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AIMS AND SCOPE

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Economic evaluation framework for Industrial Symbiosis through network lenses: a systematic literature review

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Abstract
Current economic and productive systems, characterized by huge resource consumption, cause significant environmental and social impacts, underlining their intrinsic unsustainability. This research explored circular economy models, in particular Industrial Symbiosis (IS) process, involving materials, energy, water and by-products exchange among different entities. Although the economic aspect is often considered of paramount importance, IS costs and benefits proved to be scarcely identified and properly quantified in the existing literature, since methodologies lack an organized structure to link economic outcomes to specific activities that generate value, which, in turn, remains assumed at a merely descriptive level if there's no quantification approach alternative to market value estimation. Therefore, through a systematic literature review literature (2019-2023), 61 articles were analyzed, with the objective of filling the knowledge gap by means of systematization of recent scientific evidence on IS economic aspect, pinpointing areas of potential economic advantage or disadvantage, for the final construction of an innovative and detailed IS economic evaluation framework, including revenues and costs items, calculation methodologies and specific performance KPIs. This research contributes to the broad comprehension of economic benefits, bolstering sustainable practices and network business model adoption.

Keywords: industrial symbiosis, economic evaluation, networking, industrial ecology, circular economy

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1. Introduction

The current economic and productive systems, based on a large and growing resource consumption, entail significant footprints, in terms of environmental and social impacts, proving their intrinsic unsustainability; therefore, the need to find innovative sustainable business models (Bocken et al., 2014), that can minimize negative effects and positively influence the way value is generated and distributed. Among them, the circular economy business model, aiming at creating value from waste management, transformation and recovery (Sadraei et al., 2023) represents a source of competitive advantage, combining the generation of profit from differentiated products with a conscious perspective on environmental impacts (Costanza, 2020). This business model often translates into Industrial Symbiosis (IS) processes, engaging “traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products” (Chertow, 2000), and distinguishing itself from other types of mutual interaction because, according to some authors, it associates at least three distinct entities in the exchange of two, or more, different resources (Albino et al., 2016; Chertow, 2007). Case-study analysis (Neves et al., 2020) underlines the development and wide adoption of symbiosis practices, involving a variety of industries (Lombardi & Laybourn, 2012), mainly from the manufacturing sector. Scientific literature emphasizes, as peculiar features and keys of success, cooperation and synergistic possibilities provided by geographical proximity (Boons et al., 2017; Chertow, 2000, 2007): for those reasons, the symbiotic process generally takes place inside the so-called eco-industrial parks, defined as communities of businesses that cooperate to gain economic, environmental and social advantages from the efficient share of resources (Chertow, 2000). In fact, IS models fully took shape within the eco-industrial park of Kalundborg, Denmark, although many scholars do not consider spatial proximity as a necessary or sufficient pre-condition (Neves et al., 2020; Zhang et al., 2015), exploring other possibilities for non-localized exchanges, as knowledge networks, intended to eco-innovation and efficient resource use (Lombardi & Laybourn, 2012). Indeed, by investigating temporal evolution (Mallawaarachchi et al., 2020), it can be noticed that IS definition has been enlarged, to embrace intangible exchanges, besides sharing of services and infrastructure. Moreover, three specific dimensions have been progressively integrated and deepened: willingness for network cooperation, structural and sociocultural context, and externalities linked to exchanges’ sustainability and consequential economic and environmental gains. Scientific research regarding IS framed it into the field of Industrial Ecology (IE) (Baldassarre et al., 2019; Lybæk et al., 2021), that discipline considering industrial systems similar to ecosystems, with the aim of reducing environmental impacts and closing energy and resource loops. Recently, the analysis has been broadened to the domain of Circular Economy (CE), an umbrella concept that promotes the transition towards circular models for recycling, reusing, and waste valorization, combining environmental and economic goals (MacArthur, 2013). Businesses are at the forefront of transition, and peculiar partnerships that develop within an IS are a driving force for enterprises’ shift towards production systems oriented to circularity (Costanza, 2020). The CE-focused definition certainly receives more validation at the political level, in particular from European policy landscape, which acknowledges IS as a strategic key for circularity of industrial and economic systems, within the scope of policies and programs such as the Circular Economy Action Plan (Lybæk et al., 2021; Neves et al., 2020; Wadström et al., 2021). Even if both disciplines are built on close-loops theories, CE addresses IS both as a critical dimension to evaluate circularity (Piontek et al., 2021). and as a business model in which its principles take

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shape (Ranjbari et al., 2021), clarifying the economic rationale and operative functioning, and integrating IE perspective, which provides a good understanding of IS as a sociotechnical process and its development over time (Baldassarre et al., 2019).
Focus on economic aspects can be found since the starting point of IS processes: scientific literature identifies costs reductions (Colpo et al., 2022b; Lybæk et al., 2021) and search for private advantages (Chertow, 2000, 2007) as the main *raison d'être* for symbiotic exchanges, while the acknowledgment of environmental benefits as a positive consequence of resource flows happens at a later time (Boons et al., 2017; Wadström et al., 2021). In fact, even if circularity offers a concrete manner to reduce emissions and environmental impacts linked to the use of materials along the whole value chain, it should also represent a more attractive production system for companies from an economic point of view (Piontek et al., 2021). The strategic opportunity for financial gains, often resulting from scarce raw material availability (Chertow, 2007; Faria et al., 2021), makes a spontaneous triggering of IS (Boons et al., 2017; Neves et al., 2020): researchers highlight the need to "*uncover*" (Chertow, 2007) symbiosis dynamics and their social structures, in order to incentivize exchanges and spread knowledge with the support of specific policies (Boons et al., 2017; Chertow, 2007; Lybæk et al., 2021), aiming at overcoming major operative, technological, economic-financial, knowledge and sociocultural barriers (Colpo et al., 2022b; Kosmol & Otto, 2020; Re et al., 2023; Taqi et al., 2022), and their associated risks (Henriques et al., 2020). However, even if the economic aspect is one of the most investigated, because of its primary relevance, scholars pinpoint the need to identify and properly measure economic implications, enlarging the scope of research by including quantified IS economic costs and benefits, more than merely descriptive outcomes. (Wadström et al., 2021). In fact, current analytical schemes are able to estimate economic advantages and disadvantages only through means of existing associated market value, pointing out the lack of specific frameworks for the identification and integration of all kinds of value, essential for a comprehensive evaluation of IS feasibility, beyond the market one, outlining furthermore a structured model to link outcomes to specific activities generating value. Consequently, this study was motivated to fill this knowledge gap by a systematic review of recent literature (2019-2023) in the field of IS economic analysis, from business' point of view, in order to ascertain research trends through a bibliometric analysis, in addition to outlining most cited areas of potential advantage/disadvantages. Consequently, the research conducted was oriented to answer the following questions:

RQ1: What is the research trend in the field of IS economic analysis?

RQ2: What are the most relevant areas of potential economic costs/benefits?

From the examination of 61 scientific articles, assessed on the basis of a dedicated review protocol, papers' metadata and content data were extracted about industrial sectors involved, economic evaluation and the methodology implemented. Final objective consisted in the construction of a detailed framework, innovative and different from all others because of clear specification of all cost and revenue items and their quantification methodologies, useful to consider in an IS project economic feasibility study because of their recurrence in scientific literature. In a context of growing interest in IS as a powerful tool to achieve triple sustainability goals (Neves et al., 2020), this research contributes to the systematization of recent evidence in the field of analysis, which constitutes the theoretical basis of the framework, which proves practically useful for weighing benefits

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and disadvantages that may affect firms in overall evaluation of IS projects. Further relevance of this study is confirmed by its helpfulness in overcoming economic barriers and incentivizing the adoption of IS practices and network business models.
The structure of this paper is as follows: Section 2 delineates methodological steps in conducting systematic literature review, Section 3 presents the main bibliometric results and findings useful to construct economic framework of analysis, developed in Section 4, also devoted to general discussion. Section 5 draws conclusions, limitations of the study and recommendations for future research development.

2. Methodology of Research

Systematic literature review could be defined as "a systematic, explicit, [comprehensive,] and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners" (Fink, 2019). This means that the analysis, to be called scientific, must be "systematic in following a methodological approach, explicit in explaining the procedures by which it was conducted, comprehensive in its scope of including all relevant material, and, hence, reproducible by others who would follow the same approach in reviewing the topic" (Okoli, 2015)

This approach was deemed the most appropriate to provide an in-depth summary of existent evidence on the state of the art for Industrial Symbiosis, particularly focused on benefits and disadvantages involved in economic feasibility assessment. To pursue this aim, the presented analysis adapted systematic literature review (SLR) methodology outlined by Okoli (2015), following a replicable, scientific and transparent approach based on an eight-step guide:

1. Identify the purpose: to be clear and explicit with the audience, the purpose of this study was to fill a knowledge gap by providing a deep understanding of the most up-to-date state-of-the-art on economic feasibility of Industrial Symbiosis. Generally speaking, this analysis was conducted to systematize progress in field of inquiry, develop a framework based on latest scientific evidence and make recommendations for future research;

2. Draft protocol and train the team: a written protocol document, as a road map to conduct the review, provided details and training for both reviewers, in order to guarantee consistency and uniformity of analysis;

3. Apply practical screen: in order to critically select sources for scientific evidence, screening for inclusion involved three filter criteria:

- *Publication language*: English, the one both reviewers could read;
- *Range of publication*: last five years (2019-2023), to focus on the most up-to-date progress in the field of inquiry and to uncover potential research avenues;
- *Document type*: article, to ensure peer-reviewed quality paper excluding reviews of literature.

No filter for Journal or Subject area was considered, in order to make the review as more comprehensive as possible, taking into account interdisciplinarity in analysis;

4. Search for literature: literature search was performed on Scopus and Web of Science platforms (Pranckutė, 2021).

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Frequently used by researchers across social sciences and disciplines, these databases were selected because they ensure a holistic and multidisciplinary vision of the research theme, including high-impact articles on aspects ranging from environmental engineering to sustainable development and circular economy, essential for an integrated analysis. Search string was built on concepts directly related to the research questions. In order to reach the largest number of relevant articles in the most scientific manner, a preliminary keyword pattern analysis was carried out using VOSviewer. A small representative sample of articles analyzing economical aspects of Industrial Symbiosis was used to extrapolate keywords most appropriate and cited by scholars in the field of research. Performing a brief first analysis of databases' results, researchers opted to maintain keywords combining the two criteria of breadth and specificity. On the one hand, selected keywords provided the highest number of results; on the other hand, coherence with the research theme was evaluated in order to guarantee as focused analysis as possible, excluding circular practices beyond the definition of Industrial Symbiosis (Chertow, 2000a). Moreover, the use of Boolean operators among selected terms let the researchers take advantage of database search power. This strategy led to a search string where the term "Industrial Symbiosis" was combined with synonyms identifying economic implications. In particular, the search string ("industrial symbiosis" AND ("effect" OR "economic* aspect*" OR "benefit" OR "economic* analysis" OR "cost")) was performed on databases, searching within "Article title, Abstract and Keywords". Asterisks were used because they represent any number of characters. The procedure was deemed effective to answer the research questions because it let researchers be as specific as possible, excluding circular practices beyond the boundaries of Industrial Symbiosis, aligning with the objective of constructing an economic evaluation framework as detailed as possible on specific peculiarities of symbiotic exchanges. Records identified through searching on Web of Science and Scopus were filtered according to criteria for practical screening; then, the removal of duplicates (n= 127) and not accessible (n= 8) articles led to a preliminary total of n= 323 papers for eligibility;

5. Extract data: this step involved the gathering of information that serves as raw material for answering research questions, analyzing and discussing results. In particular, the following data were extracted:

- *Keywords, Journal and year of publication*: to perform bibliometric analysis and assess evolution patterns in scientific literature;
- *Economical cost/benefit*: to give a direct answer to research question, upon which building economic assessment framework for Industrial Symbiosis;
- *Industries involved in symbiotic exchanges*: to understand what economic sectors could be interested as potential users of the framework;
- *Methodology for quantifying costs/benefits*: to comprehend what applicable calculation methodologies are for the practical implementation of the framework.

6. Appraise quality: screening in full-text for exclusion led to articles scored on the basis of qualitative quality appraisal that did not involve methodology evaluation but appropriateness in answering the research question. To ensure articles met this criterion, a preliminary review was implemented on a total of n= 323 papers, accurately reading titles and abstracts; from this step, n= 184 articles were excluded. Then, a refined assessment based on full-text was manually performed. This last step led

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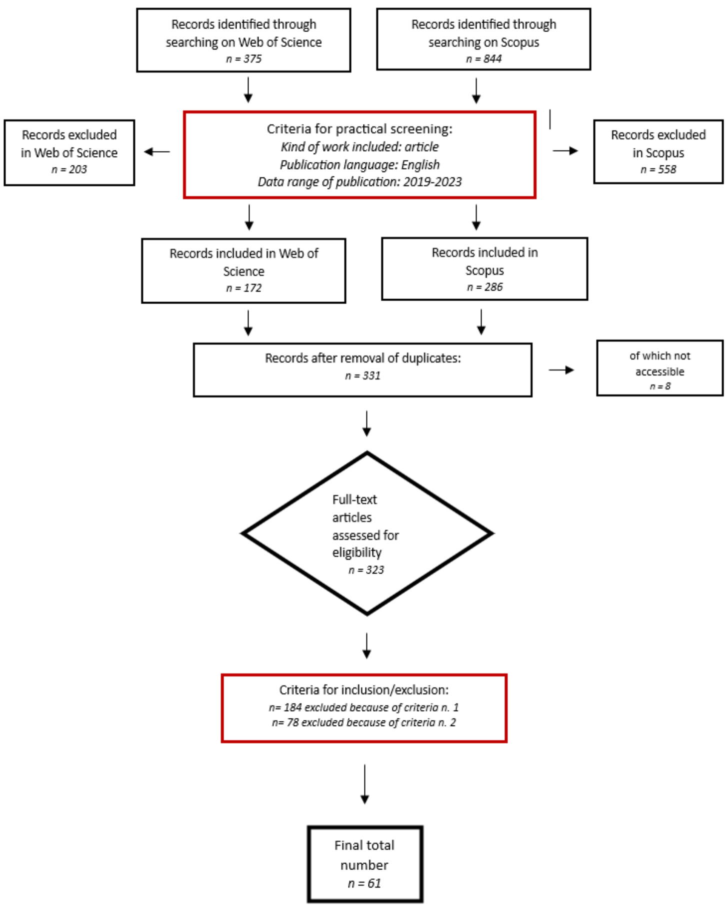
to a final total number of n= 61 articles included in systematic literature review. In each evaluation step, researchers have always confronted each other on doubts of interpretation;

7. **Synthesize studies**: charts and tables, presented in *Result* section, were drafted to map at best the extracted data and to structure the systematic literature review;

Figure 1[1]. Systematic literature review – methodological process



Source: Authors own elaboration from Okoli, C. (2015). A guide to Conducting a Standalone Systematic Literature Review.

[1] Criteria of selection are specified as follows:

- *Criteria n. 1: first preliminary title and abstract evaluation about relevance and usefulness in answering research questions;*
- *Criteria n. 2: integral paper analysis to evaluate relevance and usefulness in answering research questions.*

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8. Write the review: final step involving paper writing; in particular, a framework for economic assessment of Industrial Symbiosis was built upon analyzed literature and presented in *Discussion* section. This represented the practical implication of the study carried out, proving its usefulness especially for companies that want to test economic sustainability of industrial symbiosis projects.

Figure 1 illustrates the above-mentioned process of search, selection and screening, with the detailed number of articles involved in each phase.

3. Results

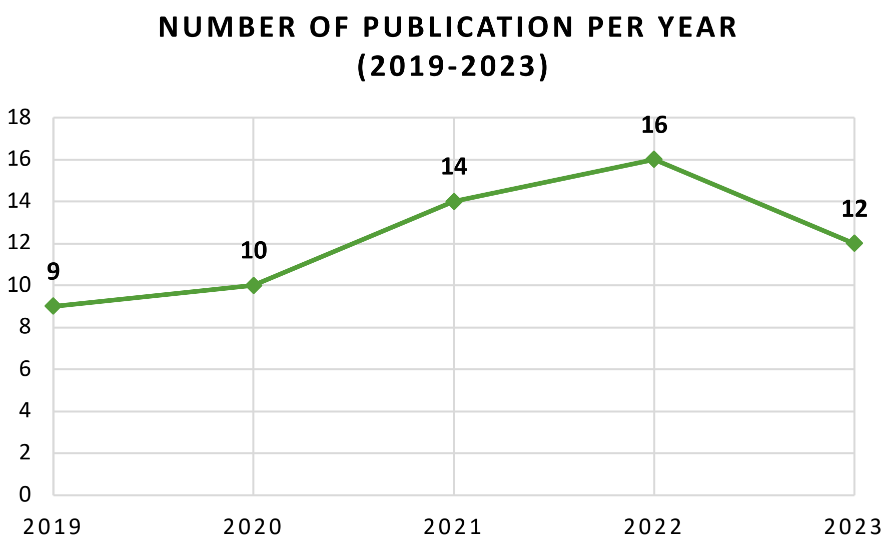
3.1 Review of Research Trends

This section is devoted to description and discussion of results emerging from bibliometric analysis of selected articles, especially useful to give an answer to the first research question, identifying evolution trends and evaluating research progress in the field of Industrial Symbiosis economic analysis. In particular, after the application of selection criteria exposed in Methodological section, the main articles' data were extracted, concerning journal and year of publication, in order to draw conclusions about the trend of research. Finally, a keywords co-occurrence analysis was conducted to deeply understand semantic relations and emerging issues, to better direct future investigations.

The following analysis comprises 61 articles included in the systematic literature review, related to economic analysis of Industrial Symbiosis and published from 2019 up to 2023. The records analyzed were written by 243 different authors, for a total of 1.069 citations.

Figure 2 illustrates publication evolution over time, starting from 2019 up to 2023.

Figure 2. Publication evolution over time, 2019-2023



Source: Authors own elaboration

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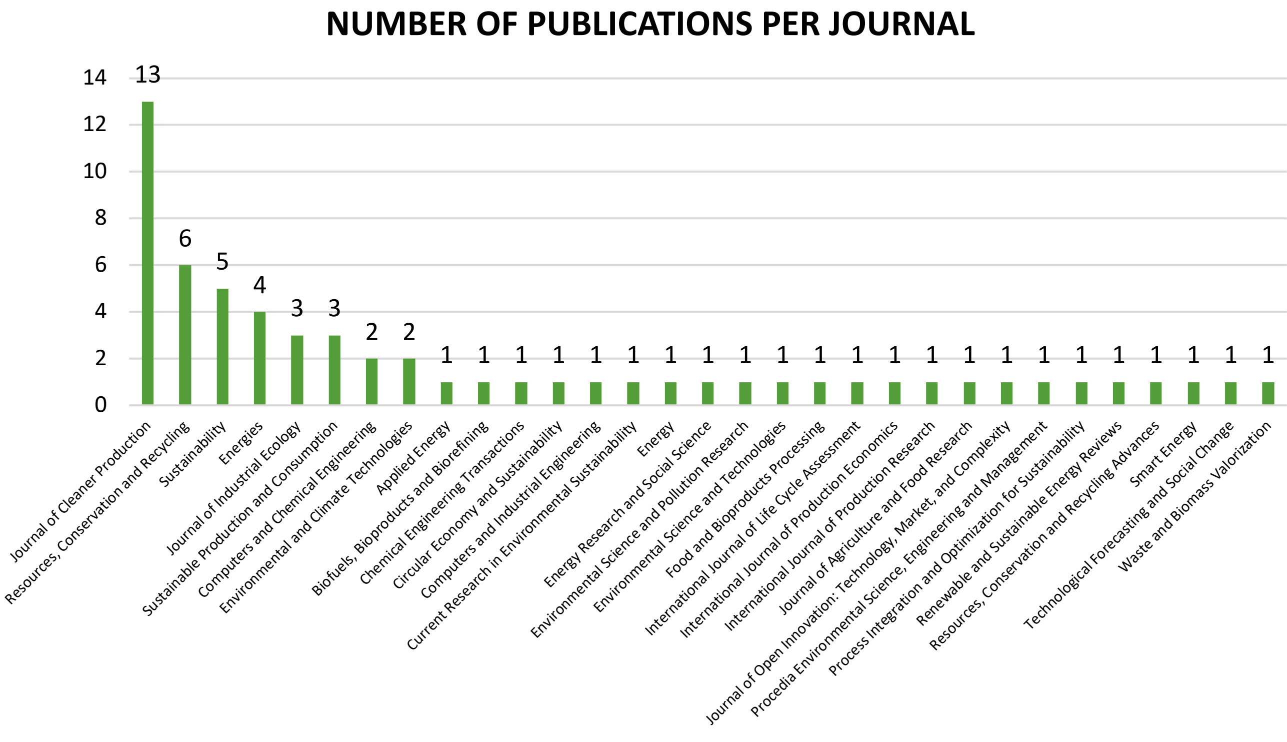
As can be seen, 2022 was the year with the highest number of articles published (16), while 2019 records the minimum of publications (9). Generally speaking, it can be noticed that the number of articles has grown steadily, reflecting an increasing interest of the scientific community that may be related to the ever-rising attention to sustainability issues and transition towards more circular production models, backed by Industrial Symbiosis within the scope of Circular Economy (Yazan & Fraccascia, 2020), for which it is relevant to assess economic feasibility, besides environmental and social implications. The growing centrality of economic issues regarding Industrial Symbiosis provides a rationale for the comprehensive recent literature systematization, conducted in this study.

Figure 3 illustrates the number of publications by journal. The 61 selected articles were collected from 31 different journals, but most appear in a few key journals.

Figure 3. Number of publications by journal



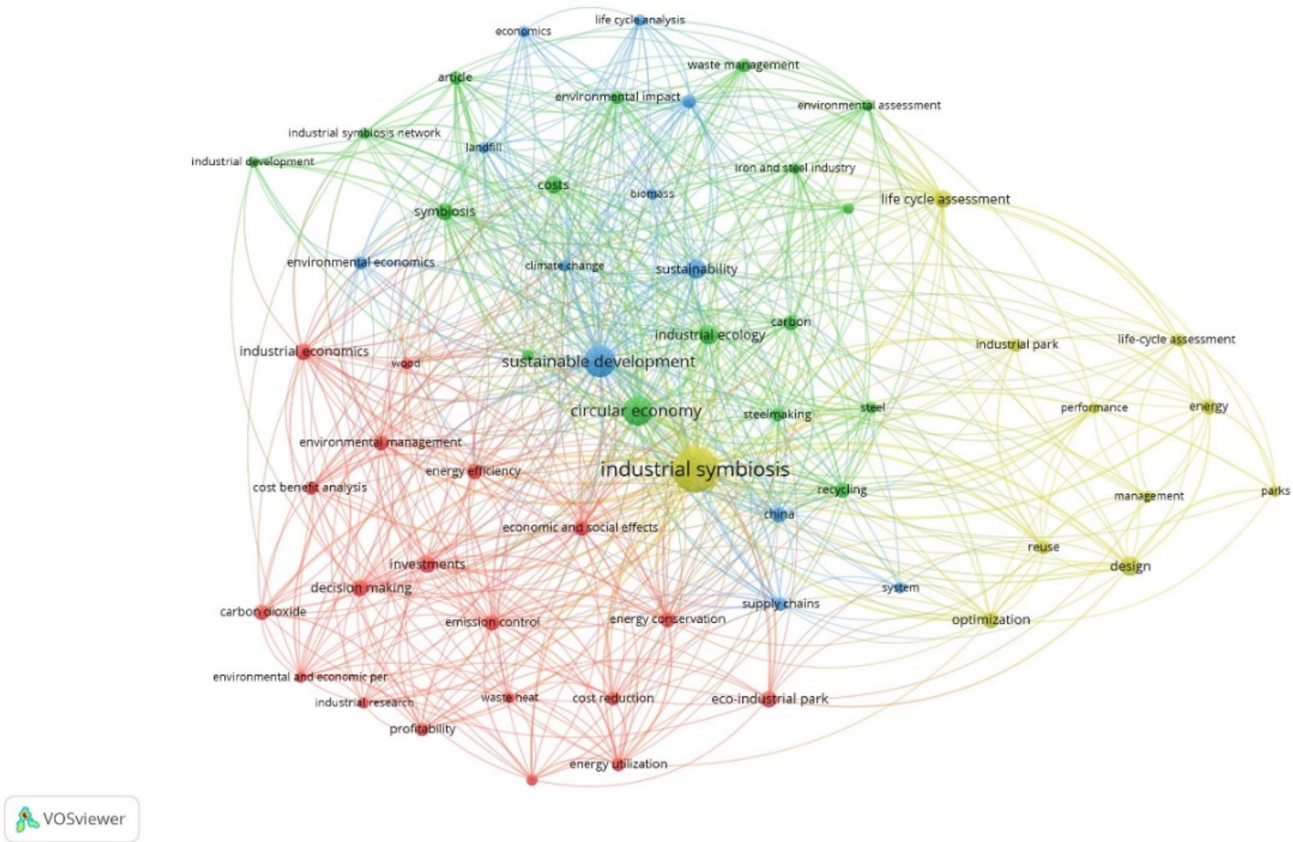
Source: Authors own elaboration

As can be seen, the distribution is not uniform: in particular, *Journal of Cleaner Production* is the most influential research journal, with 13 articles on the investigated topic, while the top 5 gather a considerable percentage of publications (nearly 51%), proving they are of special importance in Industrial Symbiosis research related to economic aspects. In conclusion, the presence of influential journals in the field of waste management, energy engineering, innovation and technology proves the interdisciplinary point of view adopted by scholars in examining Industrial Symbiosis.

VOSviewer software was then used to perform a keywords co-occurrence analysis, with the aim of enlightening hotspots and revealing most popular themes in the topic of interest. Keywords' cluster evaluation could help in the reconnaissance of semantics used for the topic, in order to understand past trends and advances in the field, and to give direction to future research. Correlations among clusters can reveal border-crossing themes and future possible links to different disciplines and research fields.

The network visualization provided by VOSviewer was created applying the "full counting" method and keeping the keywords which appeared, at least, 3 times (for a total of 59 keywords).

Figure 4. Keywords co-occurrence analysis - network visualization from VOSviewer



Source: Authors own elaboration from VosViewer

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The three most relevant keywords, linked with *Industrial Symbiosis* (number of occurrences: 45), are *Sustainable Development (*number of occurrences: 21), *Circular Economy* (number of occurrences: 19), *Industrial Ecology* (number of occurrences: 8), resulting in 2 clusters.

Figure 4 displays the keywords network split into 4 clusters. The first and largest cluster, the red one, is related to *Industrial Symbiosis outcome assessment* and it includes words like "economic and social effect", "environmental management", "cost-benefit analysis". The existence of this cluster may be motivated by the fact that evaluating the whole impact is relevant to understanding the reasons behind the spontaneous triggering of Industrial Symbiosis and also to incentivizing its implementation. The second, the green one, encompasses *Circular Economy* themes, and it is composed of words like "costs", "recycling", "waste management". The presence of keywords linked to *Industrial Ecology* justifies a particular attention devoted to interconnections between these two research domains[2], in which Industrial Symbiosis can be placed. The third, the blue cluster, is focused on *Sustainable Development* and it involves terms like "climate change", "sustainability", "supply chains"; understanding the contribution of Industrial Symbiosis to sustainable development may be the concern that led scholars focus on this topic. Lastly, the yellow cluster, though the smaller, contains words related to *Industrial Symbiosis*, which is the central research theme of this paper: "industrial park", "reuse", "design". The often concretization of Industrial Symbiosis into eco-industrial parks can validate the presence of this specifically focused topic. It is relevant to underline the connection with domains of Circular Economy, Industrial Ecology, and methodologies of impact assessment, such as "life-cycle assessment," "cost-benefit analysis," and "environmental assessment." Still, little space is devoted to consideration of social impacts, unveiling possibilities for future deepening of the subject.

3.2 Synthesis of main results

This section is devoted to description and discussion of results coming from main articles' contents and information that were deemed useful for answering research questions and building economic evaluation framework. In particular, data were extracted about research methodologies, to comprehend what calculation methods are predominant in literature for estimation of costs and benefits, industries involved in symbiotic exchanges, to understand what economic sectors could be interested, and areas of economic costs and benefits, to give direct answer to research question.

First of all, papers examined were classified into three different categories: "*Evaluation of real case studies*", focused on comparison between pre-IS – post IS scenarios, for those analysis of already implemented IS practices; "*Evaluation of symbiosis project*", oriented to the appraisal of feasibility of designed IS and/or shared facilities in a network of enterprises; "*Application on a real case-study*", for evaluation of designed IS practices applied in a real industrial context. The majority of studies involved the second category (nearly 50% of examined papers); 27% were applications on real case studies, while the remaining were evaluations of pre-IS – post-IS scenarios. This implies that there could be some difficulties in finding studies assessing implemented IS economic contribution, the generality being analysis of costs and benefits specifically attributed to a project.

[2] Differences and commonalities between Circular Economy and Industrial Ecology were extensively explained in the *Introduction* section.

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3.2.1 Methodologies

The first content data analyzed involved quantification methodologies used for IS project evaluation carried out in the selected studies for SLR. Understanding the estimation process allowed to create a basis upon which to build an integrated and comprehensive methodology within the framework of economic analysis. For this reason, Table I illustrates principal methodologies followed by examined literature in conducting the research and quantifying IS economic costs and benefits, with a brief description and the list of references which made use of each of them.

Table I. Research methodologies analysis

METHODOLOGY	DESCRIPTION	REFERENCES
Cash flows analysis	Estimation of monetary flows of revenues and costs incurred in a period of time, on the basis of financial market prices. Values could be discounted, if they involve future potential monetary flows.	Wijeyekoon et al., 2021
Cost-benefit analysis	Estimation of revenues obtained and costs incurred in a period of time, on the basis of financial market prices. It could consider external costs, primarily environmental and social, translated into monetary terms. Values could be discounted, if they involve future potential monetary flows.	Cervo et al., 2019 Pakere et al., 2021 Sun et al., 2020 Zabaniotou & Vaskalis, 2023
Cost savings and cost analysis	Estimation of items of cost associated with a project through monetary terms; if a project involves cost reduction, then it could be an estimation of cost savings, as the difference between pre and post financial costs. Values could be discounted, if they involve future potential monetary flows.	Ali et al., 2019 Hu et al., 2020 Li et al., 2021
Profit and Net Present Value (NPV) analysis	Calculation of profit margin as the difference between revenues obtained and costs incurred in a specific period of time. Values could be discounted, if they involve future potential economic or financial flows, to calculate a Net Present Value.	Colpo et al., 2022a De Souza & Pacca, 2023 Dong et al., 2022 Hedlund et al., 2022 Kerdlap et al., 2022 Liao et al., 2024 Sheppard et al., 2019
Life-Cycle Costing	Financial evaluation of total costs of a project, from its inception through to its disposal; the conventional c-LCC involves only economic costs, while environmental e-LCC and social s-LCC also consider externalities	Ali et al., 2020 Ansanelli et al., 2023 Diaz et al., 2021 Haq et al., 2020

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		Ruiz & Diaz, 2022 Zhang et al., 2022b
Agent-based model	Simulation framework for interaction of individual entities according to defined rules. Cost saving function is often included to model agent behaviors	Fraccascia et al., 2020 Yazan & Fraccascia, 2020
Game Theory approach	Theoretical framework analyzing strategic interactions among decision-makers, in which payoffs for each participant depend on the choices of all involved. To estimate economic outcomes, profit margin or economic benefit calculations are often used.	Ahmad Fadzil et al., 2022 Chin et al., 2021 Galvan-Cara et al., 2022 He et al., 2020
Linear and non-linear programming optimization model	Mathematical technique used to optimize a function subject to a set of linear or non-linear constraints. In the case of mixed-integer or multi-integer programming models, some variables could assume integer values. Financial cost analysis often provides the economic constraint, while the optimization goal could be a profit maximization	Al-Quradaghi et al., 2022 Asghari et al., 2023 Boix et al., 2023 Bütün et al., 2019 Chatterjee et al., 2021 Farouk & Chew, 2021 Goh et al., 2022 Misrol et al., 2022 Misrol et al., 2021 Yu et al., 2023
Singular or many-objective optimization model	Optimization framework that deals with a large number of objectives, often conflicting. Economic equations involving cash flows or cost savings analysis are used as constraints or optimization objectives.	Cao et al., 2020 Fahmy et al., 2021 Lyu et al., 2023 Teh et al., 2021 Yeşilkaya et al., 2020

Source: Authors own elaboration

For clarity of analysis, research methodologies could be clustered into four macro-categories:

- *Financial evaluation models*, adopted by the great majority of studies, aim to evaluate financial and economic flows, and they are built upon quantification through market values of revenues obtained and costs incurred and/or avoided in a specific period of time. This category includes cash flows and cost-benefit analysis, though this last could also incorporate external costs, as environmental and social ones, translated into monetary terms; cost savings and costs analysis, particularly recommendable to understand reductions and cost profiles of a project; profit analysis and net present value calculation.

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The temporal dimension could be taken into account by discounting financial flows and building performance indexes, as Internal Rate of Return (IRR) (Colpo et al., 2022a; Sheppard et al., 2019), Profit Index (PI) (Fahmy et al., 2021; Ruiz & Diaz, 2022) or Payback Period (PP) (Falsafi et al., 2023; Sun et al., 2020), to give a synthetic overview of economic profitability;

- *Life-cycle evaluation models*: advanced technique for quantification of total economic costs incurred all along the life cycle of a project, from its inception to its disposal. As a conventional method (c-LCC), it can be used to compare cost profiles of different projects; as a full Life-cycle Impact Assessment (LCIA), comprehensive of environmental (e-LCC) and social (s-LCC) analysis, it goes beyond economic consideration, including external costs, especially linked to eco-efficiency and environmental and social impacts (Zhang et al., 2022b), quantified by way of emission factors and technical coefficients (Ali et al., 2020; Ruiz & Diaz, 2022);
- *Decision models*: methodologies for agent behaviors simulation inside a broader network, for this reason often used in IS analysis and distribution of aggregated costs and benefits. In a game-theory model, outputs depend on cooperative approach and behavior of each participant, while agent-based models simulate actors' conduct according to different sets of rules. To model behaviors on economic reasoning, an economic-objective function, very often a cost (Chin et al., 2021; Fraccascia et al., 2020) or a net benefit (Ahmad Fadzil et al., 2022; Galvan-Cara et al., 2022) function, is included;
- *Optimization models*: frameworks for optimization of IS practices, often used in application research to existent or designed IS projects. Optimization aims at constrained maximization (or minimization) of different objectives, as frequently conflicting functions for environmental and economic goals (Cao et al., 2020; Yeşilkaya et al., 2020), expressed through cash flows analysis or financial costs (Asghari et al., 2023; Fahmy et al., 2021) and cost savings (Lyu et al., 2023) analysis.

As the final objective consisted of orientating economic evaluation framework to the most appropriate quantification methodology, this analysis led to the conclusion that a more financial focus, translating costs and benefits into monetary terms, integrated with models quantifying and optimizing external impacts all along the life cycle, beyond the mere financial sphere, is useful in obtaining a comprehensive evaluation of an IS project in its temporal range.

3.2.2 Economic sectors involved

From the analysis of economic sectors engaged in IS and circular processes, it could be stated that not all cases precisely defined type and destination of resources exchanged, and specific role (as a receiver or as a donor) of firms in symbiotic relationship. These elements turned out to be relevant, within a framework of analysis, to understand entity and subdivision of costs and benefits among resources exchange activities and agents in the network. For those articles clearly identifying exchange components, it could be observed that the principal destination (nearly 55% of cases) of resources shared, mainly biomasses, wastewater and waste heat and steam, involved production of any kind of energy (electricity, steam and heat for power production), that could be directed to an internal use or sold externally, either way contributing to economic benefit, lowering energy costs (Diaz et al., 2021; Sheppard et al., 2019; Wang et al., 2019) or as new source of revenues (Haq et al.,

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2020; Sun et al., 2020; Tan Yue Dian et al., 2021). Several studies (24%) focused on production of building materials, predominantly from slag residues, fly ashes, agro-industrial wastes and other scrap materials in the same industry.

Considering the whole number of articles examined, 34% of them explicitly outlined direct exchanges between two entities characterized as donor and receiver. Framing economic sectors through the use of ISIC[3] classification and the consideration of type and destination of wastes, analysis of direct exchanges showed that, again, the industries participating mainly as receivers were energy production and manufacturing of non-metallic products for building (43% for both), while major donors were industrial and agro-industrial sectors, especially for biowastes sharing, including domestic sector (Saeli et al., 2023). Flows of materials could engage the same industry (18% of examined articles): as example, chemical (Farouk & Chew, 2021; Lyu et al., 2023) and agrifood industry (Prieto-Sandoval et al., 2022; Raimondo et al., 2023; Yu et al., 2023), where biomasses could be turned into biological fertilizers.

A great percentage of studies (40%) focused on mutual exchanges inside industrial parks and ecological networks without an explicit definition of resource flows. Prominent examples are the agriculture and forestry sectors (Hu et al., 2020; Yeşilkaya et al., 2020), steel, iron, and cement industries (Xue et al., 2023; Zhang et al., 2022a). Inside a network, exchanges are not purely material: it is worth noting a particular study on sharing carbon permits, which led to increasing profits and overall network efficiency (Ahmad Fadzil et al., 2022).

Ultimately, economic sector analysis proved to be essential to understand main ways of interaction for symbiotic exchanges across different industrial contexts, each one with its own specificities, in order to improve flexibility of the framework for economic IS costs and benefits, highlighted by scientific literature and pointed out in the following section.

3.2.3 Cost-benefit analysis

Scientific evidence of IS economic costs and benefits was summarized in Figure 5, displaying a circular chart divided into four main sections:

- Cost reduction, as a source of economic advantage, identified by 45 examined articles (out of 61);
- New revenues, as a source of economic advantage, identified by 31 examined articles (out of 61);
- New costs, as a source of economic disadvantage, identified by 19 examined articles (out of 61);
- Revenues reduction, as a source of economic disadvantage, identified by 1 examined articles (out of 61).

It follows that, given the extracted data, cost reduction represents the most recognized IS economic implication, both by optimization application models and research on feasibility assessment.

Then, each main section of the chart is divided into all costs and revenues items highlighted by scientific literature; the size of each of them reflects the percentage number of mentions received relative to the total mentions in the domain of the corresponding main section.

[3] ISIC stands for International Standard Industrial Classification of All Economic Activities, a globally standardized system for classifying industries by a four-level hierarchy and for reporting of economic activities across countries.

Figure 5. Cost-benefit analysis – circular chart

Source: Authors own elaboration

The most observed benefit was cost reduction (blue section of the circular graph), particularly for raw materials (34% of cost reduction mentions), waste management and disposal (32%), substantially avoided, and operating and utility costs, as costs for water and energy (Cortez et al., 2022; Diaz et al., 2021; Hedlund et al., 2022; Ruiz-Puente & Jato-Espino, 2020). This advantage was revealed both by comparative studies between IS – non-IS scenarios (Cervo et al., 2019; Raciti et al., 2019; Zhang et al., 2022b), and by optimization analysis of designed and/or already implemented IS (Al-Quradaghi et al., 2022; Chatterjee et al., 2021; Lyu et al., 2023), confirming evidence in literature about the main *raison d'être* of IS (Chertow, 2000, 2007; Colpo et al., 2022a; Lybæk et al., 2021). A small, though significant, presence of reduction in capital costs must be pointed out, confirmed by studies reporting a decrease in equipment costs as one of the economic benefits, though limited, cited by companies (Wahrlich & Simioni, 2019). This reduction in costs referred to all those cases for shared infrastructure: when it comes to highly centralized and coordinated partnerships, as within eco-industrial parks, enterprises could benefit from the provision of common services and maintenance (Fraccascia et al., 2019; Wahrlich & Simioni, 2019), while installing advanced production systems, otherwise economically not viable, on already existent plants (Goh et al., 2022; Wijeyekoon et al., 2021). Then, analysis of new revenues followed (orange section of the circular graph), first of all from sales of products (62% of new revenues mentions), mainly generation of electricity and other kinds of energy (Hedlund et al., 2022; Misrol et al., 2021; Ruiz & Diaz, 2022; Sun et al., 2020). Economic advantages from sale of waste were less reported (24%): many evaluations were based on free exchanges, which can represent an avoided cost, for receivers (Raciti et al., 2019); other studies, instead, underlined the reduced value of wastes, which sometimes is overshadowed by transportation (Borbon-Galvez et al., 2021;

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Domenech et al., 2019) or treatment costs for recycling and reusing (He et al., 2020; Saeli et al., 2023). Few studies mentioned enhanced productivity (Chen et al., 2022; Dong et al., 2022; Raimondo et al., 2023; Wahrlich & Simioni, 2019) and reputational gains (Fraccascia et al., 2019).

Cost items (grey section of the circular graph) that could impact to a greater extent, according to examined literature, were, first and foremost, capital costs (37% of new costs mentions) for equipment and infrastructure (Chin et al., 2021; Sun et al., 2020), technologies (Bütün et al., 2019) and working capital (Colpo et al., 2022a), which reflect on manufacturing and other operating costs (repair and maintenance, 20%). If it is true that costs for required equipment and infrastructure are economically unviable for single entities (Colpo et al., 2022a), other studies also highlighted the need for institutional financial incentives to face capital costs for grand coalition, more capable of obtaining significant reduction of environmental impacts (Chin et al., 2021). On the other hand, scholars pinpointed that some technologies could entail lower costs, depending on the system they are implemented in and giving rise to the need for specific considerations about the industrial sector involved (Asghari et al., 2023), while the degree of nestedness could also results in total gains balancing capital costs (Chatterjee et al., 2021). In this regard, some studies (Fraccascia et al., 2019; Sellitto et al., 2021) emphasized the presence of transaction costs, that depend on interaction among enterprises involved.

Geographic localization is an IS aspect that should be investigated carefully: main studies reporting a reduction in transportation costs were focused on proximity exchanges of material resources (Goh et al., 2022; Raciti et al., 2019; Wijeyekoon et al., 2021), while others underline the need to broaden boundaries of symbiosis to reach variegate sources of waste, despite this could have an impact on resources' quality (Borbon-Galvez et al., 2021). Even if transportation costs depend on weight and chemical characteristics of wastes, whose marginal value is close to zero (Domenech et al., 2019), shipping carriers also play an important role (Ali et al., 2019), if treated as an endogenous variable whose optimization could eventually lead to economic benefits, looking for more sustainable transport strategies (Borbon-Galvez et al., 2021). However, the great majority of studies pointed out a rise in transportation costs (27%): besides representing a limiting factor for certain types of exchange, as heat flows (Lyu et al., 2023; Pakere et al., 2021; Sun et al., 2020), distance could affect, together with capital costs, decisions about symbiotic relationships economic convenience (Chatterjee et al., 2021), hindering opportunities for IS (Sellitto et al., 2021) or its full optimization (Lyu et al., 2023; Tan Yue Dian et al., 2021).

In conclusion, revenue reduction (yellow section of the circular graph) was observed in just one case (Cervo et al., 2019) as an economic loss for traditional suppliers and other stakeholders; nonetheless, this dimension should be deepened as an indirect consequence of symbiosis practices.

These findings confirmed the complexity of interactions, supporting the objective of building a flexible and integrated framework for IS economic evaluation, which takes into consideration, as mentioned above, the industrial sector and its peculiarities. These elements proved to have an impact on the overall cost-benefit profile of IS; in fact, according to different contexts, certain items could be recorded alternatively a cost or a benefit, as the circular graph in Figure 3.4 displays for capital, transportation, recycling, manufacturing and other operating costs, and certain revenues could not be realized, as for the case

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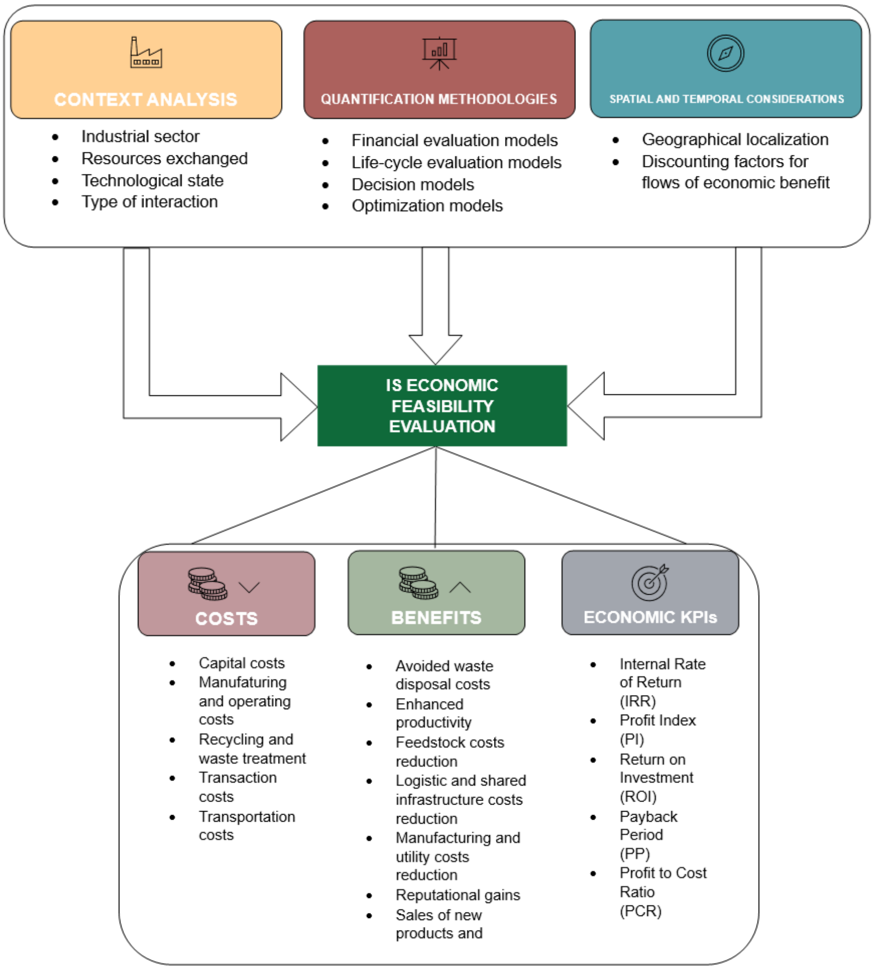
of free waste exchanges. In summary, cost-benefit evaluation must not be seen as static but rather as an evolving process influenced by externalities, exchange dynamics, and specificities of the industrial sector.

4. Discussion

Results examined in section 3.2 led to the construction of a framework for IS economic evaluation, depicted in figure 5, which implies context analysis (industrial sector and corresponding technological state, flows of resources possibly exchanged, type of interaction at the basis of symbiosis relationship), determination of proper quantification methodologies and consideration of spatial and temporal aspects, with the definition of a proper time horizon (Kerdlap et al., 2022). Economic evaluation is carried out regarding several cost and benefit items, pointed out by scientific literature, together with specific KPIs for a summative feasibility assessment and project overall vision.

Figure 5. IS economic evaluation framework



Source: Authors own elaboration

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Exchanges could involve different resources, material or immaterial: Ahmad Fadzil et al. (2002) proved how sharing carbon permits allowed for an efficient aggregate allocation, with cooperative solutions providing the greatest benefits (Galvan-Cara et al., 2022; Li et al., 2021). Optimal configurations imply an unequal realization of benefits and costs for each economic agent, so economic analysis should take into account the different roles, as receiver or donor, played by each IS participant.

Looking at calculation methodologies, financial approaches, better if implemented through the use of local accurate market values (Liao et al., 2024), should be complemented with life-cycle assessment, considering also external costs, such as environmental ones, that turned up to be paramount and worth of quantification, talking about IS cost reductions (Ansanelli et al., 2023; Haq et al., 2020; Pakere et al., 2021)

There are other kinds of aspects that need to be considered: among them, resource availability and supply security, relevant to IS location (Wijeyekoon et al., 2021), in particular when it comes to small flows of production (Cortez et al., 2022), and geographical proximity, which affects IS joining decision through transportation, infrastructure and investment costs (Ali et al., 2019; Cervo et al., 2019; Chatterjee et al., 2021; Galvan-Cara et al., 2022; Goh et al., 2022; Tan Yue Dian et al., 2021) and the possibility to exploit particular flows, as heat and steam (Pakere et al., 2021). Regarding logistic and transportation costs, some scholars argued that they could not impact positive IS overall benefit, while Borbon-Galvez et al. (2021) demonstrated that costs could even be lowered through sustainable means of transport and optimal shipping management.

Technological knowledge regarding waste treatment is also to be considered, as a barrier to IS joining (He et al., 2020): even if major benefits come from the leading ones (Farouk & Chew, 2021; Zhang et al., 2022b), some environmental-friendly techniques still seemed to be economically inaccessible, making the case for conflict between economic and environmental objectives (Cao et al., 2020; Chin et al., 2021; Yeşilkaya et al., 2020). Capital costs for advanced infrastructure and systems could both affect IS project profit in negative sense (Misrol et al., 2021), and be lowered by peculiar features of IS, such as proximity and sharing systems otherwise too expensive for a single participant (Bütün et al., 2019; Colpo et al., 2022a; Goh et al., 2022).

Scientific literature mentioned other IS characteristics preventing disruption risks but having an effect on economic outcomes: nestedness and flexibility, which could grow transaction and capital costs (Boix et al., 2023; Chatterjee et al., 2021; Fraccascia et al., 2020). Transaction costs resulted to be influenced also by trust and interaction approaches (Prieto-Sandoval et al., 2022; Yazan & Fraccascia, 2020).

This study also considered articles in the form of IS landscape analysis or industrial interviews (Cortez et al., 2022; Domenech et al., 2019; Prieto-Sandoval et al., 2022; Sellitto et al., 2021; Wahrlich & Simioni, 2019), enlightening barriers to IS implementation: proximity and procurement security, logistic costs, little knowledge and poor technological research investments, social reluctance, lack of adequate infrastructure and institutional support, also in the form of financial incentives, that proved to be essential, in certain cases, to face high capital costs (Chin et al., 2021; Haq et al., 2020).

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5. Conclusion

In a context of growing concern about industrial systems' unsustainability, it is paramount to assess the economic advantages of the transition towards circular models of production, as well as to incentivize more efficient solutions that could match sustainability objectives from an economic, environmental, and social point of view (Bocken et al., 2014). This study presented results of a systematic literature review for the last five years of research into IS economic feasibility. Bibliometric analysis allowed to notice an increasing interest in the topic, besides thematic connections' structure. Investigations brought out quantification methodologies, analysis of economic sectors involved and cost and benefit items, upon which an IS economic evaluation framework was built and commented in *Discussion* section. To sum up, some critical considerations about typologies of articles analyzed, in order to shape limitations and possible improvements. Main sources of costs and revenues, outlined in the framework, were deemed as the most considered in economic feasibility evaluation studies; by contrast, few studies were found on comparison between IS – non-IS scenarios (Ansanelli et al., 2023; Cervo et al., 2019; Galvan-Cara et al., 2022; Kerdlap et al., 2022; Li et al., 2021; Yu et al., 2023; Zhang et al., 2022b), most of all useful for a full comprehension of symbiosis contribute to economic benefit. Studies focused on optimization of productive models stressed out the presence of economic–environmental objectives trade-off (Cao et al., 2020; Chin et al., 2021; Fraccascia et al., 2020; Yeşilkaya et al., 2020), that could be mitigated by an integrated costs analysis, including environmental and social externalities, for a more comprehensive overview of IS economic impact. It is reiterated the need to adapt the framework to the specific industrial case and its peculiarities, from a technological, economical, sociocultural and normative point of view, though it could represent a good starting point for firms interested in economic consequences of IS cooperation.

5.1 Main contributions and practical implications

Given the lack of consideration and proper quantification of economic aspects of IS (Domenech et al., 2019; Dong et al., 2022; Wadström et al., 2021), this study contributed to filling the knowledge gap by systematizing recent literature on the topic of areas of IS economic outcomes and outlining integrated alternative methodologies for a preliminary approach to the quantification of IS impacts that result in costs and benefits beyond the mere market value sphere, providing a different perspective to evaluate financial flows of IS projects. Moreover, a dedicated support tool for IS economic viability was built, with the innovative ability to conciliate different features, from context analysis to calculation methodologies with spatial and temporal considerations, enhancing the implementation of IS activities by identification of cost and benefit items that could generate positive outcomes for companies involved. Though based on a solid and scientific protocol for literature analysis, this research constitutes a first and general step in the research field, limited by the lack of attention to environmental and social externalities' consequences and other kinds of implementation barriers that could generate an impact on IS joining decision.

5.2 Research limitations and future research agenda

Despite being accurately based on a well-structured search process, some methodological limits still exist. First, adopting Scopus and Web of Science databases for the last five years of research may restrict the potential number of articles in the

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sample. To prevent excluding relevant scientific contributions, other search databases should be used, as well as expanding the temporal range. Second, quality appraisal turns out to be inevitably afflicted by elements of subjectivity in judgment, which could be potentially lowered by more rigorous methods. Last, the use of selected keywords might restrict the scope of research conducted; a new analysis should be performed with another search string.

The economic evaluation framework is based on economic costs and benefits affecting firms directly and independently from the different roles played by participants. Future research agenda includes a wider focus on supra-enterprise network consequences, also quantifying environmental and social impacts in economic terms to find an IS cost-benefit distribution model encouraging an equal realization of benefits and costs for each economic agent and a continuous participation in an innovative business model for ecological industrial transition.

4. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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 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 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.

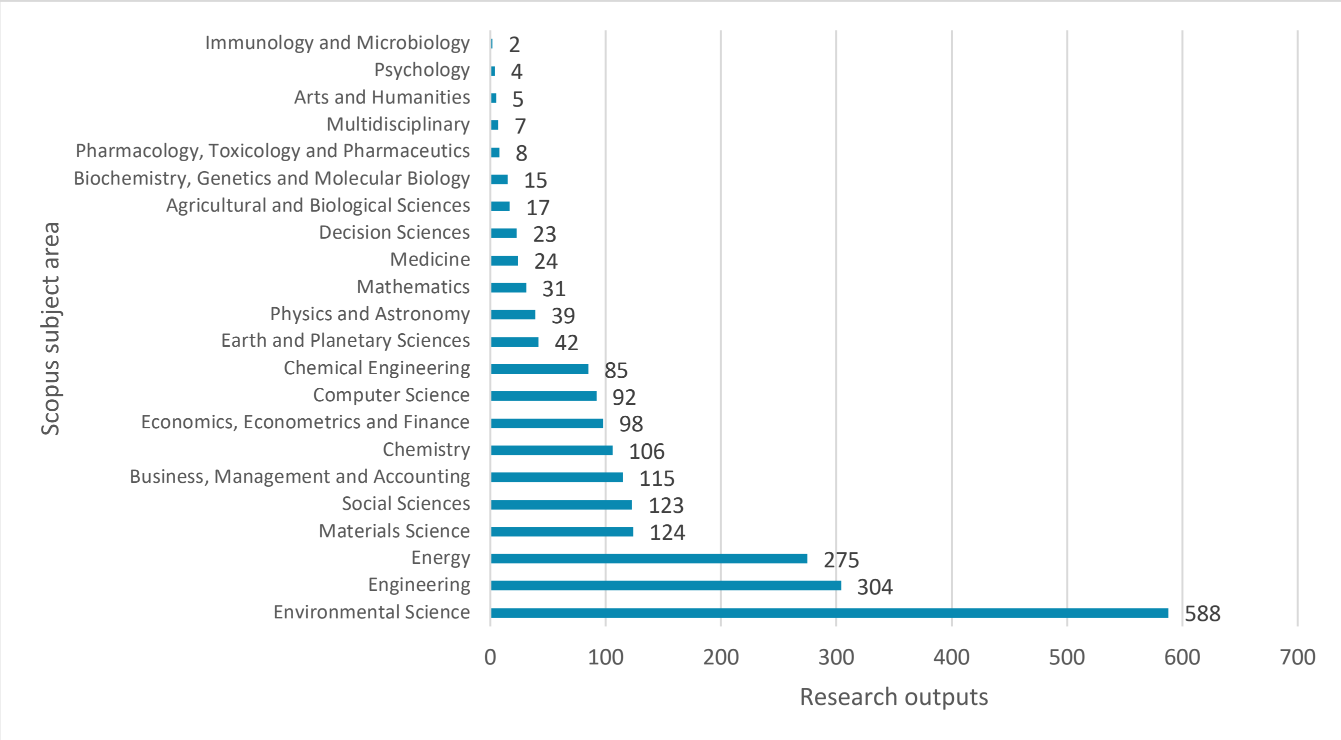
Table II. Top 10 Most Productive Countries

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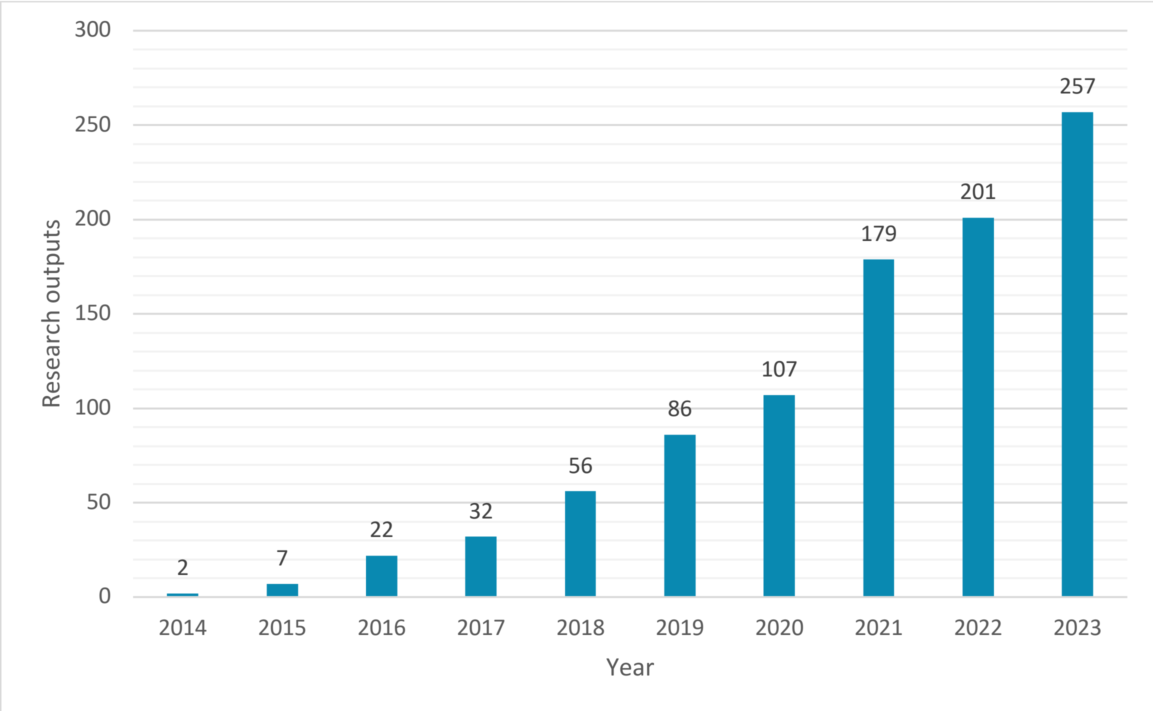
increased to 3 391, and the trend continued with citations reaching 5.628 and 8.409, in 2022 and 2023 respectively, indicating growing interest, increased impact and visibility of research on the circular economy and e-waste over the last ten years.

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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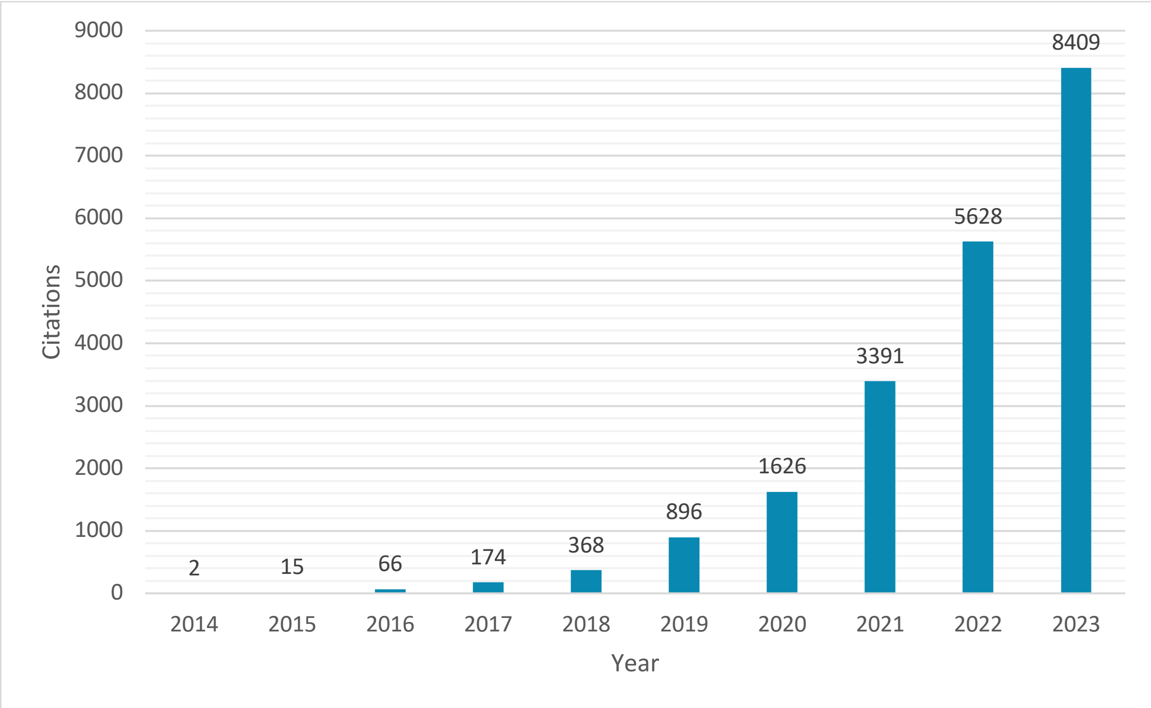
Figure 3. Citation trends for research outputs analysed



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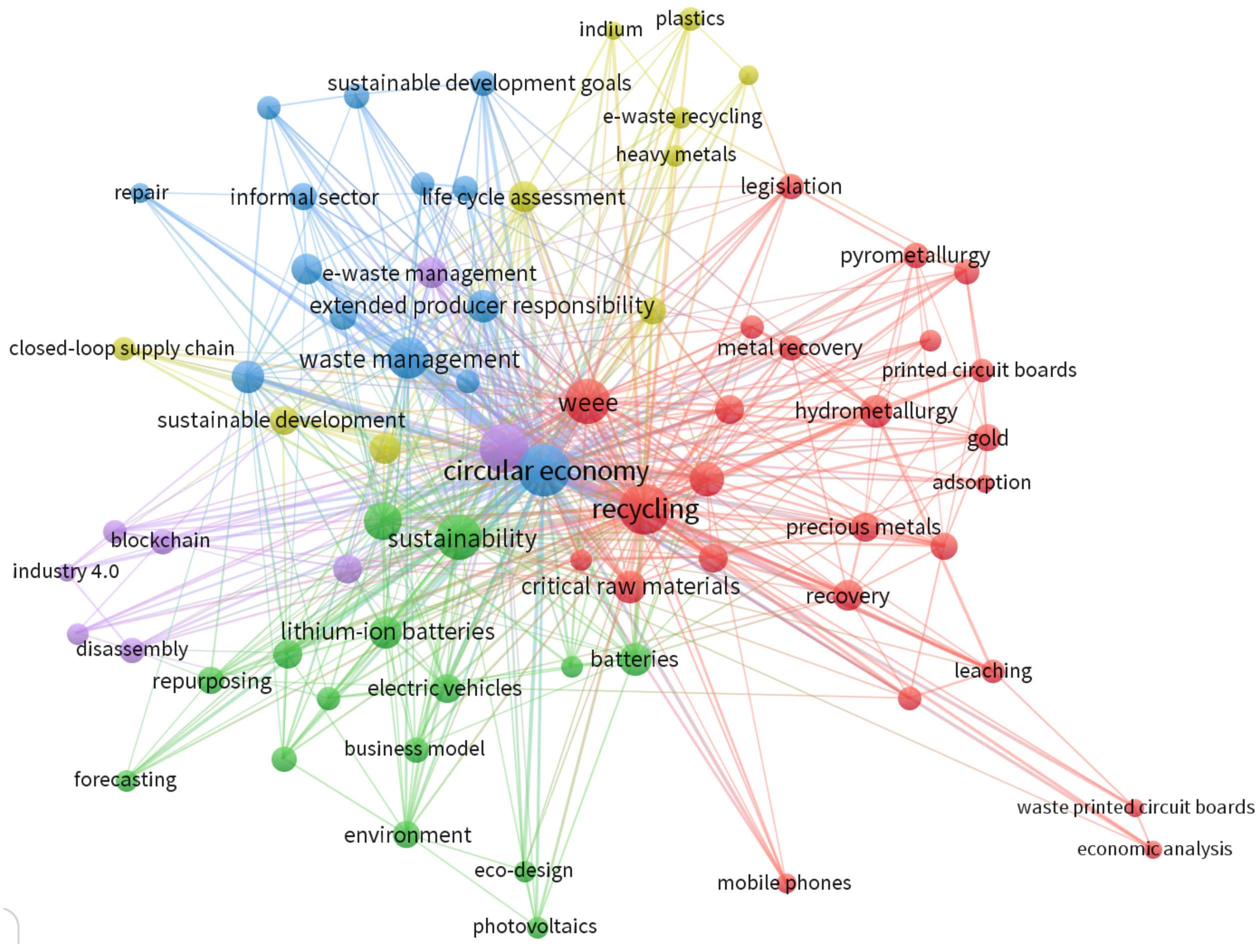
chemistry also feature prominently, illustrating the cluster's focus on sustainable extraction techniques. This cluster also touches upon the regulatory and policy frameworks surrounding the recycling of electronic waste, emphasising the need for legislation and economic analysis to support the circular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

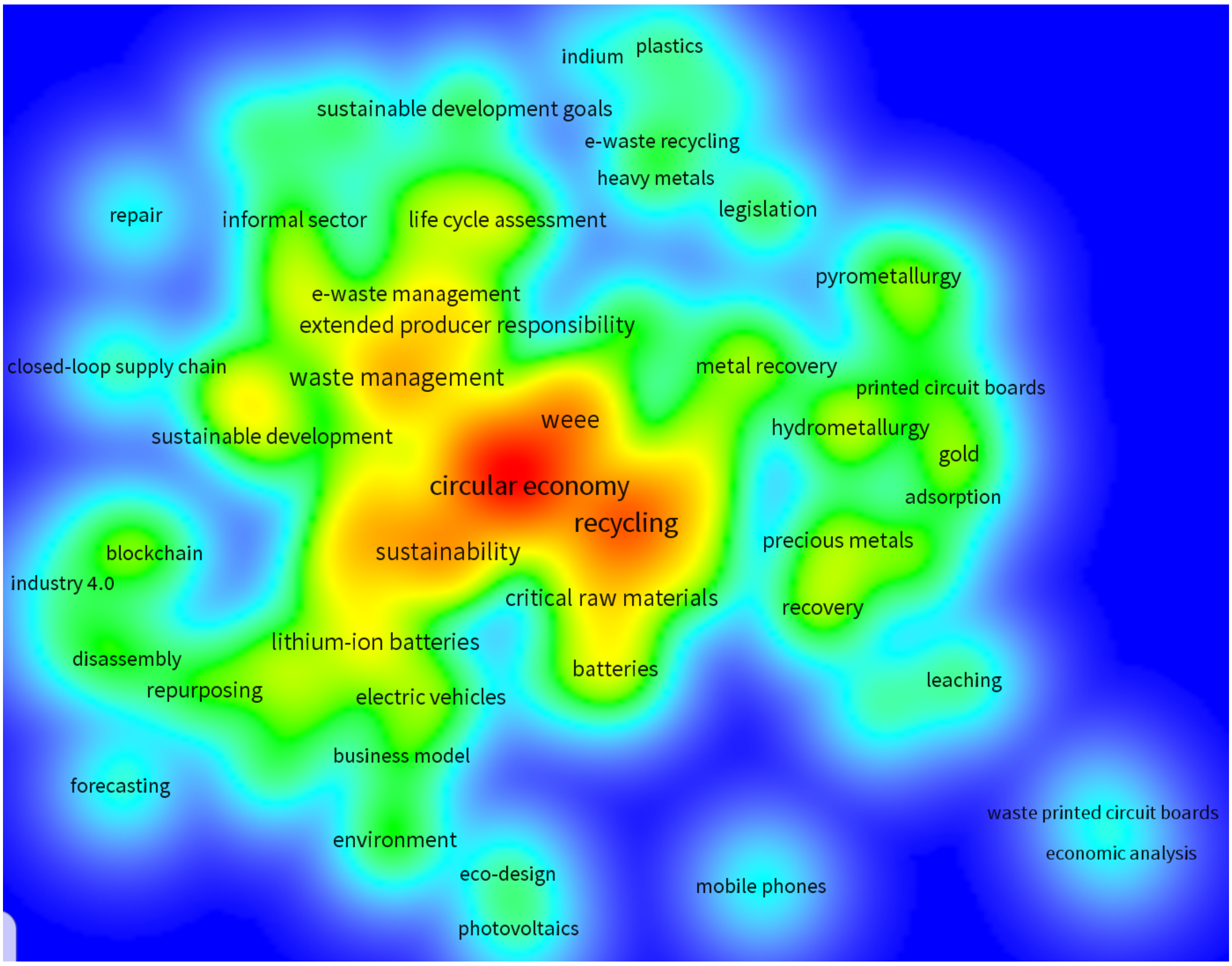
Next is the blue cluster, with 14 terms, integrating broader sustainability themes, such as the circular economy, climate change, and sustainable consumption. The cluster brings attention to consumer behaviour and policy mechanisms like the extended producer responsibility, which regulates the roles 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.

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.

- 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

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 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.

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 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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