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Review Article

A Systematic Analysis of Life Cycle Assessment Studies during 2000-2022

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Abstract
Life cycle assessment (LCA) is a widely recognized tool for environmental assessment, which has experienced a strong development both in methodology and applications. This paper aimed to perform a bibliometric analysis of LCA research during 2000-2022, considering publication types, publication trends, subject categories, journals, institutions, countries, and author keywords. Social Network Analysis was applied to recognize mapping trends, status, and hot spots in LCA research and to discover co-authorship relations and international collaborations among countries worldwide. The results of this study showed that the number of LCA publications has remarkably increased by more than tenfold over the study period. The United States, with 5885 publications (17.3%), was the most productive country in terms of the number of publications. The keywords "sustainability," "environmental impact," "carbon footprint," "circular economy," "recycling," and "climate change" were the most occurred keywords in the literature. The keyword "sustainability," growing from 221 in 2000-2011 to 2013 in 2011-2022, was the most trending keyword. The keywords "water footprint," "biogas," and "GHG emissions" exhibited the highest increase in frequency, with growth rates of 18.5, 11.2, and 7.1 times, respectively. The outcomes of this study showed the cumulative progression of the literature, thereby establishing a framework for future works in LCA research.
Keywords: Bibliometric Analysis, Life Cycle Assessment (LCA), Research Trend, Social Network Analysis (SNA)

Introduction

The world is experiencing a rise in population and escalating levels of consumption. This surge in demand is intensifying the pressure on limited natural resources, highlighting the necessity for their sustainable management. In addition, the global climate change crisis has recently put forward serious considerations to environmental impacts, especially in the recent decades (Minghua et al., 2009; Korai et al., 2017; Chand Malav et al., 2020; Sabour et al., 2020a).

The idea of life cycle assessment (LCA) was conceived in the 1960s when environmental degradation and in particular, the limited access to resources started becoming a concern (Hauschild et al., 2018). LCA addresses environmental aspects and potential environmental impacts during a product's life cycle from raw material exploitation through production, use,

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end-of-life treatment, recycling, and final disposal. LCA is also recognized as a reference method for decision support in the policy context (Sala et al., 2020). The use of LCA in research, industry, and policy-making is continuously increasing, as can be seen, for instance, in the annual increase in scientific LCA publications (McManus and Taylor, 2015) and an observed increase in the number of published LCA-based environmental product declarations in the industry (Toniolo et al., 2019; Sabour et al., 2020b; Gradin and Björklund, 2021).

The large number of publications along with the variety of discussion have been encouraging many researchers globally to investigate LCA research and summarize the related literature. Villanueva and Wenzel (2007) provide a systematic examination of life cycle assessments (LCAs) on paper and cardboard waste. Finnveden et al. (2009) review methodological developments in previously published LCA researches. Cleary (2009) presents a comparative analysis of 20 process-based LCAs of municipal solid waste (MSW) published between 2002 and 2008 in a total of 11 English-language peer-reviewed journals. Considering some properties of social networks, De Souza and Barbastefano (2011) indicate the spread of LCA studies and the configuration of a collaboration network based on co-authorship relations among researchers. Cherubini and Strømman (2011) perform a review of bioenergy LCA literature. Finnveden et al. (2009) present an overview of research trends in LCA and introduce life cycle sustainability analysis (LCSA) as a growing concept, a transdisciplinary integration framework of models rather than a model in itself. Muench and Guenther (2013) present a systematic review of environmental impacts of biomass electricity and heat LCAs. Hellweg and Canals (2014) review recent developments in LCA, including existing and emerging applications aimed at supporting environmentally informed decisions in product development and procurement, policy-making, and consumer choices.

Cabeza et al. (2014) summarize and organize the literature on life cycle assessment, life cycle cost analysis (LCCA), and life cycle energy analysis (LCEA) studies carried out for environmental assessment of buildings and building-related industry. Willers and Rodrigues (2014) present a critical evaluation of the life cycle assessment studies in the main scientific bibliographic databases (online and free access) of Brazil where the LCA methodology could be considered. Chen et al. (2014) gain insight into the publication performance of global LCA research, discover its intellectual structure, and pursue its evolution through the application of a bibliometric method with visual mapping. Using bibliometric techniques, Hou et al. (2015) explores the characteristics and implications of LCA literature published during 1998-2013. Mattioda et al. (2015) analyzes the bibliographies (papers and authors) as a basis to support the application of social life cycle assessment (SLCA) concept in product performance. Güereca et al. (2015) present a review of the history of the application of LCA in Mexico over a 15-year period, using information obtained from bibliographic research. Chau et al. (2015) provide a review on three streams of life cycle studies that have been frequently applied to assess the environmental impacts of building construction with a focus on whether they can be used for decision making. Geng et al. (2017) Wang examine building LCA-related literature, published between 2000 and 2014, by means of bibliometric methods. Li et al. (2018) provide an up-to-date bibliometric view about the current life cycle assessment for bioenergy. Visentin et al. (2019) Trentin perform a systematic and bibliometric analysis of scientific articles indexed in the databases of Scopus and the Web of Science in the field of LCA, particularly studies relating to the remediation of contaminated sites from a sustainability point of view. Mirabella et al. (2019) comprehensively present the application of LCA at city scales, emphasizing good and working points to identify and address future research agendas appropriately.

The reason for conducting the present study was the lack of a comprehensive understanding in the existing literature on LCA research despite the valuable studies presented during the past decades. The above-mentioned studies are mostly topic-specific; therefore, not covering the whole literature. In addition, the applied methodologies are not able to accurately reflect the

trends procedures. Thus, an in-depth study was strongly required to clarify the literature. This paper aimed to systematically describe the global status and trends in LCA research through the application of a thorough bibliometric and social network analysis (SNA), considering the period 2000-2022. The methodology was applied in an organized manner, focusing on clustering and network analysis.

Material and Methods

Bibliometric method and SNA were utilized to investigate trends and to specify the LCA research characteristics. As shown in Figure 1, the bibliometric method is based on five major steps (Sabour et al., 2020a):

1. Determining the units of analysis: This task entails the identification of the distinct units of analysis. These units can encompass countries, authors, articles, journals, or any other entities that hold relevance to the subject of research. This initial stage constitutes an indispensable first step within the realm of bibliometric analysis.
2. Deciding on the best database, and the most pertinent keywords: This step involves selecting a preferred database and using appropriate keywords and their combinations to narrow down the search results by applying specific dataset limitations.
3. Collecting data: The next step involves collecting data about the earlier choices and filtering them to the most related ones.
4. Analyzing the data: Following the data gathering, it is subjected to analysis using various bibliometric methodologies. This procedure involves evaluating the impact of a certain publication, monitoring the progress of a topic, or identifying the characteristics of publications.
5. Interpretation of the findings: Once the data has been examined, the conclusions are deduced through the process of interpretation. This may entail the recognition of trends, patterns, or connections within the data.

Figure 1. The major steps involved in a bibliometric analysis (Sabour et al. 2020a)

In this study, Scopus was used as the database for searching and obtaining the data. The reason for using Scopus database was that it has a considerably advanced coverage of abstract and citation as compared to other databases (Borthakur and Govind, 2018; Sabour et al., 2023). The keyword “life-cycle-assessment” was used in the search bar as title, abstract, and keywords over the period 2000-2022. Source type, subject area, document type, affiliation, author, journal, country, institution, and keywords were comprehensively investigated. A variety of document types, including Articles, conference papers, reviews, book chapters, notes, articles in press, editorial materials, short surveys, letters, conference reviews, books, editorial, notes, and books were achieved. The country of each publication was determined based on the nationality of at least one of the author's affiliations. Also, impact factor (IF), H-index, subject area, country and publisher of each journal were determined from journal citation reports (JCR), SCImago journal rank (SJR) and Elsevier.

SNA was applied to discover the relationship amongst different countries or the author keywords in various clusters of the network structure (Wang et al., 2016a). VOSviewer 1.6.19, one of the most practical visualization tools for performing SNA (Hatami et al., 2022), was utilized for performing the SNA method and creating bibliometric maps.

Results and Discussion

Chronological trends, distribution, and characteristics of publications

As shown in Figure 2, the significant portion of the publications was related to journal articles and conference papers. The total number of LCA-related publications (33864) include 67.6% journal articles (22905), 16.7% conference papers (5652), 7% reviews (2387), 5.4% book chapters (1825), 0.6% Conference Reviews (197), 0.5% book (177), 0.5% editorial (176), 0.4% notes (151), and a few short surveys, erratum, data papers, and abstract reports during 2000–2022.

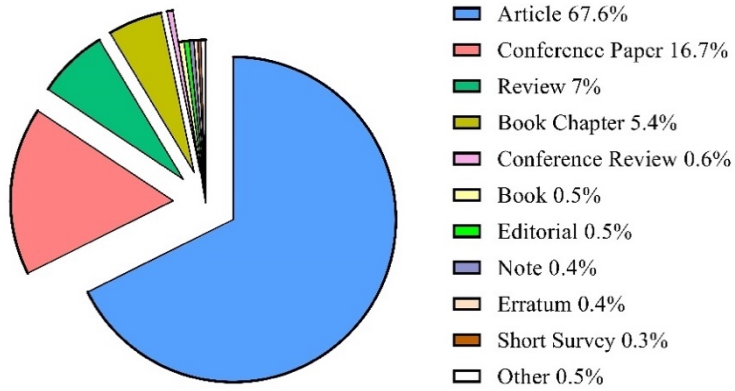


Figure 2. The distribution of various types of publications during 2000-2022

The annual number of LCA publications and the number of citations is shown in Figure 3. The LCA-related publications increased from 224 in 2000 to 4225 in 2022, with a noteworthy increase in 2012, 2017, and 2021. The annual number of citations considerably increased from 10301 in 2000 to 53776 in 2010, after which it reached a peak of 76688 in 2017, showing remarkable attention to the LCA topic. Then, it decreased to 20958 in 2022 because recent publications have not been cited widely.

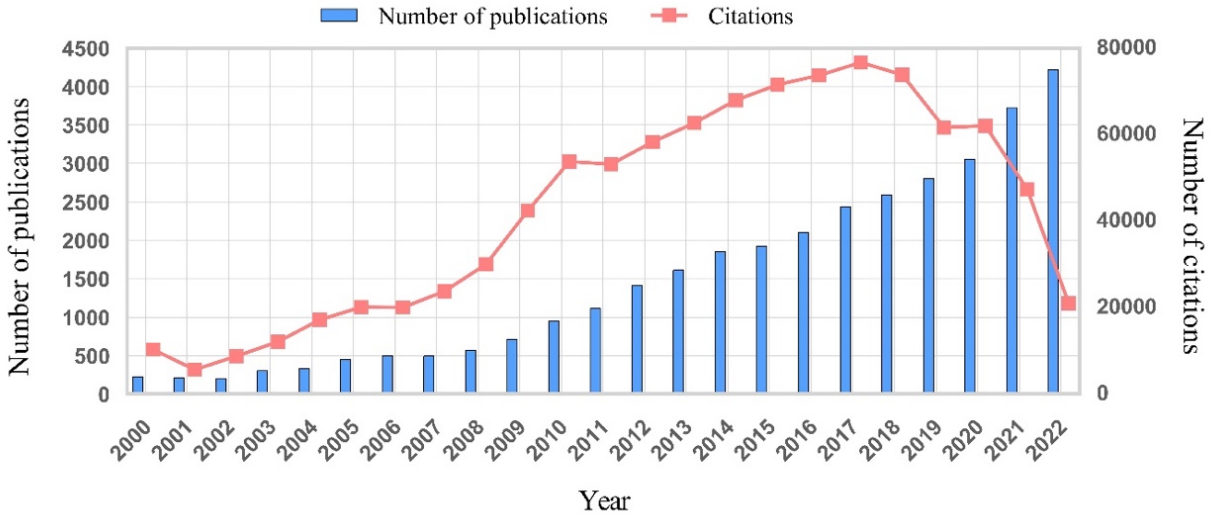


Figure 3. The trend of publications and citations by year

Analysis of subject categories

Research on life cycle assessment encompasses a vast array of academic disciplines. The selected publications are classified into 27 distinct groups according to the Scopus categorization system. It is important to note that a single document might fall under more than one category. This article focuses only on subject categories that make up more than 2% of the selected documents. As shown in Figure 4, environmental studies are prominent among the selected publications. Environmental science makes up 26.8% of publications. Subsequently, Engineering is responsible for 19.2% of all documents, and Energy is responsible for approximately 15.1% of all documents. The sum of the remaining subject categories accounts for 38.9% of the total.

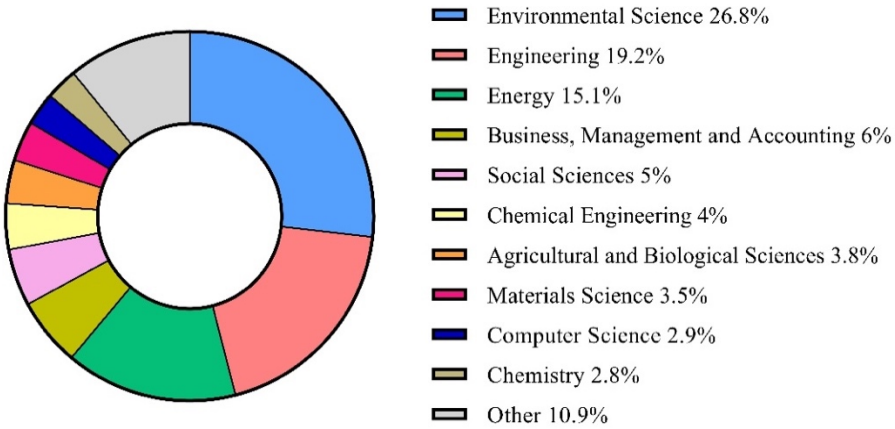


Figure 4. The most major subject categories in LCA research

Analysis of journals

Table 1 displays the ten most-productive journals with the highest number of published papers in LCA research within the study period with their respective impact factors, H-indexes, subject areas, countries, publishers, and the number of publications. One of the most common indicators to consider the article's value, the researchers who wrote those articles, and even the institutes they work in is the Impact Factor (Amin & Mabe, 2000). The Impact Factor (IF) corresponds to the average number of citations an article published during the two preceding years receives in a given year (Hatami et al., 2021). H-index is defined as the h number of articles with at least h number of citations each (Hirsch, 2005). All the information given in Table 1 has been gathered from "Scopus" and "SJR."

As shown in Table 1, 10678 articles (31.5% of all) are published in the ten journals, among which there are seven with more than 600 publications. Elsevier has been the most productive publisher in the field, and the United States, with four journals, is the leading country. In addition, the "Journal of Cleaner Production" which is ranked 4rd in IF (11.1) and 3th in H-index (268), published the highest number of articles (3357, 9.9%), followed by the "International Journal of Life Cycle Assessment" (2362, 6.9%), "Sustainability" (1051, 3.1%) and the "Science of The Total Environment" (791, 2.3%). Also, "Resources Conservation and Recycling" and "Environmental Science and Technology" had the highest IF (13.2) and H-index (456), respectively.

Figure 5 compares the trends of the top five journals with the highest number of articles. The difference in the growth schema was significant between the "Journal of Cleaner Production" and the other journals. The number of LCA-related articles in the "Journal of Cleaner Production" increased significantly during 2013- 2018.

Table 1. The top ten most productive journals in terms of number of publications in LCA research during 2000-2022

#	Source	Number of Publications	Impact Factor (2022)	H-index (2022)	Subject area	Country
1	Journal of Cleaner Production	3357	11.1	268	- Business, Management and Accounting - Energy Engineering - Environmental Science	United States
2	International Journal of Life Cycle Assessment	2362	4.8	123	- Environmental Science	Germany
3	Sustainability	1051	3.9	136	- Energy - Environmental Science - Social Sciences	Switzerland
4	Science of the Total Environment	791	9.8	317	- Environmental Science	Netherlands
5	Resources Conservation and Recycling	737	13.2	170	- Economics, Econometrics and Finance - Environmental Science	Netherlands
6	Environmental Science and Technology	612	11.4	456	- Chemistry - Environmental Science - Medicine	United States
7	Journal of Industrial Ecology	604	5.9	123	- Economics, Econometrics and Finance - Environmental Science - Social Sciences	United States
8	Waste Management	402	8.1	201	- Environmental Science	United States
9	Energies	386	3.2	132	- Energy - Energy Engineering and Power - Technology Engineering - Environmental Science - Mathematics	Switzerland
10	Applied Energy	376	11.2	264	- Energy - Engineering - Environmental Science	United Kingdom

As expected, a large number of LCA-related articles have been published in the "International Journal of Life Cycle Assessment," which is also implied by the journal name. Although this had been the most productive journal in the field until 2013 (in terms of the number of articles), from 2014 onwards, the "Journal of cleaner production" has noticeably overtaken it. Interestingly, "Sustainability" has been one of the leading journals since its inception was in 2013.

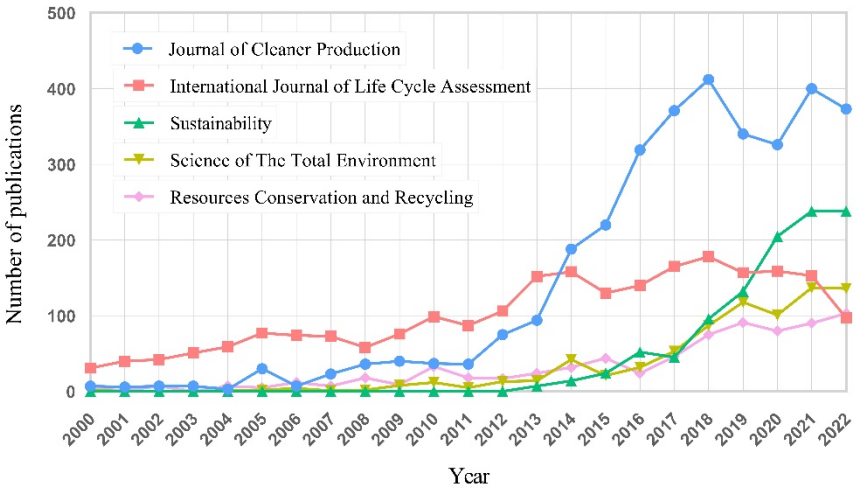


Figure 5. The growth trends of the top five journals in LCA research

Analysis of institutions

The dispersion of various publications by countries and institutions was analyzed based on at least one author of the publication. Table 2 displays the top ten most productive institutes from 2000-2022, with more than 300 publications related to LCA. The Technical University of Denmark had the most publications amongst these institutes, with 671. The first to fourth rankings are attributed to European institutions, whereas Chinese institutions occupy the fifth to seventh rankings. Notably, the top ten productive institutions do not include any institutions from the United States.

Table 2. The ten most productive institutes in LCA research during 2000-2022

#	Affiliation	Country	Number of Publications
1	Technical University of Denmark	Denmark	671
2	ETH Zürich	Switzerland	517
3	Norges Teknisk-Naturvitenskapelige Universitet	Norway	412
4	Chalmers University of Technology	Sweden	383
5	Ministry of Education China	China	377
6	Chinese Academy of Sciences	China	328
7	Tsinghua University	China	319
8	The Royal Institute of Technology KTH	Sweden	318
9	Universiteit Leiden	Netherlands	309
10	The University of Santiago de Compostela	Spain	304

Analysis of countries

Figure 6 depicts the worldwide dissemination of literature associated with LCA published from 2000 to 2022, categorizing the 195 countries of the world into nine distinct groups. Notably, the United States stands alone as the sole region to have produced more than four thousand publications on LCA.

The publications were from 141 countries, 17 of which had only one publication, and 628 (1.8%) articles had no author address information. The top ten most productive countries for total publications are shown in Table 3. More than 77% (26363) of the total articles were related to these countries. Mono-national publications demonstrate the publications that all their authors are from affiliations of one country.

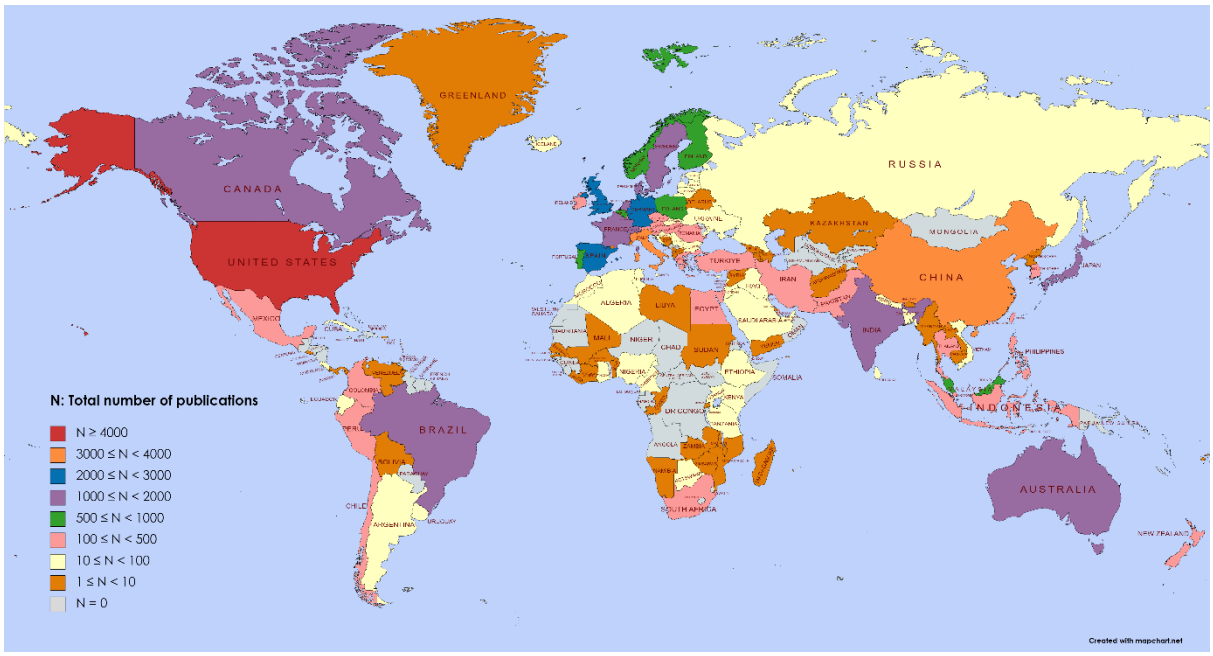


Figure 6. Geographical distribution of LCA research

In contrast, the multinational publications category represents those whose authors are from different countries (Hatami et al., 2021). The United States, with 5885 articles (equal to 17.3% of all articles in this field), ranked 1st. According to the data listed in Table 3, 31.5% of these articles have been cooperated with other countries, while 68.5% were exclusively published from the United States. China (3938) ranked as the 2nd in publication position, followed by Italy (3182) and Germany (2688). Six of the seven countries Group (G7: Canada, France, Germany, Italy, the United Kingdom, Japan, and the United States) as the largest IMF-advanced economies ranked in the top ten as presented in Table 3. They are countries with growing investigation. The Netherlands, with 63.4% of the total number of Dutch LCA publications, ranked 1st in multinational publications. In contrast, with 65.1% of the total number of American LCA publications, the United States ranked 1st in independent publications.

Table 3. Top ten most productive countries in LCA research during 2000-2022

#	Country	Total LCA publications	Mono-national publications	(%)	Multinational publications	(%)
1	United States	5885	3831	65.1%	2054	34.9%
2	China	3938	2521	64.1%	1417	35.9%
3	Italy	3182	2014	63.3%	1168	36.7%
4	Germany	2688	1549	57.7%	1139	42.3%
5	United Kingdom	2504	1058	42.3%	1446	57.7%
6	Spain	2367	1201	50.8%	1166	49.2%
7	France	1596	703	44.1%	893	55.9%
8	Canada	1503	740	49.3%	763	50.7%
9	Sweden	1380	738	53.5%	642	46.5%
10	Netherlands	1320	483	36.6%	837	63.4%

The growth trends of publications in the top five countries are shown in Figure 7. The results specified that the United States was significantly prominent in LCA publications throughout the period. It had the highest increase rate and the fastest growth from 48 articles in 2000 to 471 in 2022, while it experienced the highest growth rate between 2008 and 2014. China and

Italy were the following two countries in terms of publication growth. China has grown significantly in the last three years, becoming the leading country in LCA publications since 2021.

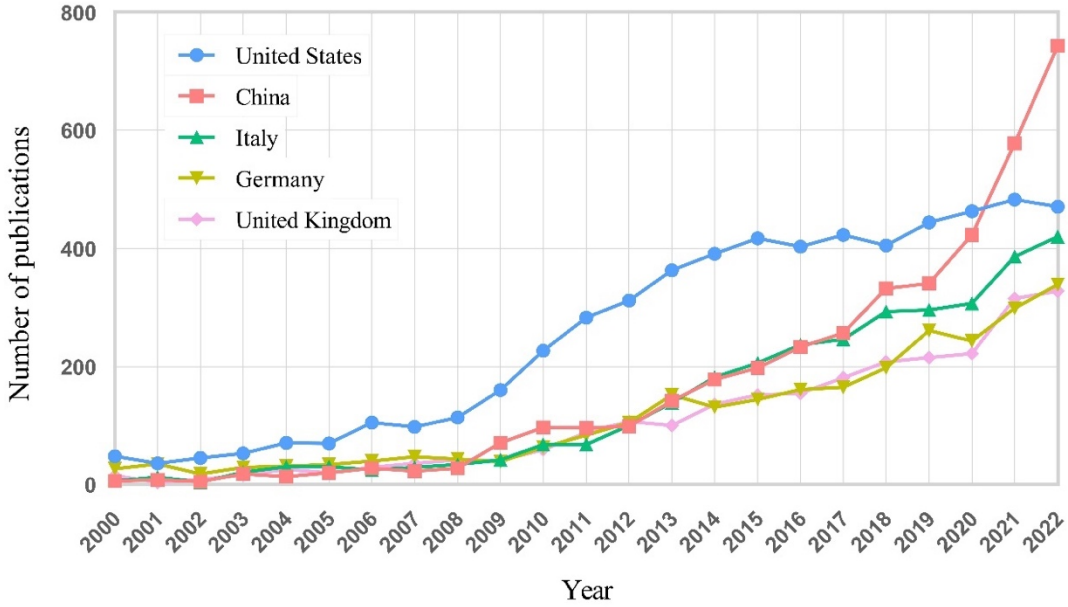


Figure 7. The growth trends of the ten most productive countries in LCA research

Based on co-authorship analysis, coauthoring relationships amongst the most productive countries in the field of LCA were described by employing VOSviewer software. As shown in Figure 8, the United Kingdom had the most significant number of cooperations with other countries (75) in LCA publications, followed by Germany (73), the United States (72), China (69), and Italy (69). The most significant citations were related to the United States.

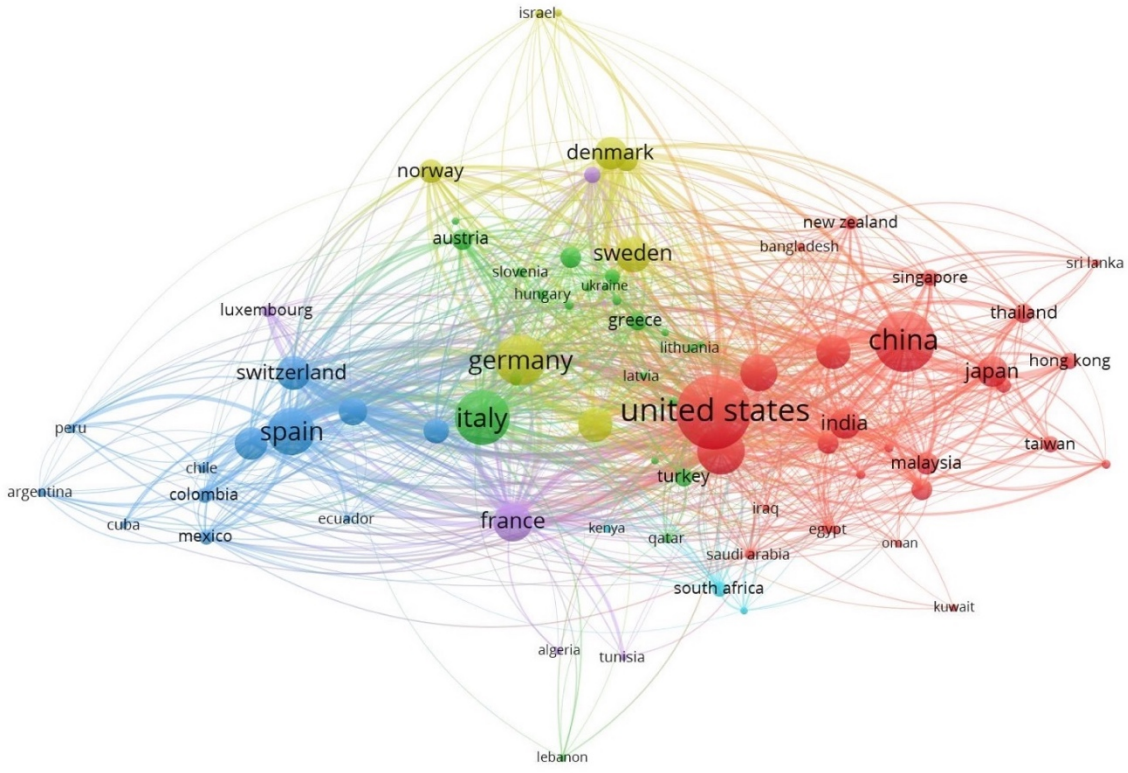


Figure 8. Collaboration relationships between the most productive countries in LCA research

Analysis of author keywords

A total of 45726 author keywords were obtained, while cluster analysis was undertaken to ascertain principal research trends, according to the author keywords, during 2000-2022. The nodes symbolize author keywords. So, the greater the size of the nodes, the higher the repetition of the keywords (Wang et al., 2016). The color of nodes indicates the related cluster of concentrated keywords on the bibliometric identified by VOSviewer.

The top 1000 keywords distributed in five clusters are displayed in Figure. 8. Several different components are included in the map. The most frequently used keywords such as “life cycle assessment,” “LCA,” “life cycle assessment (LCA),” and “life-cycle assessment,” with 12797, 3088, 2543, and 1152 occurrences have been eliminated to clarify the concentration of other keywords in the overlay visualization network map.

According to Figure 9, the author keywords are classified into five clusters, each of which contains at least 100 keywords, while the largest cluster is cluster 1 with 263 keywords, and the smallest one is cluster 5 with 127.

Cluster 1 (red) is strictly related to the publications aiming at sustainability and energy, by covering keywords such as “sustainability,” with the most occurrence among the existing keywords of all groups, “sustainable development,” “sustainability assessment,” “energy consumption,” “embodied energy,” and “energy efficiency.” Keywords of cluster 2 (green) mainly belong to studies covering global warming, by keywords such as “carbon footprint,” “climate change,” “global warming,” “greenhouse gas,” and “GHG emissions.” Cluster 3 (blue) mainly belongs to analytical issues. Keywords such as “uncertainty,” “uncertainty analysis,” “material flow analysis,” “scenario analysis,” “risk assessment,” and “Monte Carlo simulation” could be found obviously among the most-repeated keywords of this cluster. However, other keywords are also found among these harmonious keywords, including “environment,” “life cycle inventory,” and “impact assessment.” Environmental and bio-related topics are found in cluster 4 (yellow). “Recycling,” “waste management,” “anaerobic digestion,” “incineration,” “municipal solid waste,” “food waste,” “wastewater treatment,” “landfill,” “biogas,” “biofuel,” and “biorefinery” are the most frequent keywords of this cluster. The 5th cluster contains miscellaneous topics, including the keywords “renewable energy,” “china,” “electricity,” “exergy,” and “transportation.”

After eliminating top records manually, namely “life cycle assessment” keywords, the remaining top 1000 author keywords were evaluated and classified using two periods (2000-2011 and 2011-2022). Trends of publications were explored in these two periods, and SNA was operated to analyze the co-occurrence of keywords in each period. The author keywords Network Visualization maps in 2000-2011 (Figure 10-a) and 2011-2022 (Figure 10-b) are illustrated in Figure 10. The author keywords in every two periods were classified into five clusters, each of which contains at least 140 keywords.

In addition to the growth of the number of keywords in newer time periods, the usage of some keywords in publications has grown significantly (the last keyword in the first period had one occurrence, and the last one in the second period had three occurrences). “Sustainability,” “environmental impact,” and “carbon footprint” had the most considerable growth in keywords from 221, 229, 49 in 2000-2011 to 2013, 1612, and 1060 in 2011-2022, respectively. "Circular economy" was notably absent during the initial period however its frequency of occurrence increased dramatically to 789 instances during the subsequent period. “Water footprint,” “Biogas,” and “GHG emissions” were the keywords that had the most growth, with a growth rate of 18.5, 11.2, and 7.1 times. “Recycling,” as one of the most widely used keywords in the first period, has been replaced by emerging concepts such as “carbon footprint,” “greenhouse gas emissions,” and “climate change” in recent years.

Policy implications and managerial insight

This bibliometric assessment illuminates the conceptual foundation of investigation in LCA. Policymakers can gain advantages from this erudition to formulate policies grounded in robust scientific tenets.

By harmonizing regulations with the most recent theoretical advancements in LCA, policies can be formulated to be more flexible, productive, and indicative of the prevailing state of environmental science. Furthermore, the study highlights the importance of interdisciplinary collaboration in the field of LCA research. Policymakers should encourage partnerships between environmental scientists, economists, engineers, and other relevant disciplines by implementing suitable frameworks. Such collaborations can lead to more holistic approaches to addressing complex environmental challenges.

Managers can utilize this study to strategically distribute research investments within their organizations. By discerning the most influential and consequential research trends, managers can direct R&D teams toward concentrating on domains that conform to the overarching objectives of sustainability and environmental accountability. This ensures that research endeavors effectively contribute to the strategic goals of the organization.

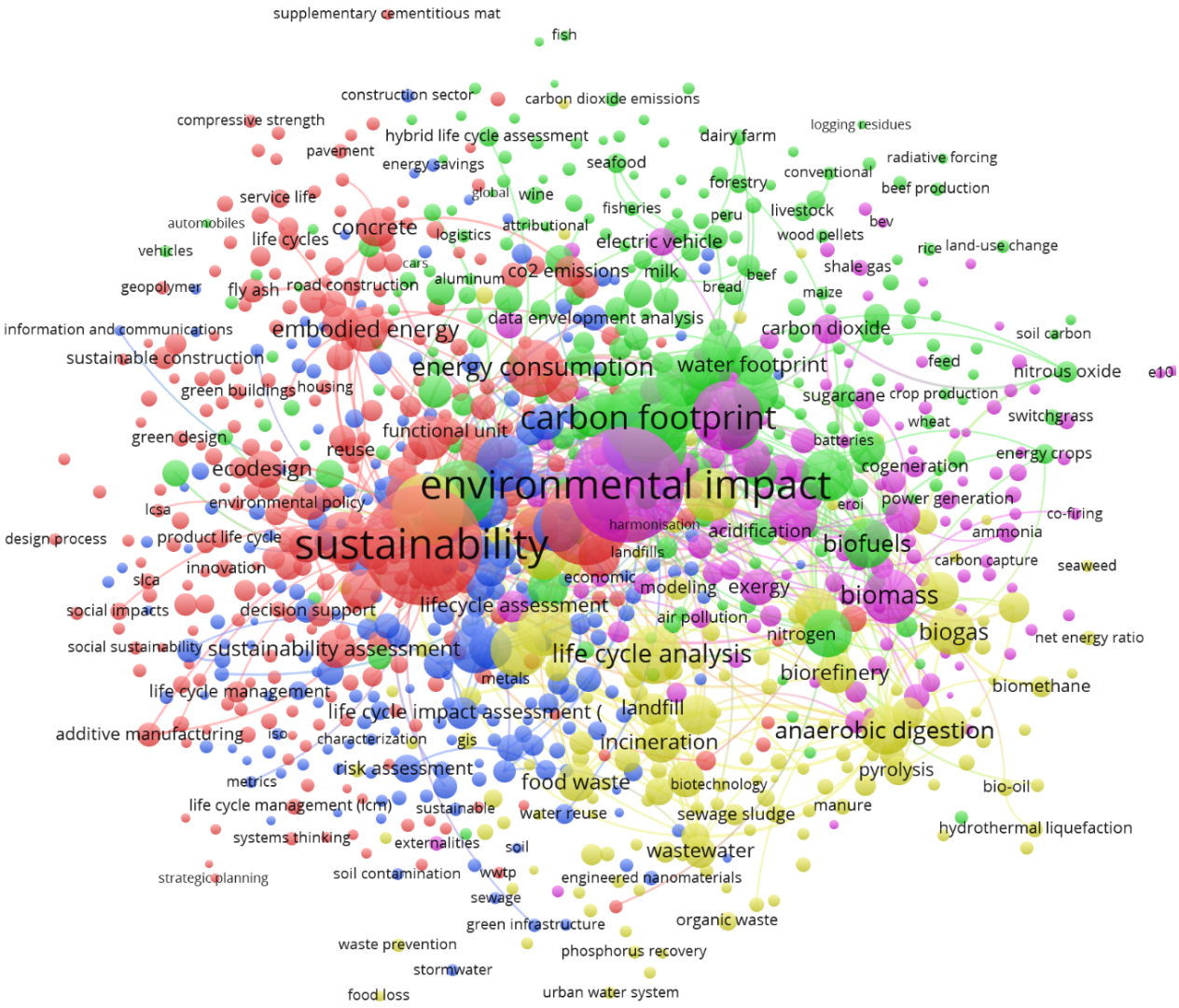
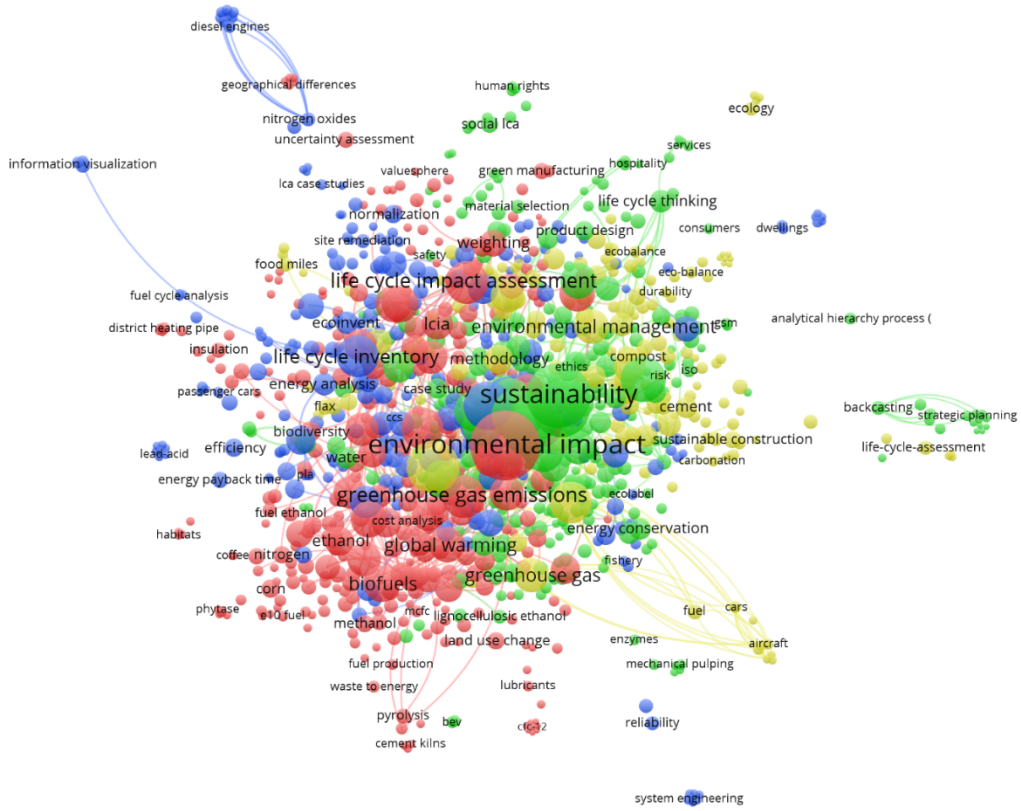
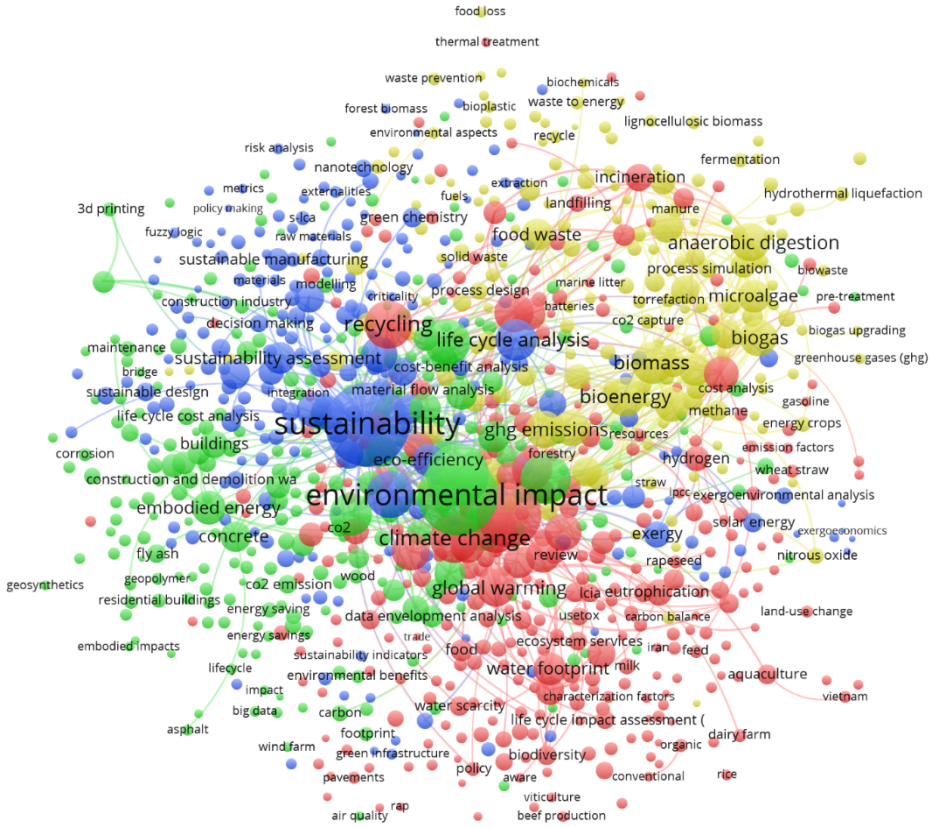


Figure 9. The author keywords overlay visualization network map (500 nodes)



a) 2000-2011



b) 2011-2022

Figure 10. Author keywords network visualization map in two distinct periods

Conclusion

A comprehensive review of LCA research was conducted during 2000–2022, using bibliometric and SNA methods. Numerous features such as publications types, publications trends, subject categories, journals, institutions, countries, and author keywords were comprehensively evaluated. A summary of the findings of this review is available in Table 4.

Table 4. The summary of the results

Item	Result
The most prevalent type of publications	Journal articles
The most major subject category	Environmental science
The most productive journal	Journal of Cleaner Production
The most productive institution	Technical University of Denmark
The most productive country	United States
The most occurred author keyword	Sustainability

The outcomes showed that LCA-related publications significantly increased from 224 in 2000 to 4225 in 2022. The "Journal of Cleaner Production," "International Journal of Life Cycle Assessment," "Sustainability Switzerland," and "Science of The Total Environment" were the most productive journals in the dataset. Among the top ten productive institutes, seven institutes belong to Europe. "Technical University of Denmark," "ETH Zürich," and "Norges Teknisk-Naturvitenskapelige Universitet" ranked 1st, 2nd, and 3rd, respectively. The United States had the highest growth rate and was also the most productive country in the LCA literature with the highest number of publications (5885), followed by China (3938) and Italy (3182). The Netherlands had the highest percentage of collaborations (63.4% of the total Dutch publications) with other countries in terms of the number of LCA publications, followed by the United Kingdom (57.7%) and France (55.9%). On the other hand, the United States had the highest percentage of independent publications (65.1%). According to the analysis of the author keywords, "life cycle assessment," "LCA," "life cycle assessment (LCA)," "sustainability," "environmental impact," "life-cycle assessment," and "environmental impacts" were much more popular than other keywords. Based on the network visualization maps during 2000-2022, a growing number of publications have been focused on "sustainability," "greenhouse gas emissions," and "carbon footprint" areas. Besides, "Circular economy," "water footprint," "biogas," and "GHG emissions" were the most increasing keywords in these 23 years. These outcomes could help researchers better understand the current situation, overall growth, and the trends of LCA research. The results will also prepare a base for prospective studies in the field.

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