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A global analysis of circular economy research using metadata and topic modeling

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Abstract

The Circular Economy (CE) is a sustainability-oriented concept that has attracted significant research attention in recent years. Despite this growing interest, a comprehensive and systematic understanding of the structure and evolution of CE research at the global level remains under investigation. This paper addresses this need by analyzing 16,424 peer-reviewed articles published between 2004 and 2024, retrieved from Scopus, through a combination of metadata analysis and topic modeling techniques. The metadata analysis examines publication trends, subject areas, leading journals and publishers, leading authors, author affiliation countries, and international collaborations. The results show a rapid growth of CE research and the expansion of its applications beyond traditional fields. They also reveal a strong concentration of publications among a small number of publishers, with two publishers accounting for more than half of all CE articles, as well as the notable presence of smaller countries, such as Finland and Denmark, among the most active affiliation countries when normalized by population. The topic analysis identifies 27 research themes across the CE literature and examines their evolution over time, revealing changes in thematic emphasis and a shift toward more implementation-oriented, technological, and application-focused research. Beyond mapping the current research landscape, the results highlight structural asymmetries, emerging research directions, and thematic shifts that can inform future research agendas and support the further development of the field.

Keywords: Circular economy, Network analysis, Topic modeling, Bibliometrics

1 Introduction

The Circular Economy (CE) *is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible* (European Parliament [12]). Moving beyond the traditional linear economy, CE seeks to close material loops through reuse, recycling, and regeneration. Its principles are widely studied across disciplines, influencing policies, business models, and technological innovations. Research on CE has gained significant momentum globally, reflecting its increasing importance in sustainability policy and practice, with institutions from various countries exploring its applications.

The aim of this study is to provide a comprehensive overview of CE research through a large-scale bibliometric and content-based analysis of scientific publications. By

examining publication trends, subject areas, journals and publishers, authors, geographic distribution and collaborations, as well as the thematic structure of the literature through keyword analysis and topic modeling, the study seeks to map the development of CE research and identify major research themes, patterns, and their evolution within the field.

Several bibliometric studies have previously examined CE research trends. For instance, Ruiz-Real et al. [23] analyzed the worldwide research dynamics on CE in the period from 2006 to 2017. The authors conducted a bibliometric analysis of 743 articles retrieved from the Web of Science database, identifying the most productive journals and countries, relevant authors, citation patterns, and key areas of knowledge. Camón Luis and Celma [5] analyzed CE-related publications using data from multiple sources (Web of Science, Scopus, Google Scholar). They identified key articles, prolific authors, leading journals, and publication trends, and presented bibliometric maps as well as a conceptual map of thematic evolution. Alnajem et al. [1] analyzed 214 CE articles gathered from the Web of Science database and covering the period 2009–2018. The authors present a bibliometric analysis of the citations, co-citations, collaborations, and keywords co-occurrence networks. Similarly, Goyal et al. [14] analyzed 2,279 CE-related publications to identify the most influential journals, articles, institutions and authors, and conducted a manual content analysis of 33 highly cited articles, revealing key research themes. Beyond general CE studies, bibliometric methods have also been applied to specific areas such as waste management [16, 20, 28], waste-to-energy technologies [4], e-waste [25], urban branding [8], the food industry [10, 18], the textile industry [15], the healthcare sector [9], the business and economics fields [11], and maritime studies [21].

Compared to these previous studies, several aspects of the CE research landscape remain less explored. Most existing bibliometric analyses rely on relatively small datasets or focus primarily on descriptive indicators such as publication counts, citations, or co-authorship networks. While these studies provide useful overviews of the field, they examine less extensively the broader structure of CE research and the relationships between different thematic areas. In addition, relatively few studies combine large-scale bibliometric analysis with topic modeling techniques to systematically explore the thematic organization and evolution of the literature. In particular, limited attention has been given to potential structural imbalances in the geographic distribution of CE research, the coexistence of technical and socio-economic perspectives, and the large-scale thematic organization and evolution of the literature. Several contentious issues have been identified in the broader CE scholarship, including definitional fragmentation, the unbalanced distribution of research across micro, meso, and macro levels of analysis, and the unclear linkage between CE and sustainability [17], gaps that a comprehensive bibliometric and topic modeling analysis can help to partially address.

To address these aspects, this study conducts a large-scale bibliometric and topic analysis of CE research using metadata and abstracts from 16,424 research articles published between 2004 and 2024. Compared to previous studies, the analysis is based on a substantially larger dataset, more than 60% of which was published after 2021, thus providing insights into the most recent developments in CE research. While earlier studies often relied on selective content analysis of highly cited publications (e.g., [14]),

this study uses automated methods to analyze the entire dataset. Specifically, it examines keyword co-occurrence patterns and applies topic modeling to identify the main thematic structures of the CE literature and their temporal evolution, while also exploring publication trends, collaboration patterns, and the distribution of research activity across countries, journals, authors, and subject areas. This integrated analysis provides a basis for identifying structural patterns and emerging thematic directions within the CE research landscape. In this way, the study moves beyond purely descriptive bibliometric approaches and offers a more comprehensive understanding of the thematic structure and evolution of CE research.

This study contributes to the CE literature in several ways. First, it provides one of the most comprehensive large-scale analyses of CE research to date, based on a dataset of 16,424 articles spanning more than two decades. Second, the study contributes methodologically by combining metadata analysis, keyword co-occurrence networks, and topic modeling to examine both the structural and thematic organization of CE research at scale. Finally, the findings highlight emerging research themes, patterns of knowledge production, and connections between different research areas, providing a basis for future empirical studies and helping to identify promising directions for further research on CE systems and policies. Specifically, the paper addresses the following research questions:

RQ1: How has CE research evolved over time in terms of publication activity and subject area distribution?
RQ2: Which authors, journals, and publishers play the most prominent role in the production and dissemination of CE research?
RQ3: How is CE research distributed geographically, and what patterns of collaboration emerge between countries?
RQ4: What are the main conceptual elements of CE research as reflected in author keywords and RE-related terms?
RQ5: What thematic structures can be identified in the CE literature through topic modeling of article abstracts, and how have these themes evolved over time?

The remainder of the paper is organized as follows. Section 2 describes the data collection process and the methodology used in the analysis. Section 3 presents the results of the metadata and topic analyses. Section 4 reports the main findings, limitations and makes suggestions for future research. Finally, Sect. 5 concludes the paper.

2 Methodology

For gathering publications related to CE the Scopus database was considered. Scopus is one of the largest scientific abstract and citation databases and is widely used in bibliometric studies due to its broad coverage of peer-reviewed journals across multiple disciplines. Journals indexed in Scopus are evaluated annually according to several quality indicators, including h-Index, CiteScore, SJR, and SNIP. These criteria ensure that the indexed journals meet established standards of scientific quality. For these reasons, Scopus has been frequently used as a primary data source in bibliometric analyses and thus provides a reliable basis for examining publication trends and research patterns in

the CE field. While no single database is fully exhaustive, the use of a single (and well-curated) source ensures methodological consistency and reproducibility of the analysis, while avoiding challenges related to data integration and deduplication across multiple databases.

The Scopus database was searched using the query string "circular economy" (inside double quotation marks) and selecting only the fields *article title* and *keywords* using the OR connector. The exact query used in Scopus was: TITLE("circular economy") OR KEY("circular economy"). This means that all returned publications must contain the exact term "circular economy" either in their title or in their keywords. This choice was made to ensure that the retrieved publications are strongly related to CE as their main research topic, rather than referring to the concept only marginally within the text. For this reason, the analysis focused on the title and keyword fields rather than broader search fields such as abstracts, which may introduce publications where the term appears only marginally and is not central to the study. In addition, the term "circular economy" has become a widely recognized and standardized concept in the academic and policy literature, and is typically used explicitly when referring to CE-related research. Therefore, focusing on this exact term provides a reliable way to capture publications that directly address the CE framework. While this approach increases the specificity of the dataset, it may also exclude some relevant studies that discuss CE-related concepts without explicitly using the term "circular economy" in the title or keywords. Therefore, the dataset (retrieved on January 17, 2025) should be interpreted as representing research that explicitly focuses on CE. Furthermore, preliminary tests with broader query formulations (e.g., including related sustainability or resource efficiency terms, or extending the search to abstracts) resulted in an increase in the number of retrieved publications, but also introduced a significant proportion of articles in which the CE concept was not central to the study, thereby increasing noise in the dataset. For this reason, a more restrictive query formulation was adopted, prioritizing conceptual precision and thematic coherence over broader coverage.

The query returned 26,940 publications. The majority are journal articles (16,424), followed by conference papers (4,021), reviews (3,241) and book chapters (2,383). The remaining 871 publications refer to editorials, books, notes, etc. The full metadata of these publications were exported, including their abstract and keywords, in CSV format. In the subsequent analysis, only the 16,424 publications of type "Article" were considered, thus focusing on only high-quality (peer-reviewed) full research papers and ensuring consistency in the analyzed material. An overview of the methodological workflow followed in this study is provided in Fig. 1.

The following dimensions are analyzed: i. publication year, ii. subject areas, iii. journals and publishers, iv. authors, v. author countries and collaborations across countries, vi. author keywords, vii. RE-words; words in the title and author keywords starting with "re" connected to main pillars of CE [6], and viii. topics, using the Latent Dirichlet Allocation (LDA) topic modeling algorithm applied to the article abstracts.

Before conducting the analysis, the metadata and textual information were inspected and prepared for further processing. For the analysis of the author keywords and RE-words, basic cleaning procedures were applied, including conversion to lowercase and removal of punctuation. For the analysis of RE-words, stemming was

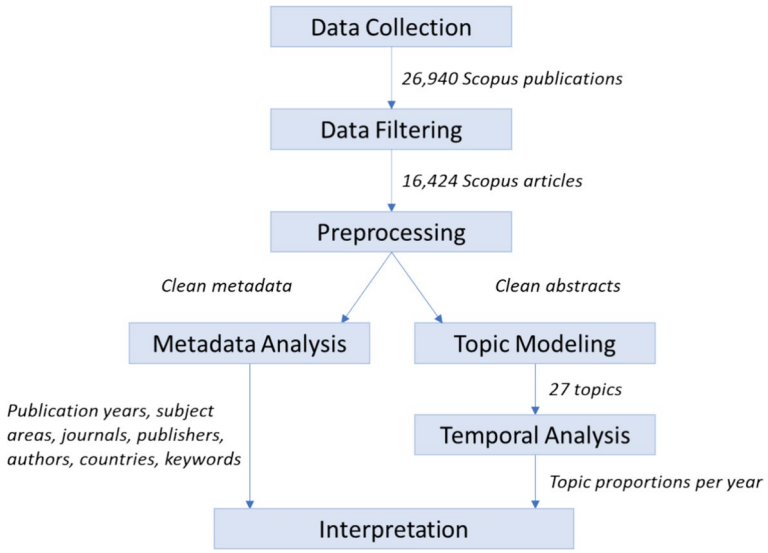

Fig. 1 Methodological workflow of the study

also applied to group related re-word forms under their base terms (e.g. "recycl" for "recycling", "recycle", etc.). Before applying topic modeling, the abstracts were pre-processed using standard natural language processing steps. The text was converted to lowercase, tokenized, and stripped of punctuation. Common English stop-words were also removed. In addition, lemmatization was applied to reduce words to their base forms and improve the consistency of the vocabulary. A dictionary and corpus were then created from the processed texts. To reduce noise, very rare and very common terms were filtered out by removing words that appeared in fewer than five documents or in more than 50% of the documents, while keeping at most the 10,000 most frequent terms.

Topic modeling was then performed using Latent Dirichlet Allocation (LDA), a probabilistic model that represents each document as a mixture of topics and each topic as a distribution over words, allowing the identification of latent thematic structures in large text corpora. LDA was selected due to its wide use in bibliometric and large-scale text analysis, as well as its interpretability and suitability for analyzing broad research domains. More recent approaches (e.g., embedding-based methods or dynamic topic models) were not considered, as the primary objective of this study is to obtain interpretable and comparable topic structures across a large and heterogeneous corpus. Several model configurations with different numbers of topics were evaluated and the final model was selected based on coherence scores (c_v). The final LDA model was trained with 27 topics, using 10 passes and 400 iterations in order to obtain stable topic-word distributions. To ensure reproducibility of the results, the random seed was fixed. The final model achieved a coherence score (c_v) of 0.5238, indicating a satisfactory level of semantic consistency among the extracted topics. This is consistent with coherence values reported in comparable LDA applications to CE-related text corpora, including analyses of social media content, where the range of coherence scores achieved across different hyperparameter configurations

has been used to select and validate optimal topic models [30]. In general, coherence scores do not have universally accepted threshold values and are primarily used for relative comparison between models [19, 22, 26]. However, values in the range of approximately 0.4–0.6 are commonly reported in large-scale topic modeling studies as yielding semantically interpretable topics. For example, Farea et al. [13] report c_v coherence values in the range of 0.398–0.587 in a sustainability-focused application, which is consistent with the value obtained in this study.

The interpretation of the topics was based on the inspection of the most representative words of each topic together with their corresponding word clouds. Finally, the temporal dynamics of the identified themes were examined by computing the average topic proportions per publication year based on the topic distributions produced by the LDA model. These yearly averages were then used to visualize the evolution of topics over time through a heatmap and a stacked area chart.

3 Results

3.1 Publication year

Figure 2 shows the number of CE publications per year. The first articles appeared in 2004, while a significant increase occurred in 2016, with the number of articles rising from 54 in 2015 to 138 in 2016 (155.6% increase). After that, the number of publications grew steadily by more than 50% per year until 2021. The increase slowed in 2022 and 2023, averaging around 17% per year, while in 2024, it rose by 32.4%, reaching a total of 4,323 articles. In absolute numbers, the largest increase in articles occurred from 2023 to 2024, with 1,059 additional publications. This data highlights the significant growth in interest in CE research in recent years.

As a result, a substantial proportion of the dataset is concentrated in recent years, which may influence the interpretation of trends by increasing the relative prominence of emerging topics. This temporal distribution should therefore be taken into account when interpreting the results. To provide additional context, Sect. 3.8 presents a temporal analysis of topic proportions, allowing a better understanding of their evolution over time.

3.2 Subject areas

Figure 3 shows the number of articles per subject area. As expected, Environmental Science is the leading subject area (9,150 articles), followed by Energy (4,906 articles) and

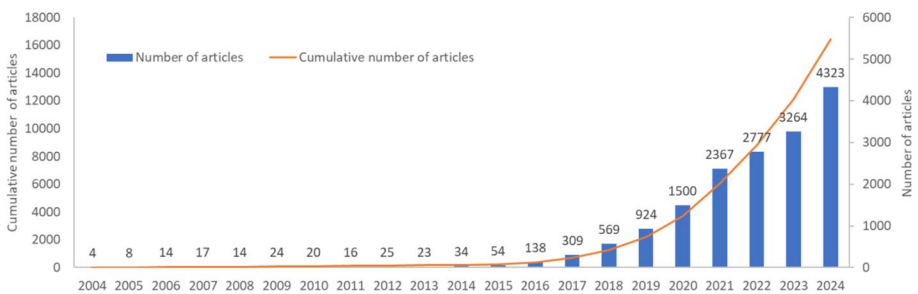

Fig. 2 Number of CE articles per year

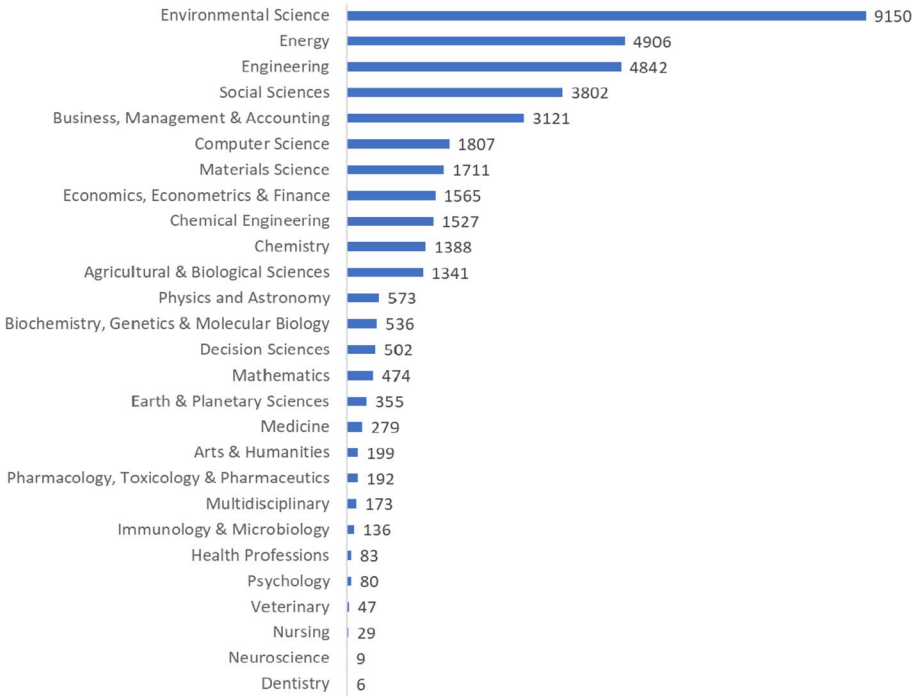

Fig. 3 Number of CE articles per subject area

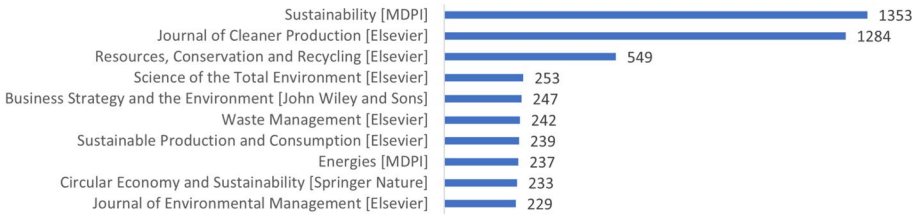

Fig. 4 Top-10 journals of CE articles

Engineering (4,842 articles). In general, it is observed that the CE concept is applied in a large variety of subject areas, including the Social Sciences, Computer Science, and Materials Science.

3.3 Journals and publishers

Figure 4 shows the top-10 journals with the highest number of CE articles. Here it is observed that the MDPI journal *Sustainability* is in the top position with 8.2% of all CE articles, followed by two Elsevier journals: *Journal of Cleaner Production* (7.8%, 1,284 articles) and *Resources, Conservation and Recycling* (3.3%, 549 articles). The first two journals published 16% of all CE articles, while the top-17 journals account for 35.8%.

Figure 5a shows the top-10 publishers. It is first noted that Elsevier far outnumbers the other publishers with 5,696 articles (34.7% of all CE articles). Second is MDPI with 3,138 articles (19.1%) and third is Springer with 1,371 articles (8.3%). Notably, two publishers (Elsevier and MDPI) published more than 50% of all CE article publications. Figure 5 (b) shows the number of CE articles per year for Elsevier and MDPI. An interesting finding

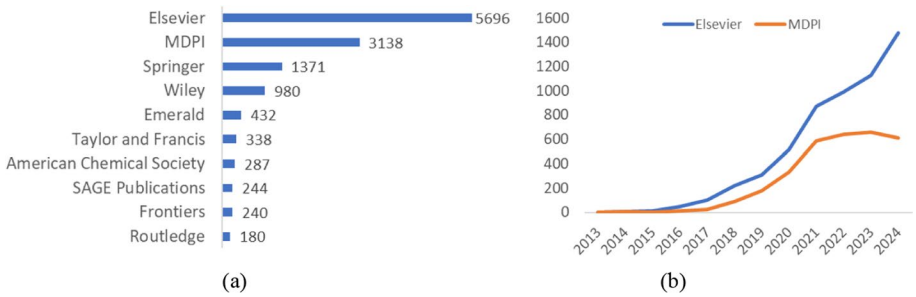

Fig. 5 **a** Top-10 publishers of CE articles; **b** Number of Elsevier and MDPI CE articles per year

is the slow growth in the number of MDPI articles from 2021 to 2023, followed by a decline in 2024.

This concentration of publications among a small number of publishers reflects structural characteristics of the academic publishing landscape, where a limited number of large publishers dominate journal indexing and output. At the same time, it may have implications for the representation of research topics and publication patterns, potentially introducing biases related to editorial policies or publication practices, and should therefore be taken into account when interpreting the results.

3.4 Authors

Table 1 presents the most productive authors in the CE dataset. Two rankings are provided: the top 20 authors appearing in any authorship position and the top 20 authors appearing as first authors. The first ranking highlights the researchers who contribute most frequently to CE publications through collaborative work. In this list, Eilhann E. Kwon leads with 41 articles, followed by four authors with 31 articles (Sungyup Jung, Yigit Kazancoglu, Simone Sehnem, and Antonis A. Zorpas). Other highly productive contributors include Nancy Bocken, Jose Arturo Garza-Reyes, and Yong Geng, each with 30 publications in the dataset.

The second ranking focuses on first authorship, which often reflects a leading role in the research. In this list, Marzena Smol appears as the most frequent first author with 22 articles, followed by Surajit Bag (16 articles) and Navarro Ferronato (15 articles). Several authors appear in both rankings, including Simone Sehnem, Luca Fraccascia, Yigit Kazancoglu, and Idiano D'Adamo, indicating both high productivity and leading roles in CE research publications.

It should be noted that these rankings reflect publication productivity within the dataset and do not account for differences in paper or journal quality, citation impact, or other indicators of research influence.

3.5 Author countries and collaborations

Figure 6 shows a heat map of author countries based on the number of articles in which at least one author has an affiliation in the country. The first country is Italy with 2,180 articles, followed by Spain (1,699), UK (1,690), China (1,542) and USA (1,089). If the results are normalized by the population of each country, a fairer estimation of each country's contribution to CE research can be obtained. Table 2 shows the top-20

Table 1 Top-20 most productive authors: rankings by total publications (any authorship position) and by first-author publications

#	Author name (in any position)	Num of articles	#	Author name (as first author)	Num of articles
1	Kwon, Eilhann E. (9,240,622,100)	41	1	Smol, Marzena (55,439,827,500)	22
2	Jung, Sungyup (55,073,290,800)	31	2	Bag, Surajit (55,757,488,200)	16
3	Kazancoglu, Yigit (15,848,066,400)	31	3	Ferronato, Navarro (57,193,131,717)	15
4	Sehnem, Simone (55,520,444,700)	31	4	Sehnem, Simone (55,520,444,700)	15
5	Zorpas, Antonis A. (6,603,816,522)	31	5	Fraccascia, Luca (56,719,697,500)	13
6	Bocken, Nancy (24,328,581,100)	30	6	Castillo-Díaz, Francisco José (57,320,672,600)	12
7	Garza-Reyes, Jose Arturo (35,310,169,200)	30	7	De Angelis, Roberta (57,201,738,797)	12
8	Geng, Yong (7,103,277,844)	30	8	Ghisellini, Patrizia (55,630,342,700)	12
9	Kumar, Anil (57,001,679,600)	29	9	Terrones-Saeta, Juan María (57,216,951,143)	12
10	Smol, Marzena (55,439,827,500)	28	10	Hou, Hongying (16,202,992,100)	11
11	Torretta, Vincenzo (55,203,392,100)	27	11	Kopnina, Helen (11,541,014,500)	11
12	Tsang, Yiu Fai (22,954,605,700)	27	12	D'Adamo, Idiano (57,217,873,519)	10
13	Ulgiati, Sergio (6,701,799,759)	27	13	Kazancoglu, Yigit (15,848,066,400)	10
14	Balkenende, Ruud (7,004,183,599)	26	14	Marrucci, Luca (57,199,327,987)	10
15	D'Adamo, Idiano (57,217,873,519)	26	15	Bressanelli, Gianmarco (57,194,720,467)	9
16	Fraccascia, Luca (56,719,697,500)	26	16	Czekała, Wojciech (55,956,882,400)	9
17	Charnley, Fiona (36,468,077,400)	25	17	Kurniawan, Tonni Agustiono (57,226,619,546)	9
18	Dewulf, Jo (7,006,029,915)	24	18	Di Foggia, Giacomo (55,604,164,500)	8
19	Luthra, Sunil (43,361,407,000)	24	19	Figge, Frank (6,602,755,604)	8
20	Ramakrishna, Seeram (57,205,523,298)	24	20	Hussain, Abrar (57,222,049,577)	8

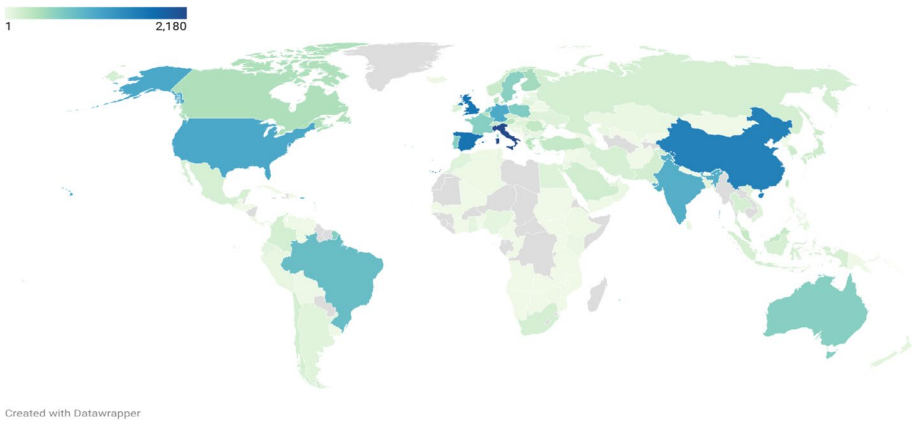

Fig. 6 Geographical distribution of CE articles

countries based on the number of articles per one million of population. The ordering is now very different. Finland is first with 85.7 articles per 1 M of population, followed by Denmark (65.5), Portugal (62.8) and Sweden (59.9). Italy is now in the 11th position with 37 articles per 1 M of population. It is observed that the top-10 countries in the list have a population of less than 20 million and the majority less than 6 million.

Table 2 Top 20 countries by author affiliations in CE articles, normalized by 1 M population

Rank	Country	Articles	Rank	Country	Articles
1	Finland	85.7	11	Italy	37.0
2	Denmark	65.5	12	Spain	35.8
3	Portugal	62.8	13	Austria	35.7
4	Sweden	59.9	14	Iceland	34.6
5	Cyprus	50.7	15	Belgium	33.6
6	Luxembourg	48.4	16	Greece	33.4
7	Netherlands	45.9	17	Estonia	33.0
8	Norway	43.5	18	Latvia	30.3
9	Slovenia	43.2	19	Switzerland	29.4
10	Lithuania	39.4	20	Brunei	28.3

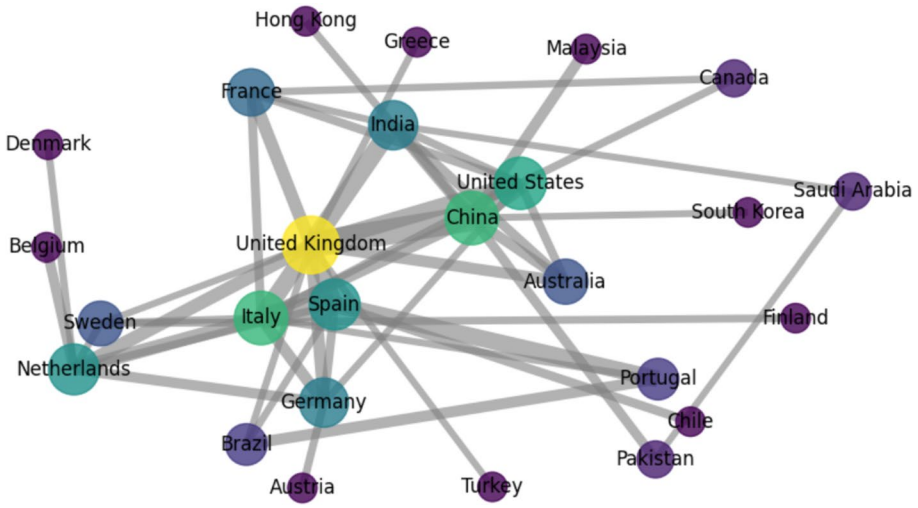

Fig. 7 Top across-countries collaborations in CE articles

The collaboration between authors in different countries is investigated by computing the number of CE articles per country pair. For example, if an article is authored by two authors with an affiliation in Greece and three authors with affiliations in Italy, one article is counted for the pair Greece-Italy. Figure 7 provides a visualization of the strongest collaboration links between countries. This network representation helps highlight the structure of international collaboration in CE research and identifies the countries that act as key connectors within the global research landscape. To improve readability, the network includes the 50 strongest country-to-country collaborations in the dataset. The line thickness represents the strength of the connection, measured as the number of articles co-authored by researchers affiliated with both countries, while the size and color of the nodes reflect the number of collaboration links of each country within this network (similar colors indicate similar levels of connectivity). Authors from China and the UK collaborate most frequently in CE articles (163 articles), followed by Italy-Spain (143 articles) and China-USA (133 articles). The United Kingdom leads the top-20 list with the most collaborations, partnering with nine other countries, while China ranks second with collaborations with six other countries.

3.6 Author keywords and RE-words

Author keywords are analyzed as provided by the authors of the publications and reflect the terminology used in the literature (rather than predefined definitions). Figure 8 displays a network of the 30 strongest co-occurrences between author keywords, excluding the keyword "circular economy" (which is present in all the articles). This network shows how frequently different keywords appear together in the same publications, and therefore it helps highlight the conceptual structure of CE research. The line thickness represents the strength of the connection measured by the number of articles in which the keyword pair co-occurs, while the size and color of the circles reflect the number of connections of each keyword within the network (similar colors indicate similar levels of connectivity). Three core, interconnected keywords are observed related to three important aspects of CE: sustainability, recycling, and waste management. The remaining keywords in the network cover other important CE aspects, including life cycle assessment, food waste, climate change, Industry 4.0, supply chains, bioeconomy, plastics, industrial ecology, and industrial symbiosis.

RE-words are defined as terms beginning with the prefix "re", representing key CE pillars (such as reuse and recycling). Figure 9 presents a network of the 30 strongest co-occurrences between RE-words. To account for linguistic morphology, stemming was applied to the identified RE-terms and their base/root forms were considered (e.g., the base form of both "recycling" and "recycle" is "*recycl*"). This network representation helps showing the conceptual relationships among RE-related terms in CE research. The line thickness represents the strength of the connection, measured by the number of articles in which the pair of RE-terms co-occurs, while the size and color of the circles reflect the number of connections of each term within the displayed network. Three core (stemmed) RE-terms are observed, *recycl, resourc, and recoveri*, followed by *reus, reclam, renew*, and *reduct*, which are altogether highly interconnected. Table 3 presents the corresponding variants of these core RE-word

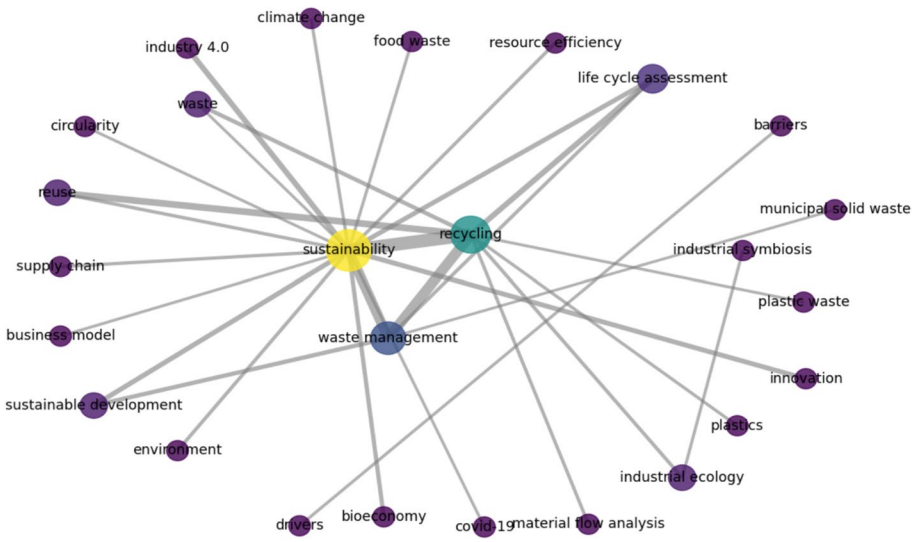

Fig. 8 Top cooccurences in CE articles between author keywords

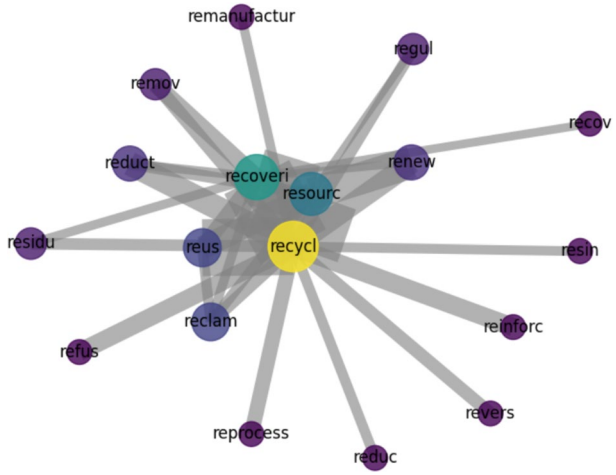

Fig. 9 Top cooccurences in CE articles between RE- words

Table 3 Core identified RE-word stems and their corresponding term variants

RE-word (stem)	Term variants
Recycl	Recycled, recyclable, recyclability, recyclables, recycle, recycling, recyclates, recyclate, recyclers, recycler, recyclings
Resourc	Resourcing, resource, resources, resourceful
Recoveri	Recovery, recoveries
Reus	Reuses, reuse, reusing, reused
Renew	Renewal, renewable, renew, renewables
Reduct	Reductants, reductions, reduction, reductive, reductant
Reclam	Reclamation

stems. i.e., how they appear in the texts. Other frequent RE-terms include *remanufactur, residu, regul, recov, resin, reinforc, revers, reduc*, and *reprocess*.

3.7 Topic modeling

While the previous metadata analysis provides a descriptive overview of the publication landscape, the topic modeling analysis that follows focuses on uncovering the underlying thematic structure and its evolution over time.

Latent Dirichlet Allocation (LDA) was applied for topic modeling on the abstracts of the collected articles. LDA is a generative statistical model that represents documents as a mixture of topics, where each topic is a distribution over words [2]. To optimize the number of topics, different approaches were evaluated and the best-performing configuration was selected based on the highest *coherence* value. The final LDA model was trained with 27 topics, using 10 passes and 400 iterations to ensure stable topic-word distributions. The variation of the coherence score across different numbers of topics is presented in Fig. 10.

Figure 11 shows the word clouds for the identified topics, illustrating the most representative words for each topic. In these visualizations, word size is proportional to the probability of the term within the topic as estimated by the LDA model. The word

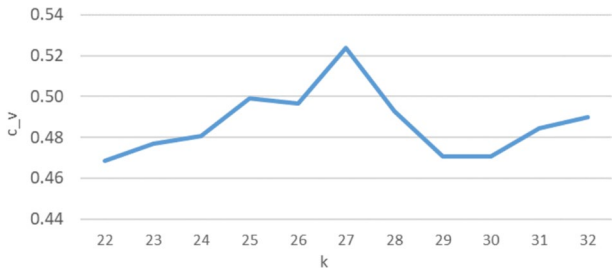

Fig. 10 Coherence score (c_v) for different numbers of topics (k)

Fig. 11 Word clouds of the twenty seven identified topics

clouds therefore provide an intuitive visualization of the topic-word distributions and help the interpretation of the thematic structure revealed by the topic modeling results. For example, *Topic 1* is about biomass conversion processes such as pyrolysis and composting, indicating waste resources management elements. *Topic 2* focuses on life cycle assessment (LCA) and environmental impact analysis of production systems, indicating a topic with an environmental management and assessment focus.

In addition to the word clouds, Fig. 12 presents an intertopic distance map generated using the pyLDAvis (Python library for topic model visualization) based on multidimensional scaling (MDS). In this visualization, each circle represents one of the 27 topics identified by the LDA model, while the distance between circles reflects the degree of semantic similarity between topics based on their word distributions. Topics that appear close to each other share a greater proportion of terms and therefore represent conceptually related research areas, whereas topics positioned farther apart correspond to more distinct thematic domains. The size of each circle indicates the relative prevalence (or importance) of the topic within the corpus. Overall, this map provides a complementary overview of the relationships among the extracted topics and helps to better understand the broader thematic structure of the field.

The intertopic distance map reveals several clusters of related topics. For example, topics related to wastewater treatment and resource recovery (Topic 11), biomass conversion and bioenergy production (Topic 16), and nutrient recovery and

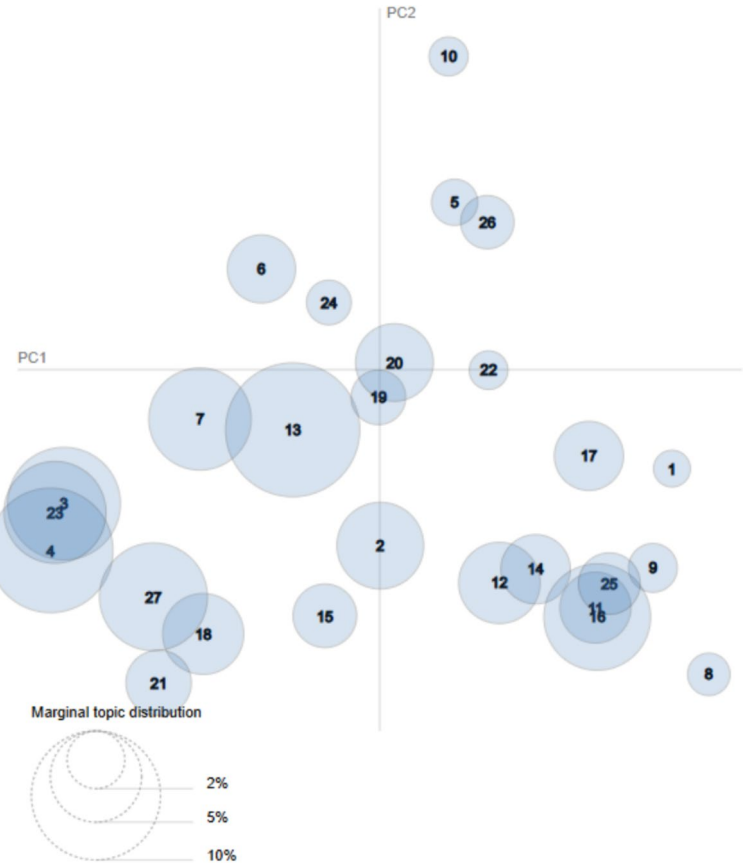

Fig. 12 Intertopic Distance Map (via multidimensional scaling)

soil (Topic 25) appear relatively close to each other, suggesting a thematic connection between these areas within the broader context of the water-resource cycle, encompassing advanced treatment, nutrient and resource recovery, and the agronomic application of composting and recycled water. Similarly, topics related to business models and sustainability transitions (Topic 3), organizational strategies for circular practices (Topic 4), and policy, governance, and supply-chains (Topic 23) appear close to each other, reflecting the conceptual proximity (within CE research) of managerial and institutional perspectives. In contrast, topics related to construction materials and the built environment (Topic 6) appear distant from the aforementioned themes, highlighting their conceptual distinction.

Table 4 provides the top-30 words of each topic, which form the basis for the interpretation of the identified themes. The results reveal substantial thematic diversity within CE research, ranging from well-established core areas to more specialized and emerging domains. Several topics correspond to traditional pillars of CE, including waste management and recycling systems (Topics 13 and 26), life cycle assessment and environmental performance evaluation (Topic 2), construction materials and the built environment (Topics 6 and 14), and energy, emissions, and climate change (Topic 20). Alongside these foundational themes, a strong presence of bio-based and agri-food related topics emerges, encompassing biomass conversion, anaerobic

Table 4 Top 30 terms for each of the twenty seven identified topics

Topic	Terms
1	Pyrolysis, oil, bio, chemical, composting, manure, co, livestock, gas, farm, product, compost, feedstock, atmosphere, animal, char, farming, cattle, m, conversion, gc, value, added, waste, cws, increase, sativa, addition, used, biomass
2	Environmental, impact, cycle, life, scenario, assessment, production, result, system, cost, lca, potential, economic, benefit, analysis, process, compared, eq, performance, based, energy, kg, reduction, co, using, different, use, emission, sustainability, indicator
3	Sustainable, business, social, research, sustainability, model, environmental, development, economic, article, change, value, new, need, paper, concept, transition, future, role, production, approach, challenge, practice, context, global, well, literature, knowledge, also, innovation
4	Ce, research, practice, framework, industry, company, approach, strategy, literature, business, circularity, implementation, finding, transition, sustainability, principle, stakeholder, innovation, adoption, level, challenge, review, model, based, gap, within, value, design, sector, case
5	Water, risk, mining, wastewater, resource, recovery, metal, reuse, urban, treatment, element, copper, earth, sc, demand, technology, use, rare, critical, associated, area, scarcity, supply, wwtps, bioproducts, potential, polyolefins, source, young, valuable
6	Material, construction, building, flow, use, resource, raw, circularity, project, stock, demolition, sector, reuse, secondary, strategy, industry, component, demand, mineral, built, analysis, environment, potential, geopolymer, primary, magnet, used, recycled, data, consumption
7	Product, design, life, process, model, new, approach, use, system, value, service, loop, case, cycle, strategy, component, paper, based, tourism, method, manufacturing, end, proposed, material, resource, reuse, tool, used, different, part
8	Kg, biogas, anaerobic, digestion, day, plant, production, digestate, mg, v, timber, total, solid, respectively, treatment, fraction, result, highest, showed, board, slurry, biomethane, organic, value, nutritional, used, period, sub, liquid, substrate
9	Feed, protein, product, film, fish, coffee, diet, growth, production, larva, content, insect, control, lipid, feeding, sp, source, animal, dairy, fatty, higher, acid, ingredient, microbial, spent, food, specie, weight, cf, level
10	Battery, recycling, vehicle, remanufacturing, eol, electric, lithium, demand, life, end, ev, cell, mobility, ion, mushroom, cobalt, libs, automotive, supply, li, future, nd, eps, solubility, formula, strategy, critical, amended, storage, market
11	Wastewater, removal, adsorption, water, treatment, rate, mg, membrane, high, model, solution, capacity, respectively, effluent, concentration, activated, microalgae, result, surface, efficiency, layer, performance, nh, cost, using, parameter, experimental, nitrogen, cod, efficient
12	Material, property, composite, thermal, sample, temperature, analysis, particle, using, based, used, application, mechanical, structure, fiber, density, different, ray, result, surface, size, spectroscopy, waste, scanning, high, powder, electron, tensile, additive, obtained
13	Waste, recycling, management, material, system, environmental, solid, recovery, collection, generation, cost, disposal, municipal, paper, reuse, rate, problem, landfill, generated, amount, result, potential, used, year, resource, data, due, method, analysis, also
14	Ash, concrete, material, waste, strength, cement, use, aggregate, property, rubber, result, test, content, fly, mechanical, slag, mixture, used, compressive, mortar, natural, sand, research, mix, recycled, mpa, also, amount, brick, asphalt
15	Country, growth, efficiency, economic, european, eu, effect, level, policy, rate, region, impact, trade, term, resource, union, environmental, significant, change, long, china, period, panel, productivity, negative, climate, increase, consumption, time, measure
16	Waste, process, biomass, using, production, acid, compound, potential, product, value, extraction, biochar, yield, high, content, used, residue, time, obtained, application, treatment, temperature, mg, showed, result, extract, method, different, chemical, solid
17	Metal, co, process, catalyst, fe, recovery, reaction, concentration, solution, chemical, iron, acid, catalytic, leaching, phase, high, cu, ii, ni, al, element, condition, salt, oxide, c, zn, using, reduction, wt, precipitation
18	Consumer, product, result, factor, behaviour, behavior, consumption, model, attitude, data, survey, company, environmental, second, intention, information, finding, market, perceived, awareness, repair, hand, influence, impact, purchase, using, perception, analysis, clothing, research
19	Food, antioxidant, agricultural, activity, system, production, olive, agriculture, agri, sustainable, health, rural, natural, leaf, ad, waste, pomace, biowaste, farmer, fw, human, bioeconomy, development, approach, fruit, local, stem, polyphenols, grape, strategy
20	Energy, emission, carbon, co, gas, renewable, production, fuel, greenhouse, technology, reduction, climate, consumption, resource, ghg, power, low, reduce, source, net, electricity, use, sustainable, generation, potential, footprint, hydrogen, process, fossil, heat

Table 4 (continued)

Topic	Terms
21	Performance, green, capability, firm, innovation, environmental, practice, enterprise, sustainable, adoption, manufacturing, impact, effect, relationship, smes, management, structural, medium, data, finding, resource, company, business, equation, role, financial, influence, result, organizational, sustainability
22	Wood, industry, steel, product, production, loss, scrap, company, chain, value, habit, agro, high, vegetable, meat, hot, hydrolysate, trading, flour, post, demand, forest, added, industrial, upstream, drug, korea, quality, processing, fluctuation
23	Chain, supply, policy, barrier, industry, management, sector, country, analysis, transition, challenge, sustainable, european, factor, implementation, government, stakeholder, research, eu, paper, strategy, development, key, towards, economic, regulation, framework, developing, regulatory, aim
24	Technology, digital, data, smart, learning, ai, machine, artificial, big, peptide, driven, information, leather, iot, operation, intelligence, application, based, model, decarbonization, process, sensor, sb, thing, industry, internet, enabled, using, analytics, leverage
25	Soil, plant, sludge, fertilizer, organic, nutrient, treatment, application, sewage, crop, content, phosphorus, compost, nitrogen, agricultural, effect, root, use, increased, control, mineral, growth, matter, substrate, pt, amendment, potential, residue, land, de
26	Plastic, recycling, packaging, textile, recycled, material, polymer, pet, polyethylene, mechanical, use, pollution, pla, printing, virgin, product, pp, based, polypropylene, fibre, post, process, biodegradable, reinforced, quality, challenge, consumer, terephthalate, recyclability, pe
27	Development, model, industrial, economic, method, based, analysis, sustainable, system, resource, decision, result, indicator, network, proposed, level, city, environmental, making, criterion, evaluation, urban, paper, eco, industry, approach, using, used, efficiency, regional

digestion, and biogas production (Topics 1, 8, and 16), nutrient recovery and soil applications (Topics 19 and 25), as well as food related terms (Topic 9), highlighting the close interlinkage between CE and the bioeconomy. This intersection reflects ongoing scholarly efforts to clarify the conceptual boundaries between these two frameworks, which share a commitment to closing material loops while placing different emphases on biological resources and the carbon cycle [27].

Notably, several topics point to technologically and industrially specific CE applications, including battery recycling and electric vehicle end-of-life management (Topic 10), metal recovery and chemical processes (Topic 17), wastewater treatment and resource recovery technologies (Topics 5 and 11), and advanced composite and additive materials derived from waste streams (Topic 12). The emergence of digitalization-oriented themes (Topic 24), explicitly linking CE with artificial intelligence, data analytics, IoT, and smart systems, represents a particularly interesting and relatively recent development, which signals a shift toward data-driven and digitally enabled circular strategies.

Beyond technical and process-oriented research, it is also observed that there are organizational, economic, and social dimensions of CE, including business models and sustainability approaches (Topics 3 and 4), firm-level capabilities and green innovation (Topic 21), consumer awareness and behavior (Topic 18), and policy, governance, and supply chains (Topics 15 and 23). The prominence of business model and supply chain research within the CE literature reflects an established and growing subfield, with dedicated scholarly efforts highlighting the centrality of circular business model innovation and supply chain redesign as enabling conditions for CE transitions at both firm and industry level [24]. The coexistence of these themes underscores the increasingly interdisciplinary and multi-level nature of CE research, spanning materials science, engineering, economics, management, policy, and social sciences.

Overall, the identified topics can be broadly grouped into two main research streams. The first includes technical and engineering-oriented topics, such as waste treatment, material recovery, energy systems, and advanced materials (e.g., Topics 1, 5, 10–14, 16, 17, 20, 26). The second comprises socio-economic and institutional topics, including business models, policy and governance, consumer behavior, and organizational strategies (e.g., Topics 3, 4, 15, 18, 21, 23). This distinction highlights the interdisciplinary nature of CE research, which combines technological innovation with systemic and societal transformation. It reflects a broader divide in the CE literature between techno-centric approaches, which emphasize material recovery, engineering solutions, and process optimization, and socio-economic approaches, which focus on governance, business models, and behavioral change. The coexistence and interaction of these strands highlight the multi-dimensional nature of CE transitions, where technological innovation and institutional change evolve in parallel.

Finally, an interesting observation is the alignment between the number of identified topics and the number of formal subject-area classifications (see Fig. 3). This shows that CE research has evolved into a relatively well-structured but internally diverse field accommodating emerging and cross-cutting themes.

3.8 Temporal dynamics of topics

Figure 13 presents a heatmap of the average topic proportions per year derived from the LDA model. Each cell represents the mean proportion of a topic across all articles published in a given year, while color intensity reflects the magnitude of the average topic proportion. To enhance the visibility of small differences among lower values, a power-law color normalization (PowerNorm) with $\gamma = 0.4$ was applied. Figure 14 complements this analysis by presenting a stacked area chart of the same data, providing a normalized representation of the relative contribution of each topic over time and allowing for a

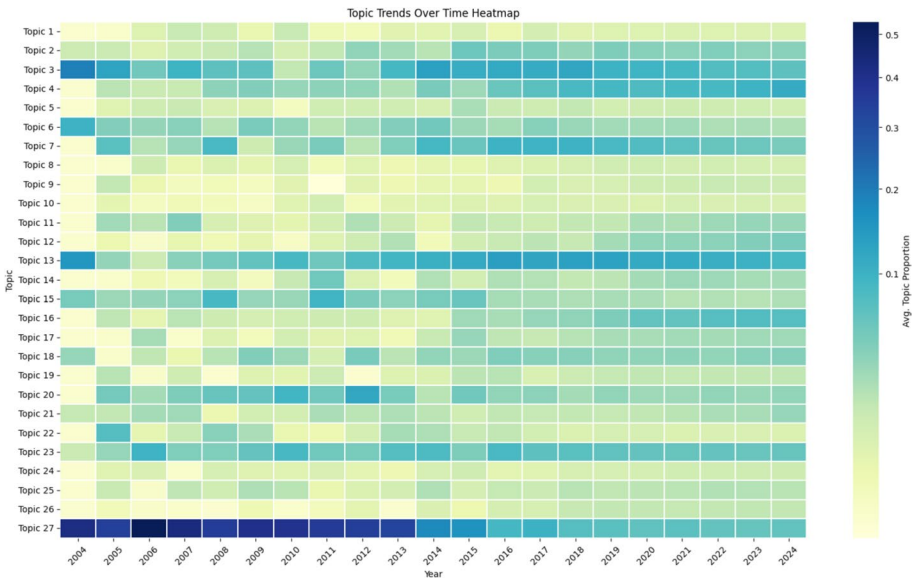

Fig. 13 Heatmap of the average topic proportions per year

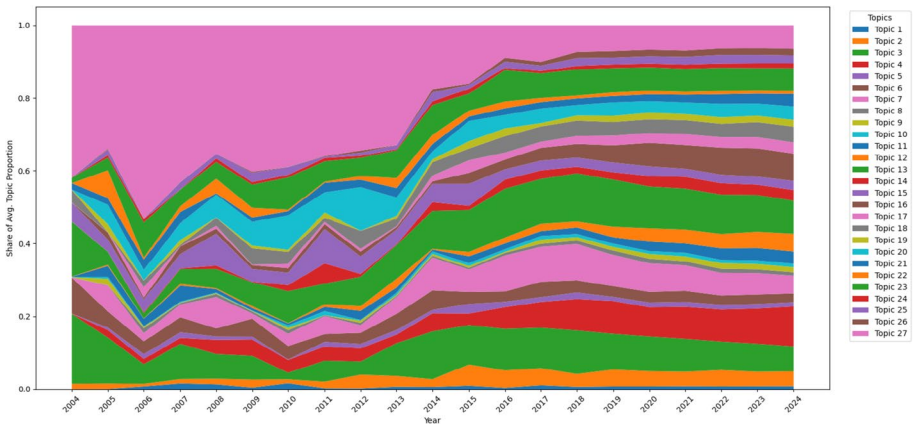

Fig. 14 Stacked area chart of average topic proportions per year

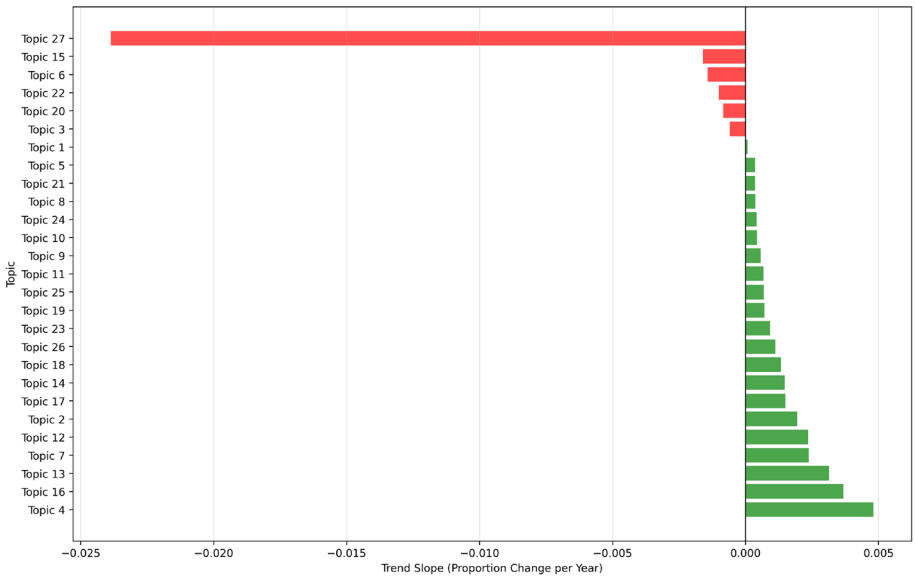

Fig. 15 Topic Growth Trends: Linear Regression Slope over all Years

quantitative assessment of thematic evolution. In this visualization, the areas represent the share of each topic in the overall topic distribution across all articles for each year, while the relative thickness of each band indicates the contribution of a given topic to the literature over time.

To quantify the strength and direction of these temporal trends more rigorously, Fig. 15 presents the linear regression slope for each topic (computed across all years). The slope represents the average change in topic proportion per year, providing a measure of trend strength that considers variations in sample size across years and is less influenced by outlier years at the beginning or end of the dataset. Positive slopes (green bars) indicate growing topics, while negative slopes (red bars) indicate declining topics.

From these figures, several shifts in the focus of the literature can be observed. First, increasing attention is noted in recent years for topics related to CE frameworks and

implementation strategies (Topic 4), reflecting growing efforts to embed CE principles into practical applications. Research on biomass waste valorization and chemical or thermal extraction processes (Topic 16), waste management and recycling systems (Topic 13), advanced materials and composite characterization (Topic 12), and waste-derived materials in concrete and cement composites (Topic 14) has also expanded, indicating rising interest in technical solutions for resource recovery. Growth is also observed in consumer behaviour and sustainable consumption (Topic 18) and plastic recycling and polymer materials (Topic 26), suggesting a broadening research agenda that includes behavioral change and material innovations. The rising attention to consumer behaviour reflects a broader recognition that individuals are central to all loops in the CE, shaping upstream product design decisions as well as downstream reuse and recycling processes — a dimension that has received dedicated scholarly attention in recent work [7].

In contrast, Topic 27 which focuses on modelling and decision-support approaches for sustainable industrial and urban systems, appears substantially more prominent in earlier years of the dataset and shows a clear decline in recent articles. A similar (but less pronounced) downward trend is observed for topics related to macro-level analyses of economic growth and resource efficiency (Topic 15), construction materials and resource flows in the built environment (Topic 6), and industrial value chains and production systems (Topic 22). These observations suggest a gradual shift in the literature from macro- and system-level analyses toward more applied, technical, and solution-driven research themes.

These trends may be associated with broader developments and focus at the same time, including increased policy attention to CE strategies (e.g., *EU Circular Economy Action Plan*), growing industrial interest in resource efficiency and sustainable materials, and the acceleration of applied research following (recent) global disruptions.

4 Discussion

4.1 Insights and implications

The results of this metadata and thematic analysis first show a strong and continuous growth of CE publications in recent years, reflecting the increasing relevance of the concept across a wide range of scientific disciplines. This trend is consistent with previous bibliometric studies that have highlighted the rapid expansion of CE research in the last decade (e.g., [14, 23]). These works similarly report a strong growth of CE publications and emphasize the interdisciplinary nature of the field, while the large-scale dataset used in this study has allowed a more detailed examination of publication patterns, geographic distribution, and thematic structures across the CE literature.

The analysis also reveals a notable concentration of publications among a relatively small number of journals and publishers. In particular, Sustainability (MDPI) and Journal of Cleaner Production (Elsevier) together account for a substantial share of CE articles, while Elsevier and MDPI publish more than half of all CE publications. This finding reflects the central role played by a few major publishing platforms in shaping the dissemination of CE research and highlights the importance of specialized sustainability and environmental journals in this field. This concentration may also have implications for the representation of research topics and publication patterns, as the dominance of a limited number of publishers can influence editorial priorities and dissemination

practices. Interestingly, the results also show a decline in the growth of CE publications in MDPI journals after 2023. This change may reflect new entrants, and broader shifts in publication dynamics within the field, possibly linked to ongoing discussions in the academic community regarding publication practices.

In terms of geographic distribution, Italy leads in absolute publication numbers, while smaller countries such as Finland rank highest when normalized by population. This finding suggests that CE research activity is not only concentrated in large research systems but is also strongly represented in smaller countries that have actively promoted CE policies and sustainability initiatives. It is observed that several Northern European countries, including Finland, Denmark, Sweden, and Norway, appear prominently in the per-capita rankings, reflecting their longstanding policy engagement with CE strategies and resource efficiency. This pattern is independently corroborated by evidence from an alternative data source: a LinkedIn-based analysis of CE companies across EU countries found that the same group of Northern European countries, led by Finland, also dominates CE entrepreneurial activity on a per-capita basis [29], indicating that the elevated academic output of these countries is embedded within a broader systemic CE orientation encompassing research, policy, and business. The collaboration analysis further shows strong international research networks, particularly involving countries such as the United Kingdom, China, Italy, Spain, and the United States.

The thematic analysis provides additional insights into the conceptual structure of CE research. The keyword co-occurrence networks highlight core concepts such as sustainability, recycling, and waste management, confirming their central role in the CE literature. At the same time, the presence of terms related to areas such as Industry 4.0, supply chains, and bioeconomy indicates the increasing integration of CE principles with technological innovation and industrial transformation.

Topic modeling using LDA has revealed a diverse set of 27 research themes covering areas ranging from waste management and life-cycle assessment to digital technologies, energy systems, and sustainable business models. Moreover, the temporal analysis of these topics indicates that the CE literature is gradually shifting from macro- and system-level analyses toward more implementation-oriented, technological, and application-focused research themes. This thematic diversity shows the interdisciplinary nature of CE research and illustrates how it connects environmental, technological, and socio-economic perspectives in the transition toward more sustainable production and consumption systems. This is also consistent with previous bibliometric studies that describe CE research as a rapidly expanding and interdisciplinary field (e.g., [14, 23]). Furthermore, the emergence of a topic explicitly related to digital technologies, including artificial intelligence, data analytics, and IoT, highlights the growing role of digital transformation in enabling CE strategies, particularly in areas such as resource monitoring, smart production systems, and circular supply chains.

These observed shifts may be associated with broader developments shaping the CE research agenda. In particular, increased policy attention at international and regional levels (e.g., the *European Green Deal* and the *EU Circular Economy Action Plan*) as well as growing industrial demand for resource efficiency and sustainable materials, and the expansion of funding initiatives targeting applied sustainability solutions, have likely contributed to the rise of implementation-oriented research. In addition, recent global

disruptions (such as the COVID-19 pandemic) have increased interest in resilient supply chains and resource security, further accelerating research on practical (and technology-driven) CE applications.

These findings provide insights into the evolving structure of CE research and may be useful for policymakers and research funding bodies seeking to understand the evolving priorities and knowledge networks shaping this field. More specifically, the identified thematic areas and trends are closely aligned with key sustainability policy frameworks, including the *United Nations Sustainable Development Goals* (e.g., SDG 12 on responsible consumption and production, SDG 9 on industry and innovation, and SDG 13 on climate action) and the *EU Circular Economy Action Plan*. This alignment highlights the relevance of CE research in supporting policy-driven transitions toward sustainable and resource-efficient systems.

4.2 Limitations

This study also has some limitations that should be acknowledged. First, the analysis is based solely on publications indexed in the Scopus database and retrieved using the exact term "circular economy" in titles or keywords. While this approach ensures a strong thematic focus, it may exclude relevant studies that discuss sustainability-related concepts without explicitly using this term or that are indexed in other databases. As a result, the findings may be influenced by database and query-specific coverage and indexing practices.

Furthermore, a substantial proportion of the dataset is concentrated in recent years, reflecting the rapid growth of CE research. This may influence the interpretation of trends by increasing the relative prominence of specific (emerging) topics.

In addition, topic modeling provides a high-level representation of thematic patterns in the literature and therefore cannot capture the full conceptual depth (and complexity) of individual studies.

Finally, the analysis is primarily quantitative in nature and does not explicitly assess the quality or scientific impact of individual publications. As a result, all articles are treated equally, regardless of their methodological rigor, impact, or contribution to the field.

4.3 Future research

From a methodological perspective, future studies can extend this work by examining the evolution of topics in greater detail, for example by applying dynamic topic modeling approaches [3], or by investigating thematic differences across countries and subject areas in order to identify geographic and disciplinary patterns. In addition, more recent topic modeling approaches, such as embedding-based methods (e.g., BERTopic), could be explored to capture more nuanced semantic relationships and complement the results obtained through LDA.

Furthermore, incorporating structured validation approaches (such as expert-based evaluation) as well as integrating quality-weighted approaches (e.g., based on citations), could provide additional insights and further strengthen the robustness of the findings. Future work could also explore the impact of alternative data collection strategies, such as broader query formulations or the integration of multiple bibliographic databases, in order to assess the sensitivity of the results to corpus construction choices.

5 Conclusion

This study provides a comprehensive, data-driven overview of the structure and evolution of CE research. It offers insights into how knowledge production in this field is organized and how it is shifting toward more implementation-oriented and technology-driven approaches. The findings have relevant implications for both research and policy. For researchers, they highlight emerging thematic areas and interdisciplinary connections that can guide future investigations. For policymakers and funding agencies, they provide evidence on the alignment of research activity with key sustainability priorities, supporting more informed decision-making in the design of CE strategies. Overall, the study contributes to a better understanding of how the CE research landscape is evolving and how it can support the transition toward more sustainable and resource-efficient systems.

Author contributions
P.F. conducted the data collection, bibliometric analysis, and topic modeling experiments. P.F. and K.T. jointly contributed to the conceptualization of the study, the interpretation of the results, and the writing of the manuscript. Both authors reviewed and approved the final version of the manuscript.

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Data availability
The data analyzed in this study were retrieved from the Scopus database using a predefined search query and method. Access to Scopus is subject to subscription and licensing restrictions, and therefore the raw data cannot be publicly shared. Details of the data retrieval and analysis procedures are described in the manuscript. Researchers with access to the Scopus database can reproduce the dataset by applying the same data retrieval procedure described in the Methodology section.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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