents almost 4% of the cases. This topic is closely linked to circular economy principles and focuses on closed-loop supply chain management, where products and materials are recovered and reused to reduce waste. Keywords like supply chain, management, and reverse emphasise the need for more efficient logistics to achieve sustainability in global supply chains (Mishra et al., 2023). The sustainable development (circular economy) topic is the most prominent, with a coherence score of 0.038, an eigenvalue of 1.94, and appearing in 67% of cases. The focus on circular economy and sustainable development highlights the widespread recognition of these concepts in addressing global environmental challenges, particularly in the context of e-waste and resource management (Zisopoulos et al., 2023). The emphasis is on reducing waste, optimising resource use, and ensuring long-term environmental sustainability.

Figure 6. Word-cloud graph of the most frequently used words

Source: Authors' elaboration from Provalis WordStat

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Figure 6 is a word cloud generated using Provalis WordStat to visually represent the most commonly used keywords from the author keywords of the analysed research outputs. This graph highlights key themes by displaying frequently used words in larger font sizes, offering an intuitive understanding of the primary topics covered in the research. Prominent keywords include "circular economy," "recycling," and "waste," followed closely by "electronic," "environmental," and "management." Other frequently encountered terms like "materials," "sustainable," and "life" further emphasise the growing focus on sustainability, environmental responsibility, and eco-friendly practices in the context of circular economy and e-waste research. Keywords such as "metals" and "batteries" also appear significantly, reflecting the increasing attention given to resource management and sustainable practices.

5. Discussion

The circular economy and e-waste research areas are key to sustainable development initiatives. This study aimed to determine the current state of research on the circular economy and e-waste, the central themes and key topics within this research, and how the circular economy addresses e-waste management challenges. To achieve this, we employed quantitative analysis techniques to address the research objectives with the aid of tools such as WordStat, VoSViewer and Provalis.

The global e-waste production growth has been phenomenal, rising from 9.2 Mt in 2014 and is expected to reach 74.7 Mt by 2030 (Kumar et al., 2022). Precious materials in e-waste are 50 times richer than mineral ore, even from the most mineral-rich mines. Recovering these minerals reduces the over-mining and exploitation of virgin and finite natural resources while creating formal jobs (Maphosa & Mashau, 2023). Recycling and reusing e-waste components promote a circular economy where resources are extracted from e-waste and reused in manufacturing EEE. In contrast, non-reusable components are recycled and disposed of in a formal way that does not endanger public health and the environment (Xu et al., 2022). Improper recycling releases toxic anthropogenic elements that threaten the environment and public health (Ragossnig & Schneider, 2019; Xu et al., 2022).

The circular economy concept was developed as a business and economic model to mitigate environmental and human health effects while ensuring resource recovery from anthropogenic materials (Xu et al., 2022). Businesses have to manage supply chain risks to eliminate product supply disruptions by adopting a circular economy. The circular economy improves productivity and efficiency and reduces environmental and health impacts. It also reduces wastage and pollution, recirculates raw materials, improves product design and extends the lifespan of EEE through repairing, refurbishing and remanufacturing.

5.1 The current state of circular economy and e-waste management research

The first objective of this research was to explore the circular economy and the current e-waste research landscape. A quantitative analysis of research outputs revealed key insights on the maturity and global relevance of this field. Journal articles dominated the output, with almost two-thirds of the total research outputs. The dominance of journal articles suggests that the circular economy and e-waste research fields are well-established areas of inquiry, supported by high-quality research outputs. The global interest in the circular economy and e-waste research is reflected in the geographical distribution of publications, with contributions from 75 countries. Italy is the most productive nation, followed by India, China, and the United Kingdom.

Other major contributors include the United States, Germany, Spain, and Australia, indicating the widespread international focus on addressing e-waste and promoting sustainable circular economy practices (Cucchiella et al., 2015). Regarding the subject areas indexed, environmental science emerges as the most prevalent, in line with the United Nations' sustainable development goals focusing on people and the planet (United Nations, 2015).

The interdisciplinary nature of the circular economy and e-waste research is evident from the subject area distribution. Environmental science is the most prominent, followed by engineering and energy. The inclusion of social sciences, business management, and materials science demonstrates the broad scope of the research, encompassing technological, social, economic, and environmental dimensions (Nascimento et al., 2019). Publication trends show a sharp increase in research output between 2014 and 2023. The exponential growth in publications, particularly after 2020, reflects the rising importance of the circular economy in achieving sustainable development goals and managing e-waste (Schroeder et al., 2019). This increase mirrors the escalating urgency of addressing e-waste challenges and promoting circular economy principles in the global sustainability agenda. The scholarly impact of the circular economy and e-waste research is further illustrated by citation trends. From just two citations in 2014, the number of citations escalated to over 8,000 by 2023, demonstrating the field's growing influence. The h-index of 81, reflects the field's maturity and significance. Highly cited papers, such as Schroeder et al.'s (2019) work on linking circular economy practices to sustainable development goals, underscore the impact of aligning sustainability efforts with global development goals.

5.2 Central themes and key topics in circular economy and e-waste research

The second research objective aimed to identify the central themes that dominate the circular economy and e-waste research. The bibliometric and text mining analysis of research outputs identified five distinct research clusters, ten research topics, and several research hotspots that represent the central themes within the circular economy and e-waste research. These findings provide insight into the focal areas of the field, with material management and resource recovery, business practices and circular economy strategies, technology integration and sustainability, recycling challenges, and environmental health and sustainable practices emerging as core themes.

The material management and resource recovery cluster show the efficient use of materials and resource recovery in e-waste, highlighting the importance of optimising recycling processes and minimising e-waste to support sustainable development. Smol et al. (2020) stress the need for effective material management to achieve circular economy goals, especially in the recovery of critical materials like rare earth metals from e-waste. The second research theme - business practices and circular economy strategies focuses on systemic approaches to integrating circular economy principles into business practices. Sustainable business models, such as those involving EPR, enable businesses to reduce environmental impact while promoting circular strategies (Gaustad et al., 2018).

The third theme - technology integration and sustainability explore the intersection of advanced technologies—such as AI, blockchain, and Industry 4.0—with sustainability efforts. These technologies are increasingly applied to improve the efficiency and traceability of e-waste management systems (Pulparambil et al., 2024). They also help address challenges such as material

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tracking and disassembly, which are critical in recycling and resource recovery. The fourth cluster addresses the challenges associated with recycling e-waste, particularly in the recovery of valuable materials and the safe disposal of hazardous substances. This theme highlights advanced recycling methods like hydrometallurgy and pyrometallurgy for metal recovery from electronics such as mobile phones and printed circuit boards (Tembhare et al., 2022). These methods are essential to ensure environmentally safe recycling processes. The final theme - environmental health and sustainable practices focuses on sustainable practices aimed at preserving environmental health, particularly in managing e-waste components like batteries and photovoltaics. Sheth et al. (2023) discuss the importance of resource efficiency and the need for sustainable disposal methods to reduce harmful environmental effects.

Key research hotspots emerged from the analysis, with the most prominent being studies related to the circular economy and recycling (Ragossnig & Schneider, 2019). Other significant hotspots include hydrometallurgy, urban mining, sustainable consumption, and EPR, which indicate growing research interest in improving recycling techniques and enhancing resource efficiency. Emerging topics include mobile phones, closed-loop supply chains, and rare earth elements, suggesting a broadening of research focus towards specific e-waste challenges (Mishra et al., 2023).

Among the ten key topics identified, EEE emerges as a critical area due to the increasing prevalence of e-waste, particularly the producer responsibility and EPR schemes (Yu et al., 2022). Another major focus is on lithium-ion batteries, which are integral to electric vehicles and renewable energy systems, highlighting concerns related to their lifecycle and sustainability (Xu et al., 2022). The raw materials and critical metals topics underscore the need for effective resource management, particularly concerning rare earth elements and materials critical for technological advancement (Andersen, 2022).

Reverse logistics has gained prominence as a vital aspect of managing e-waste, focusing on the collection and repurposing of discarded equipment to support circular economy practices. The closed-loop supply chain model emphasises the importance of integrating circular economy principles into supply chain management to enhance sustainability and reduce environmental impacts (Mishra et al., 2023). The overarching theme of sustainable development highlights the growing recognition of the circular economy strategies as essential for addressing environmental challenges and fostering economic growth. Topics such as the end-of-life cycle assessment provide a framework for evaluating the environmental impact of products throughout their lifecycle, reinforcing the necessity for sustainable practices in e-waste management.

5.3 Research gaps and future directions in circular economy and e-waste management

Despite the rapid growth and maturity of the circular economy and e-waste research, several gaps remain, offering opportunities for future investigation. One of the key gaps identified in the literature is the need for more research on the recycling of specific e-waste components, such as lithium-ion batteries (Neumann et al., 2022). While significant progress has been made in understanding general recycling processes, the recycling of complex and hazardous materials like batteries still faces technological, economic, and environmental challenges. Research by Makuza et al. (2021) and Mossali et al. (2020) highlights the potential of pyrometallurgical and other advanced recycling techniques but calls for further innovation to make these processes more cost-effective and environmentally sustainable.

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Another research gap lies in the application of circular economy principles to emerging technologies. As digital technologies continue to evolve, there is a pressing need to develop circular economy strategies that can accommodate the rapid obsolescence and disposal of devices like smartphones, laptops, and other electronics. Esmaeilian et al. (2018) point out that smart city initiatives and the IoT will generate massive amounts of e-waste in the coming decades. Future research should focus on integrating circular economy principles into the design and production of next-generation technologies, ensuring that they are easier to disassemble, recycle, and repurpose.

In addition, more research is needed to explore the social dimensions of the circular economy and e-waste management. While much of the current literature focuses on technological and economic aspects, the role of consumers, communities, and workers in advancing circular economy practices is less studied. Understanding consumer behaviour, incentivising recycling, and addressing the social impacts of e-waste on vulnerable populations are crucial areas for future research (Schroeder et al., 2019). This also includes examining how circular economy initiatives can contribute to job creation and social equity, particularly in developing countries where e-waste recycling is often informal and hazardous.

Future research should focus on developing more effective policy frameworks that incentivise circular business models and promote sustainable production and consumption patterns. Although existing policies such as EPR are a step in the right direction, there is a need for more comprehensive and coordinated international policies that address global e-waste flows and ensure the ethical management of resources (Baars et al., 2021). Researchers also suggest that policy development should be guided by LCAs and other tools that provide a more holistic understanding of environmental impact (Velázquez-Martínez et al., 2019).

6. Conclusion

This study presented a systematic literature review of the circular economy and e-waste management. The proliferation of e-waste poses significant challenges due to limited formal recycling practices, leading to environmental degradation and public health risks from toxic elements. However, adopting circular economy principles presents a promising solution by reducing waste generation, promoting resource recirculation, and extending product lifespans through repair and refurbishment. The circular economy not only addresses e-waste challenges but also fosters sustainable development by mitigating supply chain risks and creating formal job opportunities.

This study has painted the current landscape of the circular economy and e-waste research, revealing key insights into the maturity and global relevance of this field. The predominance of journal articles indicates that these areas are well-established and supported by high-quality scholarly work. This global interest is reflected in contributions from 75 countries, with Italy, India, China, and the United Kingdom leading in research productivity. The interdisciplinary nature of the research encompasses various domains, including environmental science, engineering, and social sciences, reflecting the comprehensive scope of challenges faced in managing e-waste sustainably.

This study identified five central research clusters—material management and resource recovery, business practices and circular economy strategies, technology integration and sustainability, recycling challenges, and environmental health and

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sustainable practices. Emerging topics like lithium-ion batteries and closed-loop supply chains highlight critical challenges in e-waste management and the urgent need for sustainable practices.

Despite these advancements, significant research gaps remain, particularly regarding the recycling of specific e-waste components, such as lithium-ion batteries, and the integration of circular economy principles into emerging technologies. There is also a pressing need to explore the social dimensions of the circular economy and e-waste management, including consumer behaviour and community engagement. Future research should aim to develop more effective policy frameworks that incentivise circular business models and address global e-waste flows through comprehensive and coordinated international policies.

Our findings lay a solid foundation for policymakers and stakeholders to leverage the circular economy framework in addressing e-waste challenges. Embracing circular economy principles in emerging economies, alongside integrating informal sector practices for e-waste collection and sorting, presents a valuable opportunity for sustainable management. Fostering collaboration between formal and informal sectors can further facilitate advanced recycling processes, contributing to both environmental health and economic resilience. This study emphasises the urgency of integrating circular economy practices to mitigate the environmental and health impacts of e-waste in the digital age.

7. Conflict of interest

We declare not to have any potential conflict of interest in the process from manuscript to publishing of this article.

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