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Circular economy in the building and construction sector: A scientific evolution analysis

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ABSTRACT

The building industry is responsible for considerable environmental impacts due to its consumption of resources and energy, and the production of wastes. Circular Economy (CE), a new paradigm can significantly improve the sustainability of this sector. This paper performs a quantitative scientific evolution analysis of the application of CE in the building sector to detect new trends and highlight the evolvement of this research topic. Around 7000 documents published 2005 to 2020 at Web of Science and Scopus were collected and analyzed. The bibliometric indicators, network citation, and multivariate statistical analysis were obtained using Bibliometrix R-package and VOSviewer. The co-occurrence analysis showed five keyword-clusters, in which the three main ones are: (i) energy and energy efficiency in buildings; (ii) recycling, waste management and alternative construction materials; (iii) sustainable development. The analysis showed that researchers pay close attention to "sustainability", "energy efficiency", "life cycle assessment", "renewable energy", and "recycling" in the past five years. This paper highlights that (i) the development and use of alternative construction materials; (ii) the development of circular business models; (iii) smart cities, Industry 4.0 and their relations with CE, are the current research hotspots that may be considered as potential future research topics.

1. Introduction

The building and construction sector is a key area that has significant impacts on the economy and environment [1]. This sector contributes to the economy (about 9% of the EU's Gross Domestic Product (GDP)), provides direct and indirect job opportunities (18 million direct jobs at the EU) and satisfies the people's needs for buildings and facilities [2,3]. Moreover, this sector is one of the main consumers of resources: about 50% of the total use of raw materials, and 36% of the global final energy use [4,5]. As this sector accounts for 39% of the energy and process-related emissions and the agents of acid rain, the continuation of these greenhouse gas emissions at the same rate will certainly lead to a problematic situation [4,6]. Therefore, any effort concerning global climate change and cleaner production should include this industry as a major player [7,8].

In addition to these environmental impacts, the construction and demolition projects are also responsible for about a third of the total waste generated in the EU, with a significant share being landfilled which creates serious environmental problems during the entire life-cycle of buildings, especially during the operation and end-of-life stages [9]. Moreover, it is predicted that with the current population growth rate, the middle class will increase from 2 billion to over 4 billion people by 2030 [10]. Therefore, there is a need to build more urban capacity than has been built in the past 4000 years to secure progress, contemporary and future well-being [11]. Another important issue is the price-increase of raw materials which pushes the building industry for using efficient resource alternative materials, for example by reusing and recycling [11,12]. In this context, it can be concluded that there are an urgent need and pressure in the construction industry to shift from the current paradigm into a more sustainable one with a focus on adopting the circular economy approach to ensure a more sustainable building sector [13–15].

The concept of the Circular Economy (CE), evolved from industrial ecology [16], tries to bring under one name a collection of pre-existing

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ideas from various scientific fields with shared qualities and characteristics, *e.g.,* industrial ecosystems and industrial symbioses, the 3Rs principle (reduce, reuse and recycle), cleaner production including manufacturing systems' circular materials flows, product-service systems, eco-efficiency, cradle-to-cradle design, green growth, biomimicry, natural capitalism, the resilience of social-ecological systems, the concept of zero emissions and others [17–20]. The CE paradigm is proposed to change the current production and consumption pattern of "take-make-dispose" that is threatening the sustainability of human life on earth and is approaching the planetary boundaries [21]. Steps in this direction require closing the loops by reusing wastes and resources as well as slowing material loops by developing long-lasting, reusable products [22–24]. The development and implications of CE are still progressing [25], and there is no single definition of CE because of its interdisciplinary nature [26,27]. According to the literature review on CE in the building industry by Benachio et al. [28], the most cited sources of CE definition are established by the Ellen MacArthur Foundation (EMF), as "*restorative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" [29], and in the next places are the definitions proposed by Lacy and Rutqvist [30], Pomponi and Moncaster [31], Geissdoerfer et al. [32], and Leising et al. [23], respectively. Despite this lack of a generally accepted definition of CE, there is wide agreement among scholars and practitioners that CE enhances life cycle of components, materials and products through reuse, repair, recycling, remanufacture and refurbishing [33]. In this paper, we embrace the definition of CE proposed by Kirchherr et al. [34]: "*an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers*".

The basic CE concepts of reduction, reuse, and recyclability of materials and components have been already widely implemented successfully from electrical equipment and furniture to textiles, but its application in the building sector has a shorter history and to a lesser extent [19,31,35], basically limited to waste prevention and material management (mainly focused on recycling) [36]. The construction sector has been known as one of the three sectors with high potential to implement CE strategies [37], particularly through the adoption of eco-friendly products and technologies [38]. The adopting of CE principle in the construction industry promotes the use of sustainable materials, maximizing material recovery, and avoiding unnecessary waste generation and waste disposed to landfill [39–41]. It is expected that by applying CE principles in the European built environment, it is possible to save €350 billion through resource and energy savings by 2030 [42]. However, this sector is characterized by strong project-based institutionalized practices and market mechanisms, which in many aspects do not facilitate the inclusion of CE principles [11]. For building projects, the accomplishment of the project needs inputs from a high number of stakeholders within a complex supply chain, where each chain-echelon contributes to environmental impacts and cost of the building production [11,43,44]. In this context, it is clear that the governments must play their key roles by dictating relevant guidelines and policy interventions to support CE transition in the construction industry [25].

In the literature, there are review papers and bibliometric research dealing exclusively with CE such as [28,45–51], and the relation of CE with various other concepts such as built environment [14,26,52,53], industrial symbiosis [54], industrial ecology [55], green and bio-economy [56], demolition waste sector [57], and sustainability [32]. However, to date, to the best of our knowledge, there is no work published assessing systematically and quantitatively the scientific evolution of literature referring to the theory and practice of CE in the building and construction industry from a bibliometric perspective. To contribute to fulfilling this limitation, this paper aims to detect the characteristics of worldwide literature of the CE in the field of interest through statistical analyzing the scientific works published in Web of Science (WoS) and Scopus databases from 2005 to 2020. Moreover, in the present work, the records are collected from both Web of Science (WoS) and Scopus databases that results in having a more extensive global perspective of bibliometric data [58], as well as eliminating any dependency of the results on the database [59]. Hence, another novelty of this work is to detect the characteristics of a large volume of literature published in the field of interest at the two of most influential databases.

This study provides a summary of the *status quo* of the global research on CE implementation in the building industry, including the scientific publication growth, the most influential authors, institutions, countries, journals as well as the degree of existing academic collaboration between researchers, institutions and countries. Moreover, science mapping, including the word-clustering analysis, frequency, and co-occurrence analysis of keywords were conducted to explore the intellectual structure of a field, and to seek the emerging and hot research lines and the historical developments of the topic. The findings of this article could prove useful for the academic community in identifying the gaps and potential opportunities in the current knowledge and suggesting the pathway for future research. The knowledge generated by the present study, for example the data regarding collaborations, may also provide a handy tool for investigations or policies that aim to approach the topic with the support of specialized groups [58].

2. Methodology

There are several review methods for analyzing the existing literature, such as critical review, literature review, meta-analysis, systematic search and review [60]. Bibliometrics, as a systematic quantitative literature review, follows a transparent detailed systematic method and more importantly reproducible process of review to collect and systematize information [61], while as of its quantitative nature, it is objective-oriented and includes statistical analysis of bibliometric data [60]. This method can be used particularly for transdisciplinary research to identify the geographic, scalar, theoretical, and methodological gaps in the literature [62].

Scholars assess the impact of units (*e.g.*, researchers, institutions, countries, publications, and sources) in three main metrics of productivity (assess how productive the units are), impact (measure the impact of units on other units), and integration of productivity and impact using several bibliometric indicators, such as publication count, citation count, the cites per paper and citation thresholds [63], the h-index [64,65], the g-index [66], the m-quotient [67]. These methods complement each other rather than being alternatives to one another [68]. Still, so far, the most popular indicators are the number of publications, citation count, and h-index (defined as the number of publications of an author/journal (say h) that has received at least h times citation) [69]. In this study, in addition to these three indicators, the average number of citations per document, the m-quotient, and g-index parameters are reported. The m-quotient, the result of dividing the h-index number by the scientific age of a scientist, eliminates the dependency of the h-index on the duration of each scientist's career [67,70]. The g-index, which can be seen as averaged h-index, overcomes the shortcoming of the h-index in accounting for the performance of the author's top articles [70].

In this study, co-word, co-citation, and co-authorship analyses were adopted. A brief description of each is presented below:

- Citation analysis: in a scientific article, the authors cite the related literature to support their arguments [71]. This citation indicates the relevancy of the citing and the cited document, and thus, citation analysis can help in identifying the main authors, literature, journals, source countries, or institutions [72].

- Co-citation analysis: it shows the frequency in which two documents are cited together simultaneously by another document [73]. This method, therefore, works as an indicator of how much two works share related subjects. Co-citation analysis can map the intellectual structure of a research field [71]. It is possible to identify the core themes of a research field by analyzing the links in a cluster of articles, mapping the links, and establishing the importance and proximity of topics [74,75].
- Co-authorship analysis: it examines the authors and their affiliations, to discover academic collaborations, collaborative behavior, and the schools of thought [76]. Data about collaborations could be useful for investigations and policies aiming to approach the topic with the support of specialized groups [77]. Moreover, this method has been used to investigate the development of a field [78], to identify the subdisciplines of the interdisciplinary field of a field, and to investigate trends in collaboration and productivity between subdisciplines [79,80].

In the present study, we adopted a similar approach as the method proposed in Aria and Cuccurullo [81], and Zupic and Čater [68], where five stages of (i) conceptualization of research, (ii) collection of bibliometric data, (iii) analysis of collected data, (iv) visualization, and (v) interpretation have been followed. In the first step, the research questions and the proper bibliometric methods are defined [81]. As partially shown in Fig. 1, in data collection, the search query, the database that contains the bibliometric data, the document filtering criteria, and exporting data from the selected database are carried out. Then the required preprocessing measures, including data cleaning and screening, are followed. One or more bibliometric or statistical tools can be utilized to conduct the data analysis. Later, in the data visualization step, the scholar should choose the visualization method and the appropriate mapping software. Finally, the scholars analyze and describe the findings [81].

2.1. Search query

In the bibliometric analysis, the identification of search keywords is one of the most important stages as it has major impacts on the results of the study. In most of the cases, scholars consider the search query by (i) using the generic literal concepts (*e.g.,* “circular economy” [45,82]); (ii) using wildcards to represent different combinations of characters in the construction of a query (*e.g.,* “circular econom*” [51]); (iii) using the expert-driven semantically-related terms, to identify an extended collection of keywords [83]. We use a combination of all three above-mentioned choices.

A preliminary publications retrieval was performed using the search query TS = “circular econom*” AND (“building*” OR “construction*”), in the “Topic” field of WoS Core Collection for journal articles (the Boolean operators “AND” is used to link the two fields, and “OR” is employed to combine the two fields). In accordance with Nobre and Tavares [51], we found that many articles containing the terms semantically different, but with the same meaning, were missed since the search query did not include the corresponding required terms to record them (*e.g.,* the term “circulatory economy” or “circular supply chain”). Moreover, the publication related to the CE does not necessarily use this expression to describe the underlying phenomenon in their body [26,84]. Thus, an extensive literature review was conducted to find different definitions and classifications to complete the collection of keywords.

Based on (i) the literature review conducted, specifically those reporting various definitions of CE [34], and CE in the construction industry [23,29–32], (ii) the list of keywords proposed by Nobre and Tavares [51], (iii) the keywords collection obtained from our preliminary exercise on the publications retrieval (as detailed in the previous paragraph), the authors proposed to use a formulated search query containing three main parts (see Fig. 2). The first part (TS_A), includes the terms and concepts semantically related to the circular economy; the second part (TS_B), encompasses a semantic set of keywords related to the building and construction; and the third part (TS_C), consists of commonly used terms for the CE implemented buildings. The list of terms (TS) can be consulted in Appendix A.1.

To define the logic query of the first part (TS_A), the combination of keywords proposed by Nobre and Tavares [51], and Hossain et al. [25] was used with modifications according to the conducted literature review. The together use of basic principles of the CE so-called 3R’s (reduce, reuse, recycle) in the logic query should be highlighted because when these terms are used separately, some out of the scope results are retrieved. The terms “sustainable”, and “sustainability” were added according to our embraced definition of CE [34,51].

Regarding the second part (TS_B), the wildcards of the semantic set of keywords related to the building sector, “building*” and “construction*”, were used. Using these terms, leads to the inclusion of the most relevant studies, especially as the query would atomically include works with any noun phrasal combination of the aforementioned terms, *e.g.*, residential building, building materials, building information modeling (BIM), etc.

The third part (TS_C), contains the three common expressions referring to the buildings that circular economy principles have been implemented on them, the so-called *circular building*: “*A building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles*” [31].

There could still be some relevant articles missing from this study due to employing the search query proposed. However, after a number of trials to use various combinations of the keywords and by checking

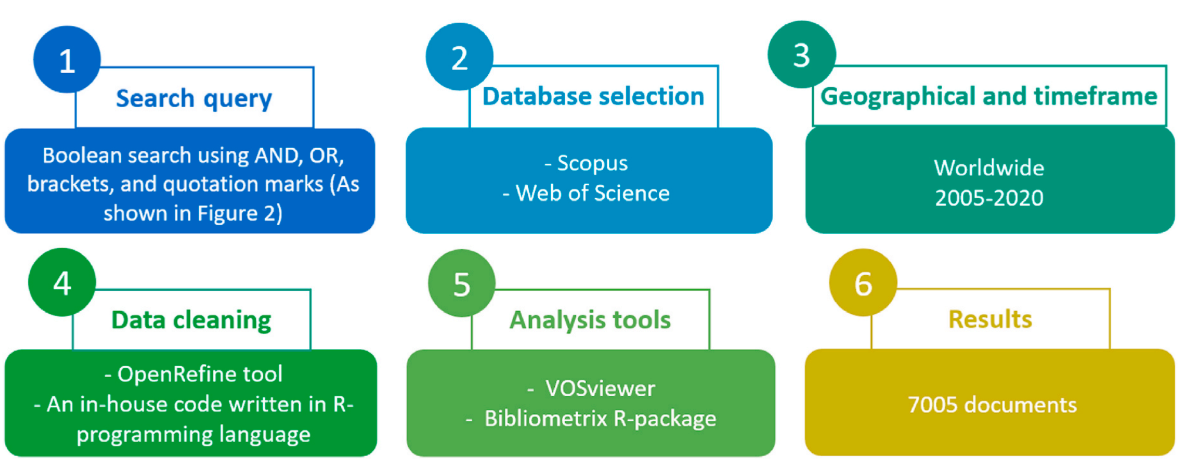

Fig. 1. The methodological framework of the bibliometric analysis.

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$$TS = \left(\overbrace{\left(TS_1 \ \mathbf{OR} \left(\left(TS_2 \ \mathbf{OR} \ TS_3 \right) \mathbf{AND} \ TS_4 \right) \right)}^{TS_A} \ \mathbf{AND} \ \overbrace{\left(TS_5 \right)}^{TS_B} \right) \mathbf{OR} \overbrace{\left(TS_6 \right)}^{TS_C}$$

$$TS_1 = \text{Circular Economy-like Terms (see Appendix 1)}$$

$$TS_2 = \text{List of Terms (see Appendix 1)}$$

$$TS_3 = \text{"Reduc*"} \ \mathbf{AND} \ \text{"Reus*"} \ \mathbf{AND} \ \text{"Recycl*"}$$

$$TS_4 = \text{"Sustainable"} \ \mathbf{OR} \ \text{"Sustainability"}$$

$$TS_5 = \text{"Building*"} \ \mathbf{AND} \ \text{"Construction*"}$$

$$TS_6 = \text{"Building Circularity"} \ \mathbf{OR} \ \text{"Circular Construction*"} \ \mathbf{OR} \ \text{"Circular Building*"}$$

Fig. 2. Search query used in both Scopus and Web of Science.

descriptive and co-word analysis of the datasets, we observed that the proposed search string provides a proper sample to capture the general research directions and different considerations of the field.

2.2. Database selection

The Web of Science (WoS) was the only tool for conducting bibliometric analysis until the creation of Scopus and Google Scholar in 2004 [85,86]. However, the lack of quality control and low reliability of bibliometric results in Google Scholar raises questions about its suitability as a bibliometric tool [87,88]. Thus, WoS and Scopus, as the two most influential databases, remain today as the main sources for citation data [88,89]. A structural comparison of these databases can be found in Martín-Martín et al. [90] and Echchakoui [91].

In this study, the records are collected from both WoS and Scopus and then merged. Considering such a large dataset improves the analysis from: (i) having a more global perspective of bibliometric analysis [58], (ii) eliminating any dependency of the results on the database used [59], (iii) following the good practice to "*supplement results retrieved from a citation database with additional publications to reach the desired level of completeness for the study at hand.*" [92,93].

In the present study, the document type was restricted to scientific articles, proceeding papers, and reviews for the case of WoS Core Collection; and articles, reviews, conference papers, and conference reviews for the case of Scopus. The search query was employed in the "Topic" field of WoS Core Collection, and "title, abstract, keywords" field of the Scopus database. The timespan was set to 2005–2020.

2.3. Data cleaning

After gathering the records from both databases, the results from not relevant categories (*i.e.,* agriculture, biology, pharmacology, medicine, etc.) were removed. In addition, an extensive effort was made to check the relevancy of the results through skimming the records' title, abstract, resulting in the exclusion of some documents, *e.g.*, those related to infrastructures such as roads, bridges, tunnels, railways, airports, etc. The WoS and Scopus use different data frames to index documents bibliographic information, and therefore, a normalization of the field was performed. Moreover, un-related words (*e.g.*, generic terms, organization names, and regional words) were excluded from the results. Finally, repetitive words are written in different ways (*e.g.*, singular and plural forms, abbreviations) were standardized and merged, for example, "Circular economy", "Circulating Economy", "Circularity", "CE", were merged to "Circular economy". The above-mentioned data refining and preprocessing tasks were performed using OpenRefine tool.

Using an in-house code written in R-programming language [94], the duplicate records were removed during preprocessing. The algorithm of duplication removal is based on the DOI, and the document's normalized term based on the title, first author's last name, the first letter of the first author's first name, and the publication year [95,96]. As a result of the retrieval and refining procedure, 7005 documents were collected from the databases.

2.4. Research tools

The Bibliometrix R-package [81], an open-source tool written in R-language, was used to perform basic bibliometric citation analysis, comprehensive science mapping analysis as well as analyzing different architectures of a bibliographic collection through conceptual, intellectual, and social structures [81]. Besides, VOSviewer [96] is used to map and visualize the networks, and to identify the structure of the study field.

3. Results

3.1. Global statistics

From the 7005 documents collected from the two databases, 55.9% records were journal articles (3913), 14.6% (1025) proceeding papers, and 23.4% (1639) conference papers, and 6.1% (428) reviews. Detailed information on the dataset is provided in Table 1. In this table, the reported statistics for the sources, keyword plus, author's keywords, and average citation per document are with taking all various types of documents into account. Publications were retrieved from 2355 scientific journals/repositories with an average of 2.7 authors per publication, and with a great majority (85%) multi-authored.

Fig. 3 indicates that there has been moderate growth in the production of literature from 2005 (64 documents) to 2008 (142

Table 1
General information about the dataset collection of circular economy in buildings (2005–2020).

Description	Results
Type of documents	
Journal Articles	3913
Conference papers	1639
Proceedings papers	1025
Review papers	428
Sources (Journals, etc.)	2355
Keywords plus	17008
Author's keywords	12643
Average citations per documents	11.17
Collaboration index	3.06
Annual growth rate	21%

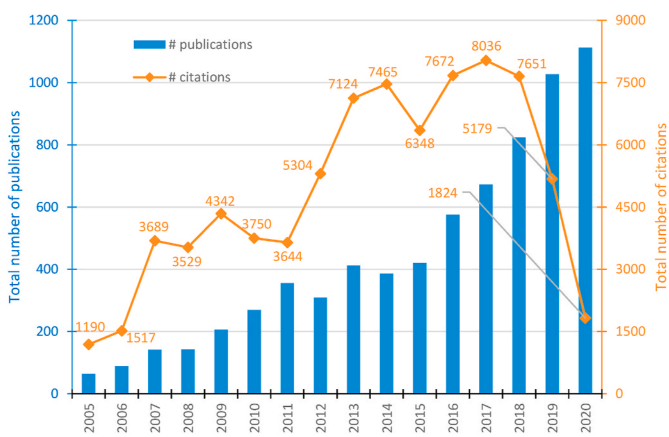

Fig. 3. Evolution of the number of publications and the total number of citations of circular economy in buildings (2005–2020).

documents). However, the number of articles had been increasing significantly since 2008, reaching 1112 records in 2020 with an average annual growth rate of 18.5%. Since the creation of EMF in 2010, the initiatives and researches on the circular economy have become more intense, which contributes and confirms the high interest in the subject in the last five years.

Concerning the evolution of the number of citations, it is similar to the growth in the number of publications (Fig. 3). This evolution is generally increasing, with a growth rate of 11% (the highest growth rate in the number of citations was recorded in 2007) although several ups and downs can be seen. As illustrated in Fig. 3, the total citation number reached a peak of 8036 in 2017, then decreased gradually arguably due to the time required to get influence from the accumulation of new publications. It can be inferred that the topic has not arrived at its maturity stage yet and, likely, will continue to attract considerably more research. As a result of the number of publications and their citations over the period under analysis have been considered as a measure of scientific productivity, influence, and interest in the subject.

3.2. Country/area statistics

In the past 16 years (2005–2020), 122 countries or regions publish on the topic analyzed. Table 2 lists the top 15 countries concerning the total number of publications, total citation, average citation per document, and h-index. Note that in this study, "UK" is a member of the European Union (EU-28) and it includes England, Scotland, Wales, and Northern Ireland, while "China" refers to mainland China, Hong Kong, Macao, and Taiwan.

Of the top 15 countries, eight were from Europe, three from Asia, two from North America, one from Oceania (Australia), and one from South America (Brazil), with any country from Africa. China contributes with 17.6% of the total of the publications, followed by the USA (10.6%). These top 15 countries are the leading players of this emerging topic, accounting for more than 70% of the number of the publication. Worthy to note that the proportion of the articles that involve international collaboration is relatively high (>27%), indicating that the topic is favorable for international cooperation.

Table 2
Top 15 publishing countries in the circular economy in buildings (2005–2020).

Country	TP	TC	SCP	MCP	TC/TP	Local h-index
China	1234	10206	877	357	8.27	54
USA	741	14522	361	380	19.60	58
United Kingdom	615	15316	291	324	24.90	58
Italy	502	6368	344	158	12.69	39
Australia	292	5535	106	186	18.96	36
Spain	283	4015	159	124	14.19	32
Germany	251	3628	109	142	14.45	27
Netherlands	187	4089	80	107	21.87	32
India	186	2586	121	65	13.90	27
Canada	172	4877	83	89	28.35	32
Malaysia	161	1893	84	77	11.76	23
Brazil	146	1637	87	59	11.21	20
Portugal	141	2385	85	56	16.91	23
Sweden	133	2591	55	78	19.48	27
France	122	1938	40	82	15.89	23

TP = Total number of publications, TC = Total number of citations, SCP = Single country publications, MCP = Multiple country publications, Local h-index = h-index calculated from the dataset.

As shown in Table 2, China has contributed most to the body of research. This country, as the first country in the world to adopt a legislation for the development of the CE [97], has been making progress in implementing and developing CE concepts for decades, both in academia and in politics [98]. This prominence is linked to the related top-down laws, policies and regulations [99], such as China's Circular Economy policies, Sustainable Development Goals (SDGs), Chinese indicator sets for the 13th Five Year Plan (2015–2020), the Green Development Indicator System, and the Ecological Civilization Construction Assessment Target System [100]. Furthermore, the high number of publications from European countries reflects the growing sustainability awareness building up in the continent, which is mainly due to the adopting the CE policy by the European Union (EU), *e.g.,* the circular economy package "Towards a circular economy: a zero waste programme for Europe" [101] and "Closing the Loop – An EU Action Plan for the Circular Economy", and its inclination towards sustainability [102]. It seems that the CE-related policies and regulations have been influential in the contribution of other top countries into the CE body of knowledge. In the USA, the dominant bottom-up political approaches have been adopted aiming to enhance circularity, mainly through eco-industrial parks initiatives at a regional scale (*e.g.,* in Baltimore, Maryland; in Brownsville, Texas; and in the Cape Charles Sustainable Technologies Industrial Park in the town of Cape Charles) [103,104].

According to the average citations per paper, Canada, United Kingdom, Netherlands, the USA, and Sweden are the top five countries with prominent academic influence. These countries are also among the top nine countries concerning the local h-index, reinforcing their leading role in the research field. Although China held a leading position in the publication quantity, it is not well-ranked in the indicators related to the influence, which indicates that the quality of their publications varies considerably.

Fig. 4 presents the evolution of the number of documents published for the top 10 productive countries, showing in all cases an increasing trend. China has been the most productive country for all the periods, with two intense growth periods, starting in 2008 and 2015, respectively. Another important finding is the take-up trend for the CE-related publications with contributions by EU countries in 2015. That could be partially explained by the European Commission (EC) strategy on CE, outlined in 2014 and a revised CE package in 2015 [101].

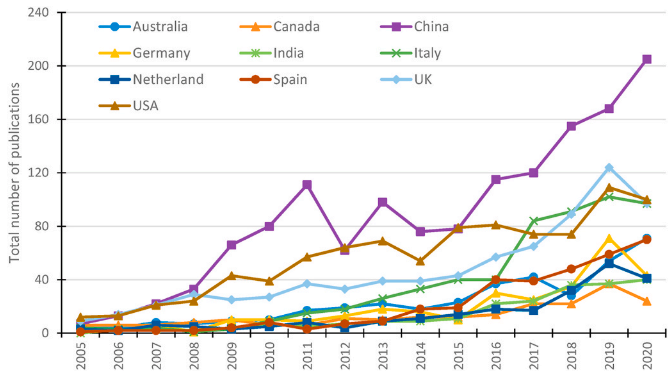

Fig. 4. Trends of publications of the main 10 productive countries in the circular economy in buildings (2005–2020).

Fig. 5 shows the academic interaction between countries through the joint publications based on the authors' affiliation, regardless of the author's order in the publication. In this figure, the node size and the thickness of the links are proportional to the number of published documents and the volume of publications the authors have published together, respectively. To facilitate the analysis, the map only considers countries that have collaborated in at least 25 documents. China, United Kingdom, United States, Australia, Netherlands, Germany, Italy, and Spain perform better than the average in international collaboration. The main interactions are between the European Union (EU) and the USA, followed by collaborations of the USA and China, the EU and China, and Australia and China. From this collaboration network, it can be concluded that the scientific research field of CE in buildings is highly international although the real cases and applications are local. While there are some exceptions, close collaborations between geographically proximate countries can be seen. In addition, except China, the developing and undeveloped countries have few cooperation with developed countries, implying that more cooperation between those countries with the developed countries should be encouraged to address environmental and resource issues at the global level.

Fig. 6 shows the interaction between EU countries. As expected, the five main publishing countries highly interact between themselves, share authorship with all the other countries, and form four clusters: (1) the biggest (in blue) led by Italy, comprises Spain, Portugal, and Greece; (2) led by the UK, includes France, Belgium, Ireland and Luxembourg (in green); (3) led by Germany, includes the Netherlands, Austria, and Czech Republic (in red); and (4) led by Sweden, includes Denmark, Finland and Lithuania (in yellow).

3.3. Institution statistics

Many organizations from academia, government, and industry have an active role in the field analyzed. The top 15 productive organizations based on the number of publications are reported in Table A.1. 12% of the articles were published by authors affiliated with these organizations. Among the 15 most productive research institutions, three are from China, two from Italy, two from Malaysia, and one from the Netherlands, UK, Norway, Iran, Sweden, Portugal, Spain, and Denmark. The Delft University of Technology has the largest number. Moreover, the geographical distribution of the top 15 most productive institutions is relatively limited, showing that the topic more attracted researchers' attention among the developed countries and China.

Fig. 7 shows that the collaboration network between the leading research institutions, with a minimum threshold to appear in the graph of 25 documents published to facilitate the analysis. 39 institutions were identified, forming seven clusters, where each cluster mainly includes

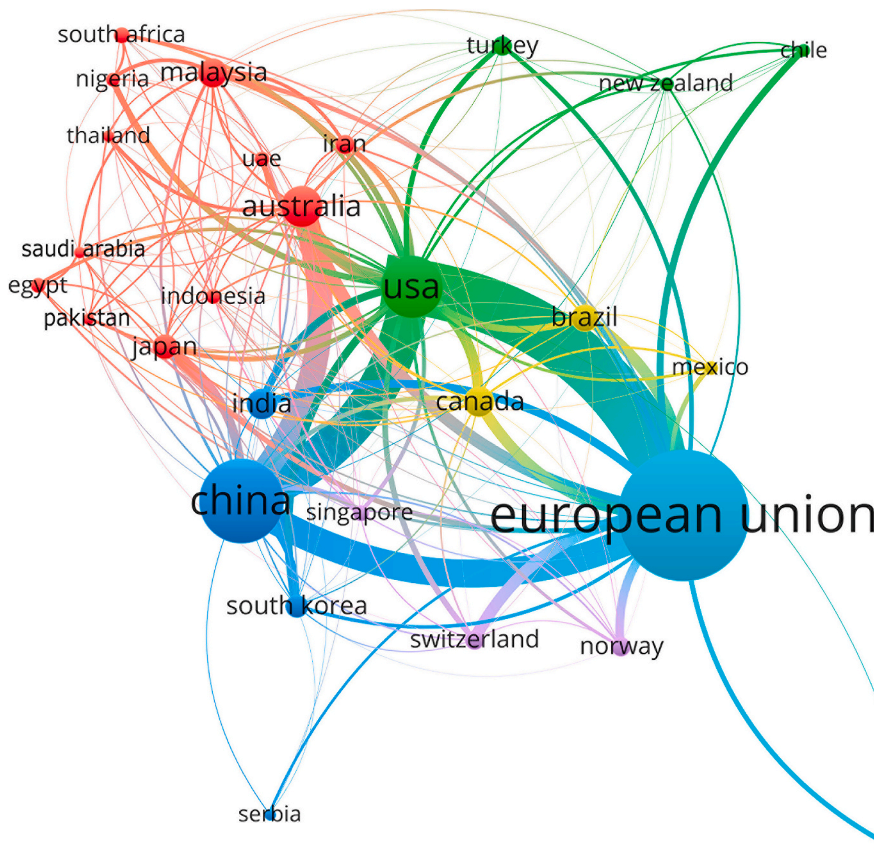

Fig. 5. Co-authorship interaction between countries in the circular economy in buildings (2005–2020).

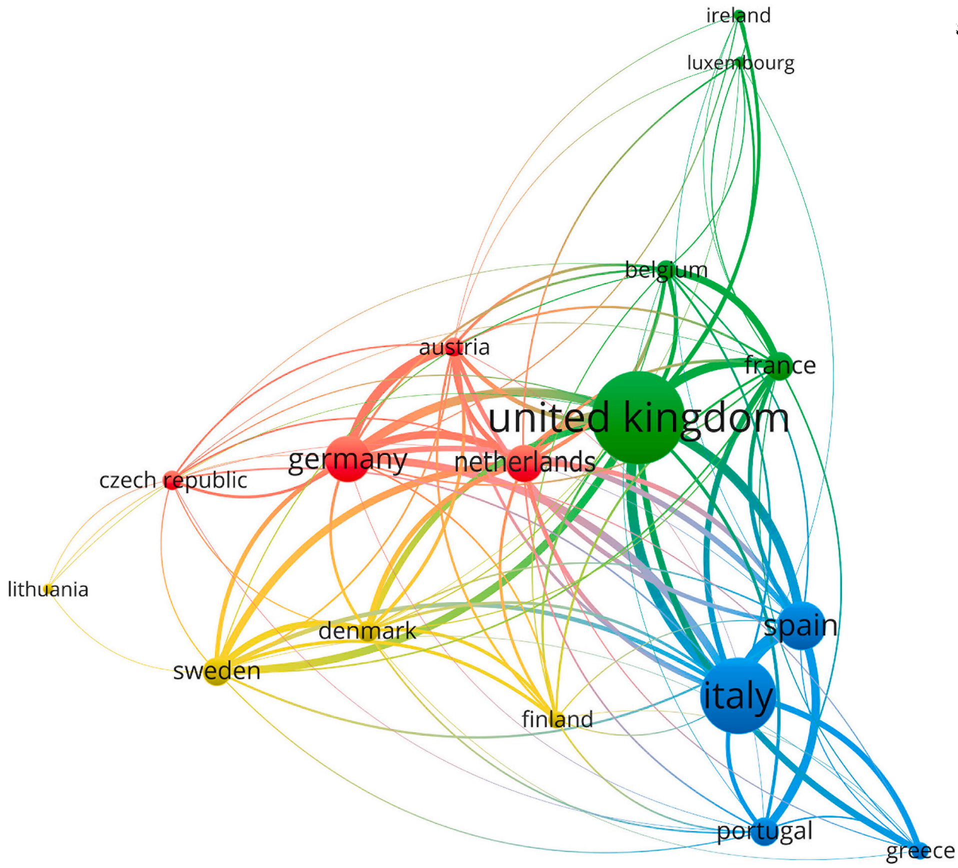

Fig. 6. Co-authorship interaction of EU countries in the circular economy in buildings (2005–2020).

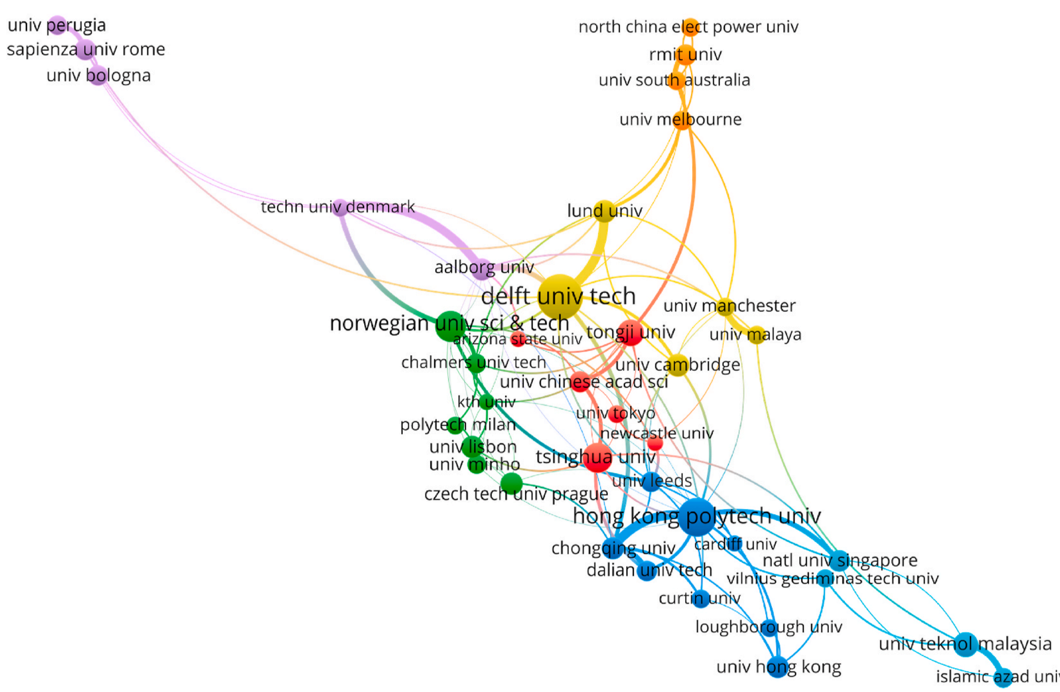

Fig. 7. Collaboration network of institutions in the circular economy in buildings (2005–2020).

institutions from the same country or region. Two reasons could explain this observation: first, it is easier and common that researchers tend to work on topics particularly popular in that region; and second, the co-authorship, implying that two authors present a similar citation profile.

3.4. Journals statistics

Publications in the field of CE in buildings are retrieved from a wide range of journals and different knowledge areas: 2355 journals and conferences. These journals are distributed in different knowledge areas such as environmental science, science and technology, energy, materials science, social science, and economics. This implies that CE theme has widely attracted the attention of many researchers in various fields as a relevant system to promote other areas environmentally and economically. Among the top 15 sources (see Table 3), some of them are from a specific edition of the conferences: IOP Conference Series: Earth and Environmental Science; WIT Transactions on Ecology and the Environment; and International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management (SGEM). The top 15 productive ones publish 27% of the total publications (TP). In particular, the Journal of Cleaner Production (IF = 7.246) was the most productive, with 409 publications (5.8%), followed by Sustainability (IF = 2.576) with 347 articles (5%), and IOP Conference Series: Earth and Environmental Science with 283 records (4%). The Impact Factors (IFs) of the journals were collected from the 2019 Journal Citation Reports (JCR).

The ranking of the source according to the h-index and number of citations are almost equal. In contrast, the conferences have a low h-index and total citations per article (TC/TP), indicating their low impact on the community. The top three publishers according to TC/TP (Journal of Industrial Ecology, Renewable and Sustainable Energy Reviews, and Energy and Buildings), are ranked 15th, 6th, and 4th considering the number of articles, indicating a high quality of the publications of these journals.

3.5. Author statistics

To find the most relevant authors, some bibliometric indicators, such as the quantity of the author's publication, the number of citations received and h-index are used. After debugging the repetition of authors' names, Table A.2 ranks the top 15 contributing authors based on the number of publications. Among them, four came from China; three came from Denmark; two came from Canada; and one from Australia, South Africa, Portugal, Sweden, UK, and Spain.

The most productive author is Yong Geng from Shanghai Jiao Tong University (China), who authored 19 articles. He is also the second most influential author, cited 976 times (*i.e.*, 51 times each), and he has the highest local h-index (16). With respect to the number of publications, Chi Sun Poon with 17 records (13 local h-index) from the Hong Kong Polytechnic University, China, and Vivian WY Tam with 16 records (7 local h-index), from the Western Sydney University, Australia, respectively. As shown in Table A.2, Morten Birkved from the University of Southern Denmark, and Md Uzzal Hossain from the Hong Kong Polytechnic University, are the top-ranked authors with regard to the m-quotient parameter, meaning that they are emerging authors and their publishing productivity was continuing to increase over time and was developed to correct for the duration of author's career. Furthermore, Yong Geng and Chi Sun Poon have the highest g-index, highlighting a high citation count received by their top publications. A remarkable case is that of Nancy Bocken, who with 12 articles co-authored, with an average of 160 per paper. This is mainly due to three highly cited papers, one of them is one of the first review papers published in the domain, while the rests are original research.

The researchers should be aware of the existing collaborations in a research field to prevent from isolation and improve productivity [105]. Fig. 8 illustrates the collaboration network of the key authors. The minimum number of authors' documents has been established on four, and authors without connections are not presented to facilitate the interpretation of the network map. The most influential authors from each cluster can be identified in most of the groups: cluster 1, in red, is led by Yong Geng; cluster 2, in green, is led by Bijia Huang; cluster 3, in dark blue, is led by Md. Uzzal Hossain; cluster 4, in yellow, is led by Chi Sun Poon; cluster 5 in light blue, is led by Jack CP Cheng; cluster 6, in orange, is led by Qinghua Zhu; and cluster 7, in purple, is led by Mingming Hu.

According to the affiliation of main authors in Fig. 8, it evident that the geographical centralization is in EU, Asia, and Australia, and therefore, it is required to conduct more research activities in other continents such as Africa, South America, and North America. Moreover, any research carried out across continents can additionally support cross-cultural awareness [106].

3.6. Research hotspots and evolution

The analysis of keywords in a research field provides an opportunity to discover some underlying information that sometimes is not self-evident. In this study, author keywords, rather than all keywords, were used to obtain a reproducible and readable analysis [107].

Meaningless words such as "research", "problem", "survey", and so on, were removed. The keywords co-occurrence network was produced using VOSviewer software as shown in Fig. 9. The node size represents the frequency, and the relative position of terms in the map reflects their relative association. This bibliometric map is created for the minimum number of keyword occurrences of 37 and contains 69 nodes and 5681 links, grouped into five clusters: (i) energy and energy efficiency in buildings; (ii) recycling, waste management and alternative construction materials; (iii) sustainable development; (iv) circular economy in urban regions; and (v) green buildings and green supply chain within the construction industry. The list of all terms above the threshold is shown

Table 3
Top 15 source journals of the study in the circular economy in buildings (2005–2020).

Sources	TP	TC	TC/TP	Local h-index	IF (2019)	IF (5 years)	Best quartile
Journal of Cleaner Production	409	10508	25.6	48	7.246	7.491	Q1
Sustainability	347	2119	6.1	20	2.576	2.798	Q2
IOP conference series: Earth and Environmental Science	283	196	0.7	5	—	—	—
Energy and Buildings	115	4170	36.3	34	4.867	5.055	Q1
Resources Conservation and Recycling	106	2353	22.2	31	8.086	7.589	Q1
Renewable and Sustainable Energy Reviews	95	3988	42.0	34	12.11	12.348	Q1
Sustainable Cities and Society	82	1043	12.7	18	5.268	5.143	Q1
Construction and Building Materials	69	1827	26.5	20	4.419	5.036	Q1
WIT Transactions on Ecology and the Environment	57	54	0.9	4	—	—	—
Building and Environment	54	1556	28.8	22	4.971	5.459	Q1
International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management	53	32	0.6	3	—	—	—
Building Research and Information	51	1199	23.5	19	3.887	4.036	Q1
Energies	51	311	6.1	9	2.702	2.822	Q1
Waste Management	50	1313	26.3	20	5.448	5.997	Q1
Journal of Industrial Ecology	45	2310	51.3	22	6.539	5.883	Q1

TP = Total number of publications, TC = Total number of citations, TC/TP = Total citations per document, Local h-index = h-index calculated from dataset, IF (2019) = Impact Factor (2019 Journal Citation Reports®), Best quartile = Journals in the 25% top journals of a category are Q1.

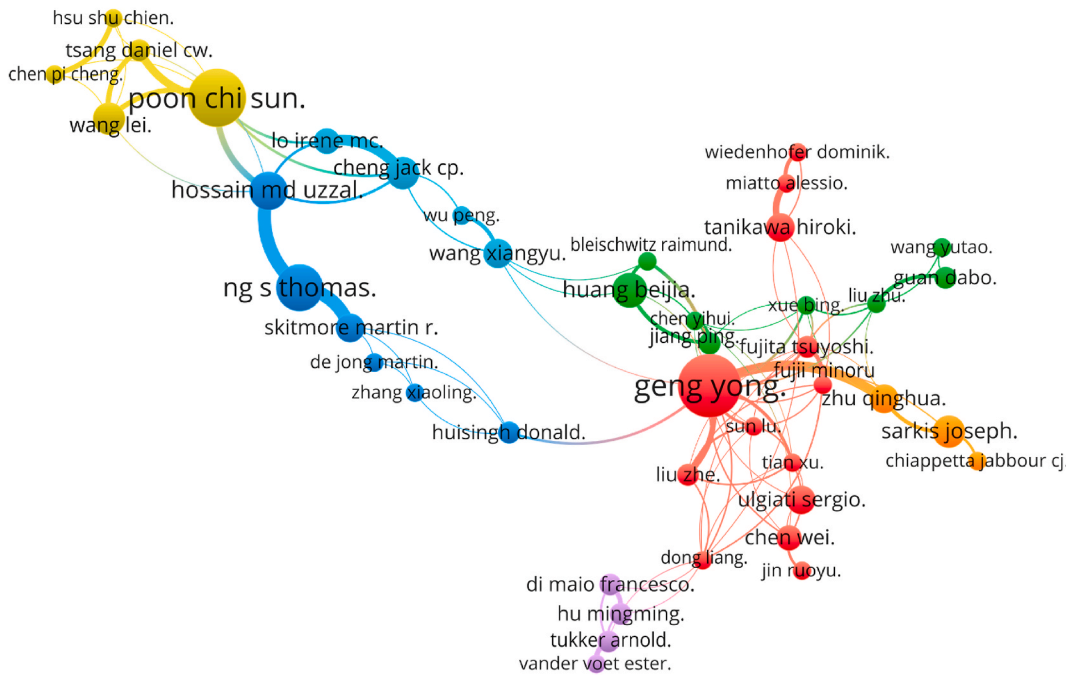

Fig. 8. Collaboration network of authors in the circular economy in buildings (2005–2020).

in the appendix (Table A.3). As can be seen, the map also identifies subtopics of the circular economy, such as recycling, reuse, waste management, energy, and energy efficiency. It also incorporates other concepts that are cross-fertilized with CE, such as industrial symbiosis, industrial ecology, sustainability, and sustainable development.

Cluster #1, in red in Fig. 9, is the most significant cluster with 21 keywords (see Table A.3). The main concerns of this cluster are energy and energy efficiency in the buildings and their corresponding environmental questions, as can be concluded from the terms “energy”, “energy efficiency”, “renewable energy”, “energy consumption”, “energy management”, “buildings”, “building energy”, “energy saving”, “energy performance”, “energy conservation”, “renewable energy”, “embodied energy”, and regarding environmental impacts from “greenhouse gases”, “CO_2 emission”, and “life cycle assessment”.

Focusing on the use of energy in the building is of high importance since the buildings (residential, commercial, and public) are responsible for consuming approximately 60% of global energy [108]. Energy is the main input during the whole life of buildings as it plays a key role in their functioning during their use. The environmental impacts associated with energy use correspond to 10% of global GHG emissions [108]. Improving the energy efficiency is probably the most relevant strategy to increase the life cycle of buildings, resulting in improved living conditions (*e.g.*, occupants’ wellness by dealing thermal comfort), lower energy costs for occupants [109,110], and reduction of environmental impacts caused by building construction and operation (*e.g.*, CO_2 emissions) [111]. Holding a building LCA provides a suitable tool to evaluate options for CE solutions, helping decision-makers to minimize the environmental impact, carbon emission, energy and cost during the whole life cycle of the building [112–114].

The appearance of the terms “refurbishment”, and “retrofitting” may suggest that performing energy retrofitting of the existing buildings, as well as building refurbishment and renovation can help to meet the concerns of the cluster.

Cluster #2, in blue in Fig. 9, has 13 nodes. The key terms of this cluster and their frequency of occurrence are presented in Table A.3. This cluster concerns mainly on recycling, waste management, and alternative construction materials in the building industry, as can be inferred from “recycling”, “waste management”, and other terms “recycled aggregates”, “recycling materials”, “recycling and reuse”, “wastes”, “construction waste”, “construction and demolition waste”, and “building materials”.

Many academic studies, stakeholders organizations, as well as government legislation in recycling and waste reduction argue the possibility of a substantial reduction in environmental impacts of building and construction materials through producing durable products and the greater use of reused/recycled materials/systems instead of natural resources during the production phase [115,116]. This is more and more relevant given the increment in the off-site fabrication of building systems, and the application of advanced technologies in production plants. For instance, it is estimated that the production of cement accounts for 5–7% of the CO_2 generated by human activities and, therefore, the substitution of cement with fly ash or other pozzolanic materials in concrete production reduces its carbon footprint [117]. According to Núñez et al. [118], waste management is one essential of the scales for measuring the CE in the construction sector that can be quantified by assessing the extent to which reducing waste generation, improving the recycling rate of solid waste, reducing the production of hazardous waste, efficient waste management, taking measures to prevent, recycle and eliminate waste, using a bill of solid waste for the manufacturing process.

Cluster #3, in green in Fig. 9, has 15 key terms (Table A.3). The main objective of the articles within this cluster is sustainability while giving the solution to mitigate the environmental impacts. The CE model has been considered as a means for achieving sustainability, and it is perceived as sustainable, which can be inferred from “environment”, “climate change”, “green economy”, “low-carbon economy”, and “low carbon” [119,120]. A sustainable building, in principle, should adopt a triple bottom line approach that addresses the economic, social, and environmental aspects of the entire building life cycle [120]. Achieving high-performance, low-environmental impact sustainable buildings can

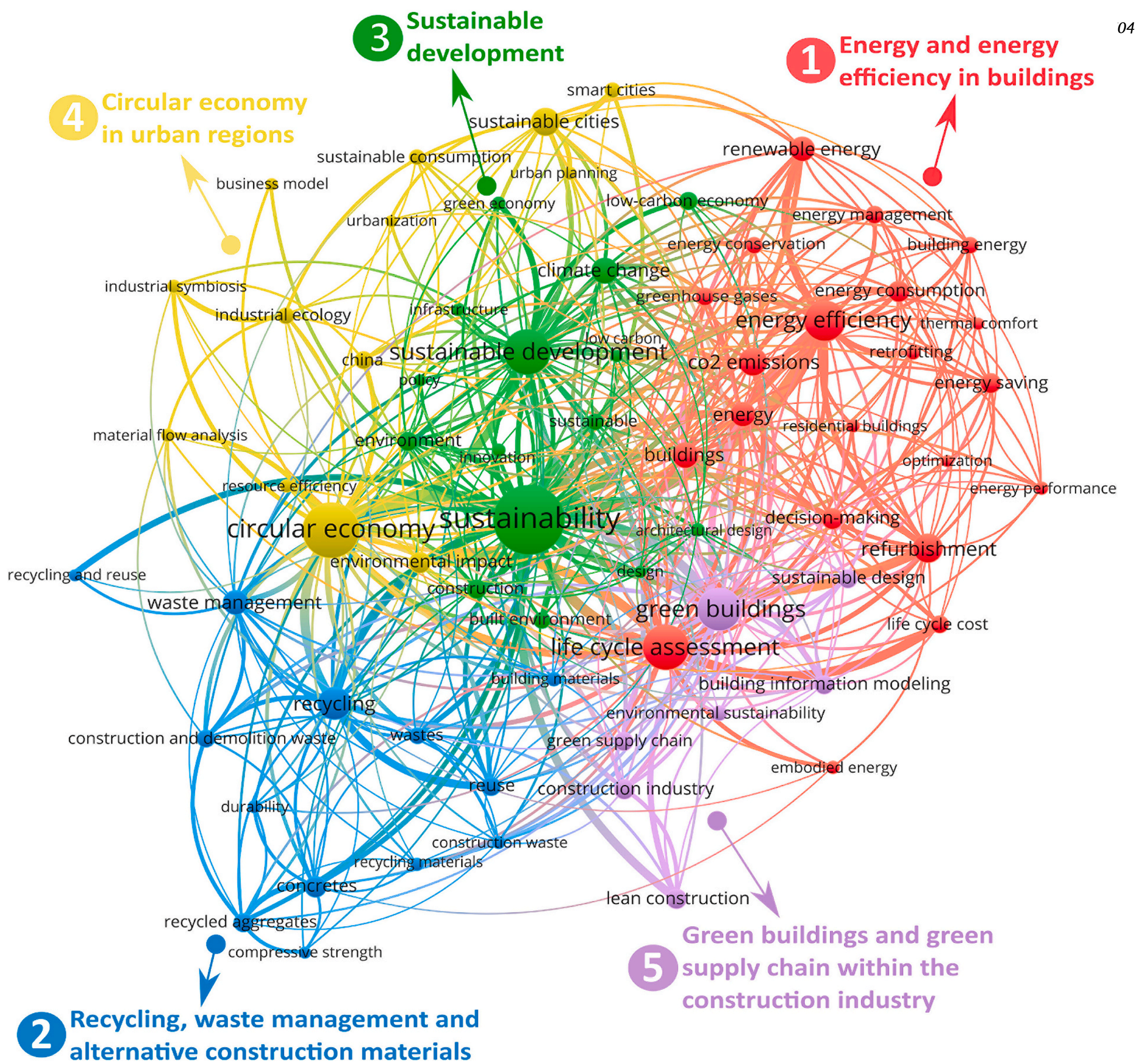

Fig. 9. Map based on co-occurrence on the authors keywords in the circular economy in buildings (2005–2020).

be followed from many aspects, including sustainable materials, sustainable operations, sustainable services, and sustainable consumption to integrate concepts of sustainability in any part of the lifecycle of a building. Here, the importance of two contested topics of technology and innovation for approaching sustainable development should be emphasized. To link economic growth with the state of the art of technology, innovation plays a central role as it can propose solutions to expand the limits of economic growth while considering that the availability of resources is finite [121,122].

Cluster #4, in yellow in Fig. 9, is formed by 15 key terms (Table A.3). Papers within this cluster focus in CE applied to city areas and urban regions, as can be inferred from "circular economy", "industrial symbiosis", "material flow analysis", "sustainable cities", "smart cities", "urban planning", "urbanization", and "transportation". The high frequency of "China" implies that this country is intensely concerned about the application of circular economy concepts in building and urban development.

"Industrial symbiosis (IS)" is a subset of the academic term "industrial ecology (IE)" which again is a subset of the "circular economy" umbrella [123]. IS is a key concept in moving towards sustainable development as it is linked to resource depletion, waste management, and pollution [124]. IE studies industrial systems and aims to identify and implement strategies that reduce their environmental impacts. One of the main focuses of the industrial ecology perspective is on quantitative evaluation of positive environmental impacts of IS using Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) [125].

Regarding city and urban development, to promote a CE of the construction sector, building design and technologies should be focused to reach the maximum amount of reduction, reuse, and recycling of material, practical strategies for energy cascading and symbiotic exchange of resources among different firms, industrial sectors, cities and regions [126].

Cluster #5, in purple in Fig. 9, is the smallest, contains seven nodes (Table A.3). The main objective of this cluster is the green buildings and green supply chain applied to the building industry, as can be concluded from the “green buildings”, “green supply chain”, “construction industry”, “lean construction”, “sustainable design”, and “environmental sustainability”.

Green buildings are designed and constructed following ecological principles [127] and have minimal influence on the natural environment and human health [128], usually consume considerably fewer resources than regular buildings, and promote occupants’ productivity, comfort, and satisfaction by providing quality thermal comfort [129,130]. The concept of lean construction shares the same goal as green buildings, and it emphasizes on the importance of reducing wastes, optimization of flows, and eliminating unproductive and unfruitful processes to approach sustainability objectives [131,132].

As suggested by Sarkis et al. [133], basically green supply chain is about the integration of environmental considerations into the supply chain, including the material flows reduction and the minimization of inadvertent negative consequences of the production and consumption processes [134]. According to Balasubramanian [135], green supply chain management in construction is based on three dimensions: environmental, economic, and operational performance. Addressing the processes involved in construction from an operational perspective, the green supply chain management includes “green purchasing, green manufacturing, green distribution (marketing) and reverse logistics” [134,136].

Fig. 10 shows the research trends based on the keywords analyzed, including the top five most-used author’s keyword per year. A minimum threshold frequency of five has been applied. As a general finding, and in agreement with Figs. 3 and 4, the perspectives of the topic are huge and have a high potential for more and deeper research works.

In the beginning, from 2006 to 2013, the key areas of research were mainly related to CE adoption measures, policies, and frameworks at different levels of countries, regions, etc., as well as the importance of the circular economy from the purely environmental aspects [25]. During 2013–2018, the researchers have focused on the challenges of CE-enabled design as an early-stage measure to promote circulatory, *e.g.,* through design for disassembly and deconstruction using design tools (*e.g.,* BIM) [112]. In the same period, *i.e.*, 2013–2018, addressing the concerns of sustainability and sustainable development as well as energy and energy efficiency within the context of the building industry have been other research areas that have attracted a lot of researchers. Since 2016, there has been some research on introducing potential methodologies for CE evaluation, such as using the LCA framework for evaluating the quantifiable benefits in terms of environmental impacts and associated costs, and materials flow analysis (MFA) for assessing the flow of materials during the entire life cycle [25]. However, there is still a lack of clear mythology and a comprehensive set of indicators to evaluate the CE adoption in sustainable building construction. Recently, 2017–2020, the researchers have focused mainly on (i) material selection, aiming to choose or substitute the construction materials with more circular materials, (ii) development of circular business models, (iii) the relation of CE with new technologies. These three research areas are detailed below as the potential research hotspots.

As shown in Fig. 10 and Cluster #2 (in blue) of Fig. 9, the current leading edge of the literature is the development and the use of alternative construction materials in the building and construction industry [137,138]. The increasing use of green building materials, bio-materials, various types of aggregates in cement, concrete and asphalt, geopolymers, fly ash, solid wastes, plastic and foam, and concrete recycled from demolished buildings can be interpreted in this direction [28,57,139,140]. The production and processing of these materials should lead to lower environmental impacts and decreasing the use of harmful chemicals [140]. Thus, their use can make a significant contribution to the transition to a circular economy.

Another hot topic is the development of circular business models within the building and construction industry [28,141], as emphasized with the recent use of the related terms to “business models” in Fig. 10. The current business models in the field are still based on the linear use of resources [142], and therefore, there is a big need for researching on CE from a systems perspective within the field, including the investigation of using new business models in enabling materials to retain high residual values [28,143].

The other research hotspot is about the link between CE and the Fourth Industrial Revolution (Industry 4.0) in the context of the construction industry. Industry 4.0 is a combination of Cyber-physical systems, the Internet of Things, Big data, and Cloud Computing, which has made possible the human-machine interconnection utilizing the information generated from different smart devices [144]. Industry 4.0 is nowadays considered as a key innovative technology in the transformation from linear to the circular economy in the manufacturing industry [144]. Industry 4.0 can reduce the emission and resource from the industrial systems by optimizing the sustainable solutions [145], and its integration with CE can contribute towards achieving the sustainable development goals [146].

Another featured topic addressed recently is smart cities and its relation to CE and industrial symbiosis. The smart city modeled around the CE principles brings together technology, government, and society within an urban context, promoting sustainable development with a little impact on the environment nature [147–149]. As can be concluded from Fig. 10 and the Custer 4 (in yellow) in Fig. 9, and also highlighted by Borghi et al. [149], future research in smart cities should be directed

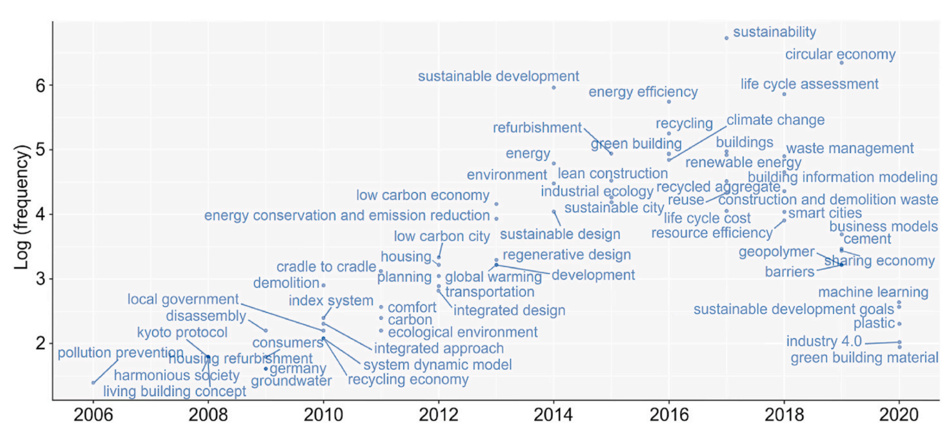

Fig. 10. Map based on authors keywords for trending topics in the circular economy in buildings (2005–2020).

towards industrial symbiosis through the development and implementation of tools for regenerative systems and symbiotic business links.

Fig. 10 also shows that the concepts of "waste management", "life cycle cost", "recycling", "reuse", "recycled aggregates", "building information modeling", the use of "renewable energies", and improving "energy efficiency" and "resource efficiency" have been among the top authors' keywords in the last five years (2016–2020). These findings in along with the keyword co-occurrence network of Fig. 9 emphasize the fact that waste management is well intertwined with CE [150]. This is because of the closed-loop nature of CE which implicates recycling and reuse as well as the shift from raw materials and fossil fuels to renewable energies, resulting to the improvement of resource and energy efficiency, wherein recycling serves as a generalized strategy to reach the goals of CE [151].

4. Conclusion

In the present study, different bibliometric methods were used to analyze 7005 publications of the circular economy within the building and construction sector for 2005–2020. In this regard, the records extracted from WoS and Scopus were merge and were analyzed consequently using Bibliometrix R-package and VOSviewer.

The number of publications has continuously increased with an average annual growth rate of 21%. During the first years, the publication growth was lower, however, since 2014 it has encountered a significant increase. This recent acceleration indicates that CE in the construction sector is a hot area that is receiving more and more attention. Results showed that China is the country with more publications (18% of total), but it has a low number of citations per document, indicating that the impact varies considerably. In terms of the number of publications, the USA (741) and United Kingdom (615) are ranked second and third, respectively. The Delft University of Technology is found to be the most productive institution, followed by Hong Kong Polytechnic University. The majority of the top 15 institutions showed a cooperative relationship with other institutions. Among the authors, Yong Geng (19 publications, local h-index = 16), Chi Sun Poon (17 publications, local h-index = 17), and Vivian WY Tam (16 publications, local h-index = 7) are the most prolific authors. Besides, from the collaboration networks, it concluded that the scientific research field of CE in buildings is highly international although the real cases and applications are local. Therefore, international co-authorships, co-funding, and policy co-programming are relevant for policy options and agendas. In terms of the major sources of publications, the Journal of Cleaner Production (5.8%), Journal of Sustainability (5%), and Journal of Energy and Buildings (1.6%) were the three most influential.

Co-occurrence map and chronological co-occurrence analysis showed that "sustainability", "sustainable development", "life cycle assessment", "green buildings", "energy efficiency", and "recycling" had the most frequency, while "waste management", "life cycle cost", "resource efficiency", "reuse", "recycled aggregates", "renewable energy", and "building information modeling" burst recently (after 2017). In addition, the analysis showed five keyword-clusters, which in order of size and significance, are: (i) energy and energy efficiency in buildings; (ii) recycling, waste management and alternative construction materials; (iii) sustainable development; (iv) circular economy in urban regions; (v) green buildings and green supply chain within the construction industry. Moreover, this paper identified that (i) the development and use of alternative construction materials; (ii) the development of circular business models; (iii) smart cities, Industry 4.0 and their relations with CE, are the current research hotspots that can be considered as future research directions. We believe that further investigation of these interdisciplinary research topics would increase our understanding of the more effective implementation of the CE concepts in the sector, which proves helpful in promoting sustainable construction and addressing the sector's environmental concerns.

As with every research, this study possesses some limitations, mainly related to the intrinsic nature of the bibliometric approach. First of all, keywords were chosen based on previous literature and several trials to ensure scientific significance and avoided pollution in the dataset. However, there may be related works that are not covered by the proposed search, yet more keywords may increase the noise in the sample and the risk of including unrelated articles. Second, this study used both WoS and Scopus. The global perspective may be improved with the inclusion of other databases. Additionally, much effort in driving CE has been made by not-for-profit organizations, supra-national and world organizations and institutions (*e.g.,* the Ellen MacArthur Foundation, European Commission, and United Nations Environment Programme), and has been published as grey literature studies. Even though the applied methodology in this paper is not capable of those reports, it is recommended to include them if a deeper content-related state of the art is of interest. The finding of this study showed an unfair geographical balance of the studies carried out among CE-actors (governments, institutions). Hence, it is encouraged to replicate this study for each continent, or two or more specific countries (especially from developed and in developing countries).

CRediT authorship contribution statement

Masoud Norouzi: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Marta Chàfer:** Methodology, Writing – review & editing. **Luisa F. Cabeza:** Conceptualization, Methodology, Writing – review & editing, Project administration. **Laureano Jiménez:** Validation, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Dieter Boer:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing 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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Appendices.

Appendix A.1

Search query used in WoS and Scopus database:

(TS= ((

("Circular econom*" OR "Circular business model" OR "Circular competence indicator" OR "Circular corporation" OR "Circular ecology" OR "Circular industr*" OR "Circular management" OR "Circular product*" OR "Circular supply chain" OR "Circular technology innovation" OR "Circular transition framework" OR "Circular value chain*" OR "Circulatory econom*")

OR

((("3R" OR "5R" OR "6R" OR "Reutilisation of product*" OR "Reduc* material*" OR "Reduc* water" OR "Reduc* energy" OR "Reduc* emission*" OR "Reduc* greenhouse gas*" OR "Reduc* waste" OR "Recycl* water" OR "Recycl* wastewater" OR "Recycl* material*" OR "Recycl* resource*" OR "Recycl* waste*" OR "Recycl* component*" OR "Recycl* element*" OR "Reus* water" OR "Reus* material*" OR "Reus* waste" OR " Reus* element*" OR "Reus* component*" OR "Design* for reassemb*" OR "Design* for disassemb*" OR "Design* for deconstruct*" OR "Design* for demolition" OR "Design* for adapt*" OR "Material* circularity indicator*" OR "Design* for flexib*" OR "Adaptive design*" OR "Bioeconom*" OR "Biomimicry" OR "Carbon capture and storage" OR "Carbon capture and utilization" OR "Carbon dioxide recovery" OR "Carbon emission reduction" OR "Carbon footprint reduction" OR "Closed loop" OR "CO2 emissions reduction" OR "Collaborative consumption" OR "Collaborative econom*" OR "Collaborative model" OR "Collaborative technolog*" OR "Complex circular ecosystem" OR "Cradle to cradle" OR "Development model in circular" OR "Eco cycle industry" OR "Emission cutting" OR "Emission reduct*" OR "End of life" OR "End of waste" OR "Environmental oriented supply chain cooperation" OR "Environmental supply chain cooperation" OR "Environmentally responsible manufacturing" OR "Extended producer responsibility" OR "Green econom*" OR "Green manufactur*" OR "Green remanufactur*" OR "Green supply chain" OR "Industrial symbiosis" OR "Intra county cyclic econom*" OR "Low carbon city strategies" OR "Low carbon development" OR "Low carbon econom*" OR "Low carbon enterprise" OR "Low carbon future cit*" OR "Low carbon governance" OR "Low carbon hotel" OR "Low carbon innovative system" OR "Low carbon office" OR "Low carbon policy" OR "Low carbon scenario" OR "Low carbon technolog*" OR "Low carbon transition" OR "Optimal model circular" OR "Refurbishment" OR "Regenerative design" OR "Regenerative econom*" OR "Remanufacturing" OR "Resource recirculation" OR "Resource recovery" OR "Restorative econom*" OR "Sharing cit*" OR "Sharing econom*" OR "Sharing societ*" OR "Sharing value system" OR "Sustainable business model" OR "Sustainable cit*" OR "Sustainable consumption" OR "Sustainable industrial development" OR "Sustainable logistics" OR "Sustainable materials management" OR "Sustainable resource use" OR "Sustainable supply chain network" OR "Sustainable waste management" OR "Waste prevention" OR "Waste recovery" OR "Waste reduction" OR "Waste to energy" OR "Waste to materials" OR "Waste to resource" OR "Waste to value" OR "Zero emissions" OR "Zero waste" OR "Lean construction*")

OR

("Reduc*" AND "Reus*" AND "Recycl*"))

AND

("Sustainability" OR "Sustainable")))

AND

("Building*" OR "Construction*")))

OR

("Building circularity" OR "Circular construction*" OR "Circular building*"))

. (*continued*).

Appendix A.2

Table A.1
The top 15 most productive institutions in the circular economy in buildings (2005–2020)

Affiliations	Number of publications	Country
Delft University of Technology	116	Netherlands
Hong Kong Polytechnic University	89	China
Tsinghua University	77	China
Norwegian University of Science and Technology	74	Norway
Tongji University	69	China
University of Technology Malaysia	64	Malaysia
University of Cambridge	56	United Kingdom
University of Lisbon	55	Portugal
University of Bologna	50	Italy
Lund University	49	Sweden
Islamic Azad University	49	Iran
Sapienza University of Rome	48	Italy
Polytechnic University of Madrid	47	Spain
Aalborg University	45	Denmark
University of Malaya	45	Malaysia

Appendix A.3

Table A.2
Top 15 most productive authors in the circular economy in buildings (2005–2020)

Author	Affiliation	Country	TP	TC	TC/TP	Local h-index	Local g-index	Local m-quotient
Geng Yong	Shanghai Jiao Tong University	China	19	976	51.4	16	19	1.1
Poon Chi Sun	The Hong Kong Polytechnic University	China	17	551	32.4	13	17	0.9
Tam Vivian WY	Western Sydney University	Australia	16	261	16.3	7	16	0.5
Birgisdottir Harpa	Aalborg University	Denmark	15	55	3.7	5	7	0.8
Aigbavboa Clinton O	University of Johannesburg	South Africa	14	15	1.1	2	3	0.4
de Brito Jorge	University of Lisbon	Portugal	13	454	34.9	8	13	0.5
Ng S Thomas	University of Hong Kong	China	13	145	11.2	7	12	0.7
Birkved Morten	University of Southern Denmark	Denmark	13	96	7.4	6	9	1.2
Bocken Nancy	Lund University	Sweden	12	1921	160.1	9	12	1
Oyedele Lukumon O	University of West of England (UWE)	United Kingdom	12	262	21.8	7	12	0.7
Haas Carl	University of Waterloo	Canada	11	81	7.4	5	9	1
Sanchez Benjamin	University of Waterloo	Canada	11	72	6.5	4	8	1
Hossain Md Uzzal	The Hong Kong Polytechnic University	China	10	244	24.4	8	10	1.3
Garcia Navarro Justo	Universidad Politécnica de Madrid	Spain	10	107	10.7	5	10	0.6
Nygaard Rasmussen Freja	Aalborg University	Denmark	10	50	5.0	4	7	0.7

TP = Total number of publications, TC = Total number of citations, TC/TP = Total citations per document, Local h-index = h-index calculated from dataset, Local g-index = g-index calculated from dataset, Local m-quotient = m-quotient calculated from dataset.

Appendix A.4

Table A.3
List of author's keyword occurrence and their frequency in the circular economy in buildings (2005–2020)

Cluster 1	building energy (70); buildings (145); CO2 emission (177); decision-making (105); embodied energy (47); energy (132); energy conservation (65); energy consumption (107); energy efficiency (330); energy management (73); energy performance (43); energy saving (98); greenhouse gases (79); life cycle assessment (391); life cycle cost (74); optimization (41); refurbishment (180); renewable energy (140); residential buildings (43); retrofitting (56); thermal comfort (40)
Cluster 2	building materials (53); compressive strength (39); concretes (102); construction and demolition waste (78); construction waste (33); durability (49); recycled aggregates (84); recycling (224); recycling and reuse (37); recycling materials (49); reuse (88); waste management (132); wastes (70)
Cluster 3	architectural design (48); built environment (65); climate change (151); construction (83); design (40); environment (88); green economy (46); infrastructure (38); innovation (43); low carbon (40); low-carbon economy (75); policy (41); sustainability (837); sustainable (67); sustainable development (388)
Cluster 4	business model (39); China (75); circular economy (569); environmental impact (107); industrial ecology (71); industrial symbiosis (44); material flow analysis (44); resource efficiency (49); smart cities (61); sustainable cities (170); sustainable consumption (59); urban planning (48); urbanization (38)
Cluster 5	building information modeling (89); construction industry (95); environmental sustainability (57); green buildings (367); green supply chain (83); lean construction (92); sustainable design (90)

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