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Review

Life Cycle Assessment Research Trends and Implications: A Bibliometric Analysis

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Abstract: Acknowledging the importance of sustainability and implementing measures to achieve the UN's 17 Sustainable Development Goals (SDGs) by 2030 represent a holistic approach to promoting peace and prosperity for the planet and its inhabitants. LCA is a valuable tool for organisations to enhance sustainability and reduce environmental impact. There has been a notable increase in LCA research subjects, indicating a recognition of its significance in promoting sustainability. The field has experienced a significant expansion in the past decade, with a 30% annual percent growth rate in LCA publications since 2010. In the most recent 4 years alone, 47% of all LCA publications since 1991 were produced. This paper presents a comprehensive review of LCA research from 1991 to 2022, with a specific focus on the period from 2019 to 2022. The study identifies research avenues and trends in LCA research using diverse bibliometric analysis techniques alongside content examination and the SciVal topic clusters prominence indicator. This comprehensive approach reveals evolving trends, such as an increased emphasis on practical applications for global sustainability goals, LCA's expansion into bio-based materials due to plastic pollution concerns, and quantification of circular economy benefits in solid waste management. Moreover, deeper exploration of energy-related sustainability aspects and the integration of LCA into early product development for eco-conscious design are observed. These trends signify widespread LCA adoption across industries to address energy and design-related sustainability challenges. The study acknowledges interdisciplinary collaboration among researchers, industry, and governments, shaping a robust LCA research landscape. China's heightened contributions as a leading contributor to the field have reshaped the global LCA landscape mirrored in the evolving prominence of journals, institutes, and funding organisations.

Keywords: life cycle assessment; bibliometric analysis; research trends; hotspots

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1. Introduction and Background

1.1. Life Cycle Assessment

"Life cycle assessment (LCA) is defined as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, the latter are a consecutive and interlinked stages, from raw material acquisition or generation from natural resources to final disposal" [1]. This evaluation process involves four main stages, namely, (1) Goal and Scope, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation. LCA serves as a quantitative tool for assessing and minimising the environmental impacts of various entities, such as products, technologies, materials, processes, industrial systems, activities, or services along their entire life cycle.

The roots of LCA can be traced back to the late 1960s and early 1970s, when increasing concerns about industrial processes' environmental impact emerged. The enactment of the US National Environmental Policy Act (NEPA) in 1969 necessitated federal agencies to evaluate the environmental effects of their actions, leading to the development of methodologies such as Environmental Impact Assessment (EIA). LCA's origin can be attributed to the life cycle study of beverage containers conducted by Midwest Research Institute (MRI) (currently known as Franklin Associates Inc., Charleston, SC, USA), initiated by Harry Teasley, a Coca Cola executive [2,3]. The MRI methodology developed into "Resource and Environmental Profile Analysis" (REPA) [4,5].

Prior to the early 1990s, diverse theoretical frameworks and nomenclatures were employed to conduct investigations on the material, energy, and waste flows of a product's life cycle. These frameworks and names included resource and environmental profile analysis, eco-balancing, integral environmental analyses, environmental profiles, and cradle-to-grave assessments (to distinguish from Environmental Impact Assessment (EIA) and Ecological Risk Assessment (ERA)). This divergence in terminology and methodology complicated the recognition and adoption of LCA as an analytical tool [6].

During the period spanning the 1970s and 1980s, which marked the dawn of the LCA conceptualisation decade, the general public's awareness of environmental issues had increased, with an emphasis on environmental protection, energy and resource efficiency, pollution control, and solid waste management. The LCA-related studies during this period were typically product-specific in nature, targeting items, such as milk packaging [7], beverage containers [8], lightbulbs, and baby diapers [6]. Despite sharing similar goals, these studies produced highly divergent results, leading to a lack of widespread acceptance and application of LCA as an analytical tool [9].

During the 1980s and 1990s, the burgeoning need to address the entire life cycle of a product or multiple alternative products in response to market demands emerged as a critical concern. The expansion of impact categories, such as noise, land use and biodiversity, as well as the extension to economic and social repercussions, further intensified the urgency to develop a more comprehensive framework for LCA [6]. Beginning in 1990, the Society of Environmental Toxicology and Chemistry (SETAC) organised a series of workshops to facilitate extensive exchanges among LCA experts, culminating in the formulation of a harmonised LCA framework in 1993, known as the Code of Practice [10]. This served as the basis for the development of ISO standards 14040, 14041, 14042, and 14043. Subsequently, these standards were amalgamated into ISO 14040 and 14044 when the standards were updated in 2006 [11].

The 1990s and 2000s witnessed the standardisation of LCA and the emergence of the first scientific journal articles on LCA in esteemed sources, such as the International Journal of LCA (IJLCA), Journal of Cleaner Production (JCP), Resources, Conservation and Recycling (RCR), Environmental Science and Technology (EST), and Journal of Industrial Ecology (JIE) [6]. Figure 1 derived from the Scopus database, displays the yearly number of documents published by source from 1993 to 2022.

At the outset of the twenty-first century, LCA has attracted increased attention and developed into an interdisciplinary research field that is applied in a range of subject areas. The standardisation of LCA, along with increased awareness of environmental burdens, has expanded the scope of LCA-related study subjects and applications. These include methodological development, with a focus on impact assessment methodologies, such as eco-indicator 99 [12], CML 2002 [13], IMPACT 2002+ [14], as well as on system boundaries and allocation methods [15,16], dynamic LCA [17], spatial differentiation in LCA [18], risk-based LCA [19,20], economic input-output models for environmental life-cycle assessment [21,22], hybrid LCA [23], Data Quality Assessment (DQA) [24–26], industry-specific LCA applications studies and guidelines (e.g., construction [20], agricultural and energy sectors), as well as policy and organisation-based applications (e.g., EU packaging legislation) [6]. Additionally, LCA has broadened its scope to encompass economic and social aspects, such as Life Cycle Costing (LCC) [27,28] and Social Life Cycle Assessment (S-LCA) [29,30].

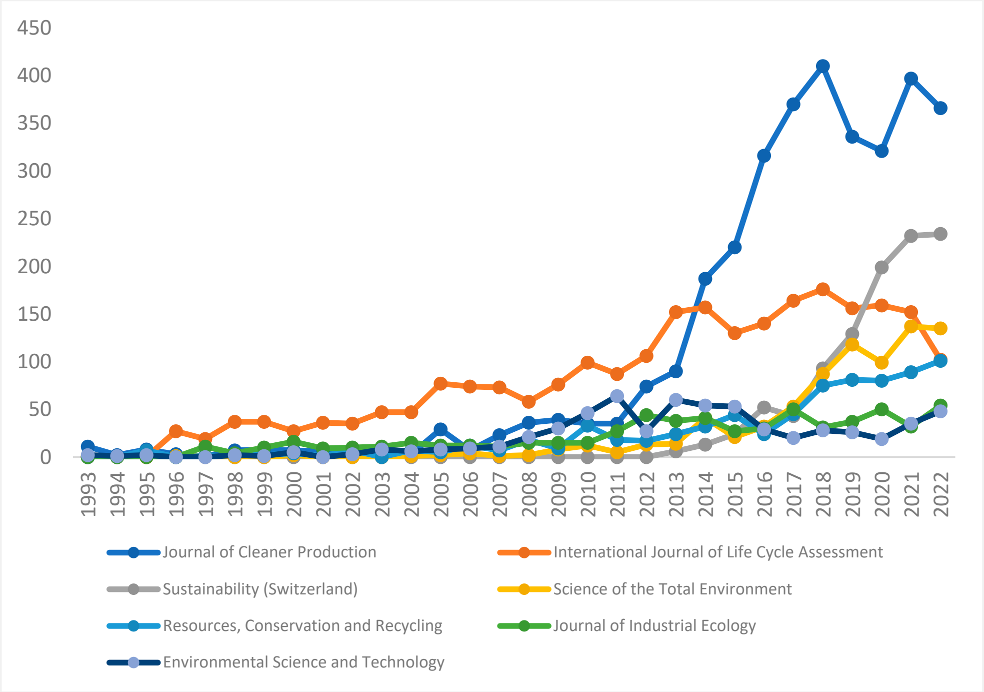


Figure 1. Documents per year by source (1993–2022). Search on Scopus database on keyword "Life Cycle Assessment" OR "Life-Cycle Assessments" Within Title OR Abstract and Author Keywords OR Indexed Keywords "Life Cycle Assessment" OR "Life-Cycle Assessments" OR "Life Cycle Inventory" OR "Life Cycle Impact Assessment (s)" OR "Comparative Life Cycle Assessment (s)" OR "LCA".

The International Life Cycle Partnership was established in 2002 by the United Nations Environment Programme (UNEP) and SETAC to facilitate the widespread use of dependable life cycle knowledge, integrate life cycle thinking into practise, and improve supporting tools through enhanced data and indicators. The adoption of the sustainability concept, encompassing three dimensions of people, planet, and profit, has witnessed significant growth since the replacement of the United Nations' eight Millennium Development Goals (MDGs) in 2000 with the 17 United Nations Sustainable Development Goals (SDGs) in 2015. This growth has been driven by several factors, including technological advancement, environmental concerns, and social challenges. Consequently, contemporary LCA research has deepened, encompassing more specific research subjects, such as the application of machine learning and artificial intelligence in LCA [31], ecodesign and Life Cycle Management (LCM) [32], and LCA-based assessment of the sustainable development goals [33].

1.2. Research Gap

Several authors have undertaken reviews to summarise the development of knowledge and literature in the field of LCA over various time periods. For instance, Finnveden et al. [16] provided an overview of recent advancements in LCA methodologies and highlighted emerging issues related to various stages of LCA, such as goal and scope, attributional and consequential LCA modelling, inventory analysis (including system boundaries, data collection, and allocation), improvements in databases, input-output, and hybrid LCA. Similarly, Guinée et al. [6] conducted a chronological review of LCA from the past, present to the future, highlighting the key contributors, hotspots of development, and emerging topics in different periods. Hellweg and Canals [34] provide a comprehensive review of recent developments, challenges, and opportunities in LCA and its diverse applications in supporting environmentally informed decisions across multiple fields. The authors emphasise the importance of advancing LCA methodologies in the future to enhance regional detail, accuracy, and broaden the assessment scope to include economic and social aspects.

Literature reviews, systematic reviews, and meta-analysis were the primary research methodologies employed to review the literature, involving sampling techniques and content analysis of restricted number of articles [35–38]. While these methods may be useful for analysing specific research areas with limited numbers of publications, bibliometric analyses offer a wealth of related information, allowing for a comprehensive understanding of the entire intellectual landscape of the topic [36,38].

In light of the considerable growth in LCA-related publications as presented in Figure 2, a comprehensive bibliometric analysis was conducted by a number of authors [39–46] to identify primary and emerging themes and to map LCA research trends and related contexts, including the characteristics of LCA publications, subject areas, co-authorship, collaboration, co-citations, journals, affiliations, keywords co-occurrence, and research focus.

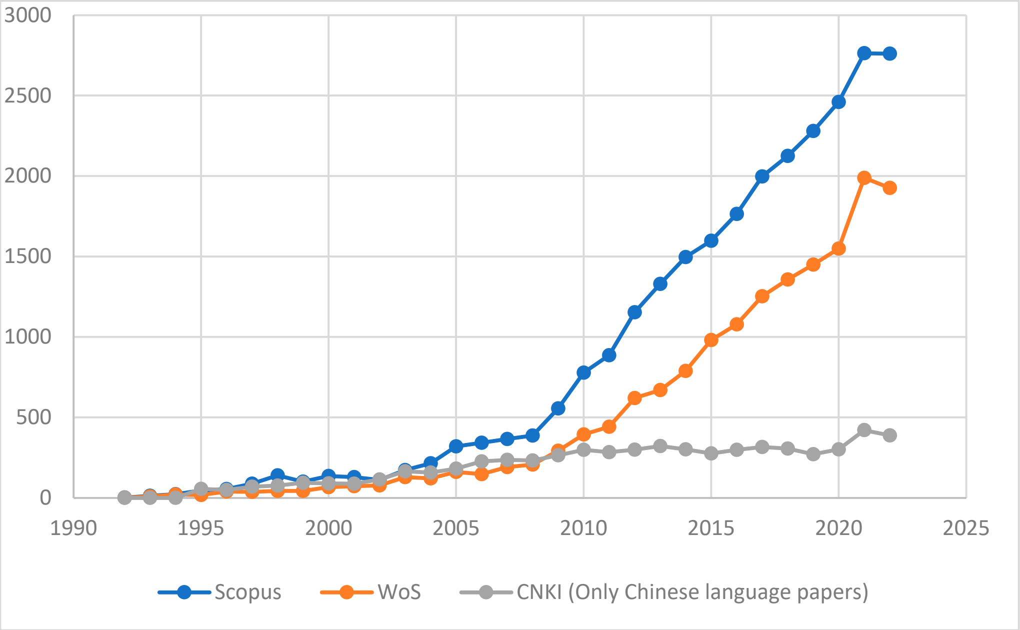


Figure 2. Evolution of LCA publications (1991–2022). Search on Scopus, WoS platform, and CNKI databases (only Chinese language papers) on keyword “Life Cycle Assessment” OR “Life-Cycle Assessments” Within Title OR Abstract and Author Keywords OR Indexed Keywords “Life Cycle Assessment” OR “Life-Cycle Assessments” OR “Life Cycle Inventory” OR “Life Cycle Impact Assessment (s)” OR “Comparative Life Cycle Assessment (s)” OR “LCA”.

The methodology used for retrieving publications revealed notable inconsistencies in the inclusion of key LCA research articles within the bibliometric literature review, as well as discrepancies in author affiliation [47]. In future LCA bibliometric reviews, attention should be given to recent research findings to provide a more up-to-date perspective of the LCA research field [41]. Additionally, to enhance the validity of bibliometric review findings, researchers should consider using supplementary databases such as Scopus or Cambridge Scientific Abstracts [43]. Although the Web of Science platform (WoS (In this paper, the abbreviation "WoS" refers to the Web of Science platform, the contents of which are accessible at https://www.webofscience.com/wos/woscc/basic-search access on 1 July 2023)) database is commonly used in scientometric studies and related tools, it is relatively new to tracking LCA research and may not be as comprehensive as the Scopus database [42]. In contrast to Chen, Yang [41] and Hou, Mao [43], both of which used WoS exclusively and claimed that the latter covers a wider range of LCA journals as well as a variety of literature types. Gaurav, Bihari Singh [46] reported a higher LCA-related publication count per year for WoS compared to Scopus from 1991 to 2018.

Another limitation of previous bibliometric studies is the omission to identify and assess the contributions and impacts of funding organisations within the broader LCA research domain, as well as on specific LCA research topics.

Figure 2 displays the emergence of the LCA concept from 1991 to 2022, as observed by Scopus, WoS, and China National Knowledge Infrastructure (CNKI) (only Chinese literature) databases. The overall number of LCA-related publications in Scopus has expanded by 352% (30% Annual Percentage Growth Rate (APGR)) since 2010, with 47% of all publications published within the last 4 years. Given the constantly evolving nature of LCA research, ongoing tracking and updating of the intellectual environment of this topic through bibliometric analysis is crucial for remaining current with the latest advancements in the field, identifying emerging trends and new research areas, evaluating the impact of previous research, and assessing the effectiveness of research funding.

1.3. Research Objective

The major objective of this study is to comprehensively analyse LCA research over a 31-year period, with a specific focus on the span of 2018–2022. By employing quantitative bibliometric analysis techniques, the study aims to achieve the following key goals:

- Research Performance and Progression: Investigate the patterns and shifts in LCA research publications across the years to analyse the performance and progression of research activities.
- Research Trends and Hotspots: Identify major topic clusters within LCA research through a combination of techniques, such as topic clusters prominence indicator, visualisation, knowledge map analysis, and content analysis.
- Database Assessment: Quantitatively assess the factors contributing to disparities in LCA publication counts between Scopus and Web of Science, providing practical recommendations for future LCA bibliometric studies.

Through these interconnected objectives, the study seeks to provide a comprehensive understanding of the intellectual landscape, research trajectory, and prominent areas of interest within the field of LCA, offering an updated and insightful view of LCA research in the most recent 4 years.

The current research article is organised as follows: In this initial Section (Section 1) an introduction to the background of LCA is provided (Section 1.1), along with a review of the limitations of previous bibliometric studies on LCA (Section 1.2). An overview of the research objectives is presented in Section 1.3. The subsequent sub-Section (Section 1.4) offers a general outline of the bibliometric analysis, including a description of the main techniques used in the study. The methodology employed in this study is detailed in Section 2. The results of data analysis and interpretation, including performance analysis and science mapping, are presented in Section 3. This section delves into publication characteristics, research progress, performance, as well as research hotspots and trends (Section 3.3). Finally, the discussion and summary of the study results, along with the discussion of limitations and future directions, are presented in Section 4.

1.4. Bibliometric Analysis

Pritchard [48] posits that bibliometrics pertains to the utilisation of mathematical and statistical approaches to books and other communication media. Hawkins [49] characterises bibliometrics as the implementation of quantitative analysis techniques toward bibliographic references encompassed within the literature corpus. Bibliometric analysis, as elucidated by [50], involves a computer-assisted scientific methodology that can delineate central research themes and prominent authors along with their associations via comprehensive examination of all publications within a specific domain.

According to Broadus [51], bibliometric analysis entails quantitatively measuring the physical constituents of publications, bibliographic references, and other pertinent elements to demarcate the research domain. This approach enables researchers to uncover emerging trends in the performance of articles and journals, collaborative patterns, research components, and intellectual structure of a particular research area. Donthu et al. [36] maintain that bibliometric analysis is useful for comprehending and mapping the cumulative scientific knowledge and evolutionary nuances of established disciplines, providing a solid foundation for advancing a discipline in novel and meaningful ways. However, Ramos-Rodríguez and Ruíz-Navarro [52] suggest that the scope of the study should be sufficiently large to warrant bibliometric analysis since this approach is specifically designed to handle voluminous bibliometric data.

Bibliometric methods have been widely employed in diverse fields, including business and management research [36,53,54], medicine [55,56], environmental science and energy [56–58], and engineering [59,60]. The proliferation of bibliometric analysis can be attributed to its ability to handle the vast volume of scientific publications in these areas [36], which contrasts with traditional literature reviews that typically have a narrower scope and examine a smaller number of papers [35]. Moreover, the emergence of comprehensive scientific databases, namely Scopus and Web of Science, which offer vast bibliometric information and advanced analytical capabilities, alongside the availability of bibliometric software, such as Gephi and VOS viewer, have facilitated the practical analysis of bibliometric data [36,61]. Over the past 4 years, 5195 (Using a search in the Scopus database, the keyword "Bibliometric analysis" was explored over the period from 2018 to 2022) publications have been published with the term "bibliometric analysis" in the title, indicating the widespread adoption of bibliometric methods across various disciplines.

Bibliometric analysis has gained significance in the research field of LCA in recent years. Several studies have used bibliometric methods to explore LCA-related literature, yielding valuable research findings. Notable examples of bibliometric studies on LCA include de Souza and Barbastefano [39], Chen et al. [41], Qian [42], Hou et al. [43], He and Yu [44], and Gaurav et al. [46]. These studies have used various bibliometric techniques, including co-citation and social network analysis, to identify knowledge diffusion patterns, research hotspots, and publication evolution and performance. A summary of the main aspects of previous LCA bibliometric analysis review publications is presented in Table 1.

Table 1. Summary of themain aspects of previous LCA bibliometric analysis review articles.

Author	Title/Theme	Time Span	Database and Records	Publications Search Criteria
Gaurav et al. [46]	Recent progress of scientific research on life cycle assessment	1991–2018	Scopus: 10,524 WoS: 7726	Within: Title, keywords, and abstract fields of a publication Language: All Search String: "Life cycle assessment *" OR "life cycle analysis *" OR "life cycle sustainability assessment *" OR "life cycle sustainability analys *" OR "ecobalanc *" OR "eco balanc *" OR "eco-balanc *" OR "Resource * and environmental profile analys *" OR "cradle-to-grave analys *" OR "cradle to grave analys *" OR "LCA" OR "Life-cycle assessment *" OR "life-cycle analys *" OR "life-cycle sustainability assessment *" OR "life-cycle sustainability analys *"
He and Yu [44]	Research trends in life cycle assessment research: A 20-year bibliometric analysis (1999–2018)	1999–2018	Web of Science: 20,153	Within: Title, keywords, and abstract fields of a publication and Keywords Plus®. Language: English Document Type: (Article OR Review OR Proceeding papers) Search String: "life cycle assessment *" OR "life cycle analys *" OR "Life cycle sustainability assessment *" OR "life cycle sustainability analys *" OR "life cycle inventory" OR "life cycle impact assessment" OR ("eco balanc *" OR "ecobalanc *")

Table 1. *Cont.*

Author	Title/Theme	Time Span	Database and Records	Publications Search Criteria
Hou et al. [43]	Mapping the scientific research on life cycle assessment: A bibliometric analysis	1998–2013	Web of Science: 6616	Within: Title, keywords, and abstract fields of a publication Language: All Document type: All Search String: "Life cycle assessment" OR "life-cycle assessment"
Chen et al. [41]	A bibliometric investigation of life cycle assessment research in the web of science databases	1998–2013	Web of Science: 7782	Within: Title, keywords, and abstract fields of a publication Language: English Document type: All Search String: "life cycle assessment *" OR "life cycle analys *" OR "life cycle sustainability assessment *" OR "life cycle sustainability analys *" OR ("eco balanc *" OR "ecobalanc *")

* In search systems, the asterisk (*) acts as a wildcard. It retrieves words that start with the given letters and can end with any combination of letters that follow or for any phrase that includes a truncated term.

2. Materials and Methods

The bibliometric analysis process and techniques employed in this paper closely correspond to those outlined by Donthu and Kumar [44]. This methodology encompasses two primary stages: (1) data retrieval and (2) data analysis and interpretation, encompassing performance analysis, science mapping, content analysis, and topics clusters prominence. Figure 3 visually represents the bibliometric analysis conducted in this study, providing an illustrative overview of the employed methodological framework.

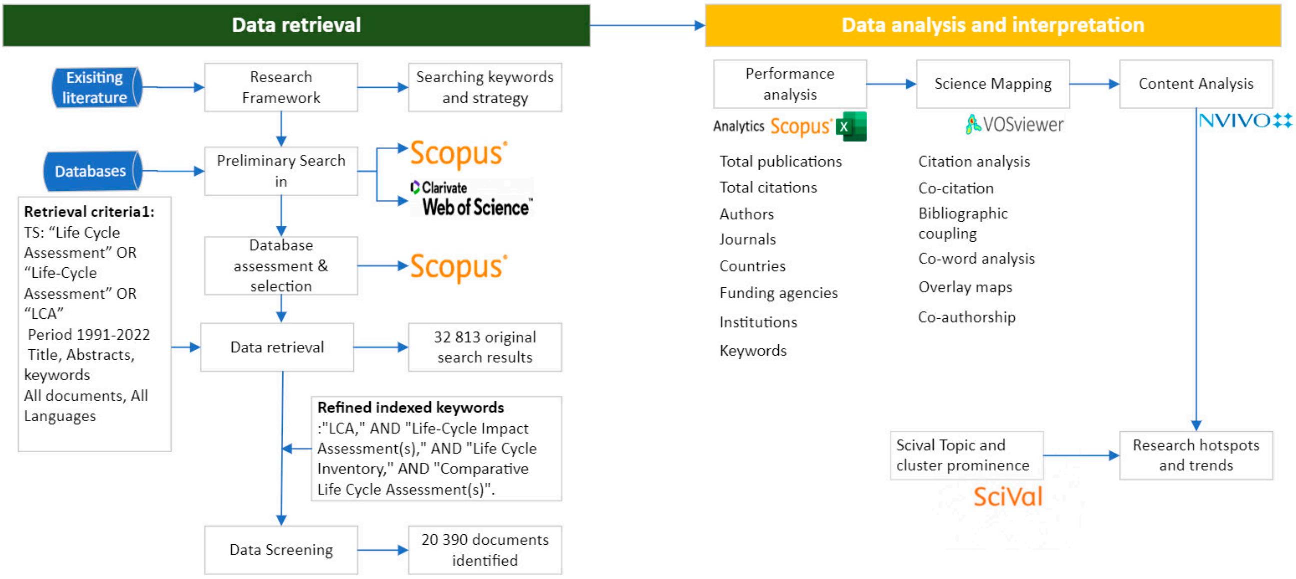


Figure 3. Methodological scheme of the study.

Bibliometric analysis techniques can be classified into two categories, namely, performance analysis and scientific mapping. This methodology involves the use of quantitative techniques, such as citation analysis on bibliometric data, which refers to units of publication and citation [44].

Performance analysis involves the use of quantitative indicators derived from bibliographic data to evaluate and measure the productivity, impact, and influence of scholarly publications, researchers, institutions, or countries. This approach can help identify trends, patterns, research strengths and weaknesses, inform strategic planning, and guide funding decisions [44,62,63]. The present study employs three indicators: Total Publications (TP), Total Citations (TC), and h-index to evaluate research performance. The h-index is a measure of both productivity and impact, defined as the highest number of publications that have received at least that number of citations.

Science mapping is a data analysis and visualisation technique used to study the structure and development of scientific fields by examining bibliographic data. By identifying patterns and relationships among publications, authors, institutions, and keywords, science maps allow researchers to explore important research themes, collaborations, and trends in a field, and identify potential research gaps or emerging areas of interest [64–66]. This paper employs various techniques for science mapping, including co-citation analysis, bibliographic coupling, citation network analysis, keyword co-occurrence analysis, and cluster analysis, to study the structure and development of LCA research field.

Research trends

Research trends constitute a densely cited network of a group of recent articles with a shared thematic focus [62]. In the early stages of its development, a research front exhibits robust links between citations within its cluster. As it progresses, additional citations, often from diverse scientific domains, lead to a gradual attenuation of these connections [63]. Identifying fronts aids in prioritising research areas and funding [63]. Prediction of trends helps to efficiently navigate literature, identify promising avenues, and guide efforts [64].

Prediction of research topic trends involves considering expert opinions, which might introduce bias, or quantitative analyses, which also have limitations. Researchers are increasingly turning to quantitative methods like bibliometrics, scientometrics, or informetrics to address potential biases and enhance accuracy [64].

Three primary scientometric methodologies are employed to discern research trends: analysing shifts in scientific production dynamics, exploring citation patterns and their variations, and conducting content analyses [63]. These approaches are often combined in various permutations to comprehensively capture the evolving landscape of research.

In addition to the aforementioned methods, this study will incorporate the Prominence Indicator to identify emerging topics. The Prominence Indicator, introduced by the SciVal database, gauges current topic momentum through recent citations, views, and CiteScore values [65]. Although useful in predicting future research trends, it is essential to note that prominence signifies overall demand and visibility, not necessarily importance [65].

In this study, the topic clusters identified through keyword co-occurrence analysis will be input into the SciVal (SciVal serves as a research analytics tool that measures metrics collected from the Scopus dataset) analytic tool. This input will be used to determine topic clusters and their Prominence Indicators.

2.1. Database Selection

The scope and selection of the scientific field databases is a crucial factor in assessing the reliability and accuracy of bibliometric analysis for research evaluation [42]. The leading databases for academic research are Scopus, Web of Science, Google Scholar, PubMed, IEEE Explore, and Science Direct [66,67]. WoS and Scopus stand as two universally acknowledged and competitive citation databases, essential for diverse research purposes [68,69]. These databases have been pivotal for large-scale bibliometric studies, with WoS traditionally being the main reference for published research until the advent of Scopus as viable alternative [66].

Scopus, an Elsevier product, is a multidisciplinary citation database that comprises peer-reviewed literature, with its data incorporated into other Elsevier research tools, such as Pure, Mendeley, SciVal, and ScienceDirect [70]. The Web of Science, formerly known as the Web of Knowledge, is an all-encompassing database comprising of records from bibliographic databases, including the Social Sciences Citation Index (SSCI) and the Science Citation Index Expanded (SCI-EXPANDED). The database is interdisciplinary in nature and has been acquired by Clarivate, in particular, SCI-EXPANDED employs the author finder option to explore the peer-reviewed literature's multidisciplinary citation database [71]. Based on the database evaluation outcomes detailed in Section 3.1, Scopus is selected as the database source for this study.

2.2. Study Design

The focus of this investigation pertains to publications that are exclusively centred on or applying LCA. The exact terms "Life Cycle Assessment" or "Life-Cycle Assessment" were used as the primary search string, with refined indexed keywords including "LCA", AND "Life-Cycle Impact Assessment(s)", AND "Life Cycle Inventory", AND "Comparative Life Cycle Assessment(s)". Data retrieval was executed on 28 February 2023, with a primary search area within title, abstract, authors, and indexed keywords in the Scopus database. This approach is justified as searching all fields of publications using "LCA" or "Life Cycle Assessment" could yield documents with little to no relevance to LCA. As a result, a total of 20,390 LCA-related documents were identified. The study covers a time span of 31 years (1991–2022), selecting 1991 as the starting point due to Scopus and WoS identifying the earliest LCA paper. The data retrieval date should sensibly capture all publications from 2022. Liu's work [72,73] underscores the challenge of low availability rates of abstract and author keywords information before 1990 in indexed databases. This arises from a lack of systematic data collection, potential omission, and the absence of information in some publications. Furthermore, databases might lack the necessary reference data for generating corresponding keywords. However, the standardisation of LCA in the 1990s and its historical emergence led to earlier publications being primarily found on specialised platforms like SETAC and US EPA, where data collection was constrained.

This initial oversight resulted in the unintended exclusion of significant classical works, potentially diminishing their recognition. While papers predating 1991 may not align with the refined LCA standards introduced in early 1990s, their enduring im-portance is duly acknowledged. This study adeptly navigates these limitations by skillfully incorporating early works, enhancing the analysis of LCA's dynamic evolution and lasting impact.

2.3. Software Tool

In this study, the primary software tool used for conducting network analysis and science mapping was VOS viewer. The tool is an open-source program created by scholars at Leiden University in the Netherlands, which facilitates the visualisation and examination of bibliometric networks through the creation of a term map. The software has been widely employed in bibliometric research across diverse fields, including the social sciences, humanities, science, and technology. The term map generated by VOS viewer is a two-dimensional map wherein terms are arranged based on their relatedness, with the distance between two terms serving as an indicator of their degree of association. VOS viewer implements the clustering technique to aggregate nodes of strong links into clusters, with each cluster representing a specialty [74]. By adjusting the relevant parameters, VOS viewer is an optimal tool to visualise and analyse emerging trends and changes in scientific literature, which aligns with the objectives of this study.

3. Results

3.1. Database Assessment

Authors often query the differences between Web of Science and Scopus, prompting authors to undertake a comprehensive comparison of these databases [75]. However, both databases may exhibit biases that favour certain subject areas over others, such as an overrepresentation of English language journals at the expense of non-English ones, and a potential limitation of the study could be comparing data from only one country [76].

The preliminary examination of the Scopus and Web of Science (WoS) databases was conducted by searching for the exact term "Life Cycle Assessment" in the titles, abstracts, or author keywords fields. The results of this search revealed a broad spectrum of publications in both databases. WoS had a total of 25,125 publications, while Scopus had 32,813 records, indicating a difference in the number of publications between the two databases.

The objective of this preliminary assessment was to identify the primary contributing factors to variances in publication counts between two databases. To achieve this, a thorough comparison of key bibliometric indicators was conducted for the aggregate publications published in 2018. The analysis focused on deduplicating documents and examining disparities across document types (i.e., articles, conference papers, and reviews), language, and the inclusion of Chinese language LCA literature. To further explore the dissimilarities observed, a search was performed for identified papers within both databases to discern discrepancies in keywords, terminologies, and title format. The results of the initial assessment study of the databases are summarised in Table 2.

Table 2. Summary of the preliminary assessment of databases.

	Databases			
	Total	**Scopus**	**WoS**	
Publications	3107	1750	1357	
Deduplicated publications		Encompassed within Scopus (not referenced in WoS)	Encompassed within WoS (not referenced in Scopus)	Main Driven Factors
Difference in articles	776 (25%)	676	100	- Author keywords - Special characters and symbols
Difference in Conference papers	155 (5%)	154	1	- Publication year
Difference in Reviews	62 (2%)	62	0	- Publication year - Low coverage
Chinese language papers	28 (1%)	28	0	- Low coverage of Chinese language literature
French, German, Polish, Spanish, Korean, Japanese Language papers	14	11	3	- Low coverage of other languages literature

The analysis reveals that Scopus outperforms WoS in terms of record counts for all the evaluated factors. Specifically, Scopus includes 676 articles, 154 conference papers, 62 reviews, 28 Chinese language papers, and 11 other language papers that are not referenced in WoS. On the other hand, WoS contains 100 articles, 1 conference paper, and 3 other language papers that are not referenced in Scopus. In terms of articles, all non-referenced articles are encompassed in both databases.

The inclusion of the search term “Resource and Environmental Profile Analysis” in the LCA search string yielded a limited number of publications. Specifically, Scopus and WoS databases retrieved one additional publication, related to the paper of Hunt and Franklin [77] “the Resource and Environmental Profile Analysis of Beer Containers”. Both databases covered the same date range; however, Scopus had 27% more publications than WoS between 1991 and 2022. This finding contrasts with the studies conducted by Chen, Yang [41] and Hou, Mao [43], who used WoS exclusively and reported that it covered a wider range of LCA journals and literature types. Similarly, Gaurav et al. [46] found that the WoS database had higher LCA-related publications count per year than Scopus.

Table 1 shows that the authors [41,43,44,46] used more LCA-related keywords in their search strings, such as “life cycle sustainability assessment*”, “life cycle sustainability analysis*”, and “ecobalance* compared to the paper under review, indicating a comprehensive search scope. However, this factor does not significantly affect the difference in publication record counts between the two databases since the primary research keyword used is the same in both databases (i.e., life cycle assessment).

Variations in record counts are primarily attributed to the following reasons: (1) Disparities in publication years, such as in the case of Summerscales and Dissanayake [78] "Allocation in the life cycle assessment (LCA) of flax fibres for the reinforcement of composites", which is indexed as 2017 in Scopus but 2018 in WoS. This factor is primarily associated with conference papers, as exemplified by Gue et al. [79] and Ruben et al. [80] publications. (2) Differences in title and terminologies formats, particularly the use of special characters and symbols, such as /, (), "", -, and:, as evidenced by Gear et al. [81] "A life cycle assessment data analysis toolkit for the design of novel processes (–) A case study for a thermal cracking process for mixed plastic waste" and "A novel methodology based on LCA+ (plus) DEA to detect eco-efficiency shifts in wastewater treatment plants". (3) Variances in author keywords, such as the inclusion of irrelevant keywords to LCA or the use of different author keywords in both databases. For example, Tricase et al. [82] "A comparative Life Cycle Assessment between organic and conventional barley cultivation for sustainable agriculture pathways" is an LCA-relevant paper, but its author keywords consist of non-relevant (not standardised) LCA terminologies (i.e., Life Cycle Analysis, Comparative Assessment). (4) WoS has low coverage of conference proceedings compared to Scopus, with a 197% difference between the two databases. (5) Scopus includes significantly more Chinese and other language papers than WoS.

Recommendations

Constructing a relevant search string is crucial to obtain the most pertinent outcomes from a database search. The search string comprises of keywords, truncation symbols, and Boolean operators. To conduct a preliminary investigation, it is recommended to use the exact term "Life Cycle Assessment" in designated databases and filter the results based on highly cited papers, indexed keywords, and analysis function provided as a database feature. Scopus indexed keywords are standardised to vocabularies derived from Elsevier's thesaurus and account for synonyms, various spellings, and plurals. WoS Keywords Plus are generated by an automatic computer algorithm and are words or phrases that frequently appear in the titles of an article's references.

The screened indexed keywords should be employed as a search string within the title OR Abstracts AND Author keywords OR indexed keywords, depending on the research objectives, Boolean operators, location, research subjects, languages, type of documents, and search span. It is advisable to establish the research span between $N - 1$ and $N + 1$ if N represents the search year (period). Authors of LCA studies must enhance the indexing of their papers and signatures to aid in creating a more precise mapping of worldwide LCA research and enhance the dissemination and communication of their work [47].

3.2. Data Analysis and Interpretation

3.2.1. Characteristics of Publications

Table 3 presents an overview of the linguistic composition of LCA publications during the time periods of 1992–2018 and 2019–2022. The dominant language of LCA literature in both databases is English. Specifically, in the period of 1992–2018, a total of 11,632 LCA publications in English, accounting for 96% of the total relevant records in Scopus. Chinese is the second most prevalent language in Scopus with 320 articles (2%), followed by German and Spanish. In the period of 2019–2022, a total of 8003 LCA publications in English were recorded, representing 99% of the total records in Scopus. Chinese is once again the second most frequently used language, accounting for 71 articles (1%), followed by Spanish and Portuguese. The extant literature suggests that even in several countries where English is not the primary language, such as China, Japan, and Germany, the use of English in LCA contexts is prevalent.

Table 3. Distribution of languages in LCA publications (1992–2022).

	1992–2018		**2019–2022**	
Language	**No. of Publications**	**%**	**No. of Publications**	**%**
English	11,632	96	8003	99
Chinese	241	2	79	1
Japanese	75	1	2	-
German	38	-	9	-
Spanish	32	-	12	-
Portuguese	22	-	11	-
French	16	-	3	-
Korean	8	-	2	-

Despite Scopus including a greater number of Chinese published journals compared to WoS, as meticulously investigated by Miguel et al. in 2019 [83], it is important to highlight that a significant proportion of Chinese language scientific journals remains absent from both databases. This observation was emphasised by Xie and Freeman [84], as well as Weishu Liu [85], in their works. While Chinese researchers have the option to publish their work in both national and international journals, the lack of a bibliometric database covering both Chinese and English scholarly literature presents a challenge for assessing the output of Chinese researchers [84].

To ascertain the evolution of LCA publications in the Chinese language and gain insights into their potential impact on LCA literature, an initial analysis was performed using data sourced from the China National Knowledge Infrastructure (CNKI). The CNKI is a comprehensive database of scientific journals and other materials published in China. The search string used was “Life Cycle Assessment” OR “Life-Cycle Assessment”, and the search area was limited to academic journals in all fields. The initial search resulted in a total of 13,573 publications, which were refined by selecting only papers with author keywords “Life Cycle Assessment” OR “LCA”, resulting in 1754 records.

The analysis indicates a significant increase in the number of LCA publications in the Chinese language, exemplified by an ascending trend line squared value of 0.9. This trend is evidenced by the progression from 56 documents per year in 1995, to 88 in 2001, 298 in 2010, and 450 in 2022, suggesting a likelihood of its ongoing continuation, as depicted in Figure 2. Thus, Chinese LCA research performance should be considered as a valuable source of literature for future studies related to LCA. It is worth noting that Chinese is the second most common language for LCA publications, and therefore a combination of WoS, Scopus, and Chinese bibliometric databases should be used to evaluate Chinese research performance [84].

3.2.2. Evolution of Scientific Production

According to Chen et al. [41], the number of LCA publications in WoS has experienced a notable increase, rising from 98 total publications in 1998 to 1313 total publications in 2013. The annual growth rate of LCA publications has averaged between 100 and 150 publications since 2008, as reported by Hou et al. [43]. As shown in Figure 2, the evolutionary pattern of published literature in Scopus since 1991 indicates an exponential growth trend.

Upon review of the chronological distribution of LCA publications, two notable turning points are evident. The first of these occurred in the year 2001, which followed a decade of standardisation in LCA from 1990 to 2000. The overall release rate of LCA publications increased by a substantial 653% between 2001 and 2006. Since 2006, exponential growth in LCA publications has persisted, which can be attributed primarily to the release of the ISO 14040:2006 edition. This growth trend could potentially be shaped by scientometric factors, as underscored by Mike and Pardeep [86], where the notable shift in the logarithmic curve in 2004, coinciding with Scopus's launch, implies a subsequent accelerated expansion. Notably, subsequent additions of journals have outweighed the impact of the initial 2004 release and subsequent backfilling endeavours. Delays in database entries, along with the inclusion of early access contents in WoS since 2017, as elaborated by Liu [87], may also contribute to this intricate growth trajectory.

Over the past 3 years, the total number of publications has demonstrated a consistent growth trend, with an average of 2565 publications per year. However, in 2022, a minor decrease was observed in the overall number of publications across both databases, compared to the count recorded in 2021. It is worth noting that this decrease could be attributed to disparities in publication years, as outlined in Section 3.1. Specifically, the publications indexed in the first month of 2023, which account for 495 records, could pertain to the year 2022.

The recent surge in publications related to LCA could be attributed to several factors, including the COVID-19 pandemic. The pandemic created opportunities for researchers to conduct focused research activities without the distractions of office life. However, the pandemic also posed challenges for research activities that require in-person interactions. Research studies by Raynaud et al. [88] and Aviv-Reuven and Rosenfeld [89] suggest that there has been a significant increase in COVID-19 publications, which may have led to a decrease in non-COVID-19 papers. Nevertheless, since LCA research applications typically do not require laboratory or fieldwork, the pandemic period could be considered a possible contributing factor to the recent increase in LCA publications.

Research is a multifaceted process that involves several factors, including access to funding, data and resources, opportunities for collaboration, and the quality of supervision. The quality of research output cannot be solely determined by the quantity of publications, but also by the impact and significance of the research findings. The recent surge in LCA publications may trigger concerns regarding their quality and validity, as frequently cited in the LCA literature. Moreover, the recent global crises, such as environmental and social shifts, financial instability, technological disruption, policies, and political turmoil, may have affected the LCA publication trends.

3.2.3. The Most Cited and Prolific Authors

Between the years 1999 and 2018, Moreira and Feijoo, both affiliated with the Spanish University of Santiago de Compostela, emerged as the two most prolific authors. Figure 4 depicts a density visualisation that portrays the co-citation patterns of highly cited authors during the time span from 1992 to 2022. Heijungs, Jolliet, Huijbregts, Hellweg and Frischknecht have contributed the highest to the number of total citations. In Table 4, the 20 most productive authors from 2019 to 2022 are presented, along with various bibliometric indicators, such as TP, affiliation, h-index, total documents, and total citation trends. The ranking of authors is based on TP, and in cases where authors have the same TP, the ranking is determined by TC.

In the period spanning from 2019 to 2022, Moreira has consistently maintained the top position owing to a publication record of 68 articles. Feijoo, secured the second rank with 57 articles, while Finkbeiner, occupied the third rank with 50 records. Notably, among the top 20 authors, Azapagic, from the University of Manchester, England, occupied the first position in terms of TC, with 2137 citations, followed by Dewulf, from Ghent University, Belgium, with 1983 citations. The evolution of citation counts aligns with the observed growth pattern in the total number of LCA publications as illustrated in Figure 5.

The national and institutional affiliations of the authors included in the list of the 20 most productive authors exhibit significant variability. Notably, no single country or institution is found to dominate the list, except for the University of Santiago De Compostela in Spain, which is represented by three authors on the list.

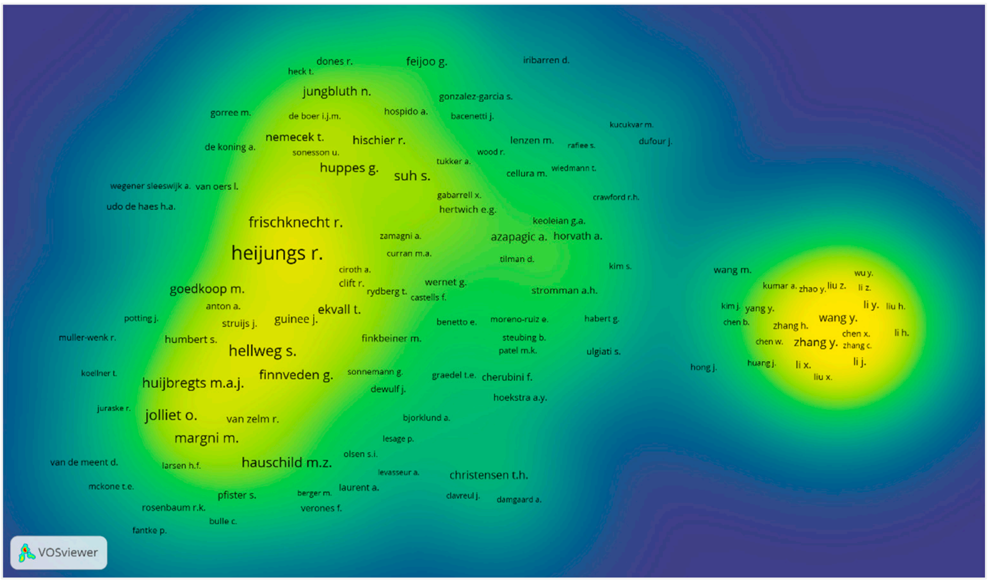


Figure 4. Co-citation density (Every data point (author) is assigned a colour based on the concentration "number of cited papers per author". These colours serve as indicators of the density, ranging from yellow denoting higher density and blue indicating lower density). Visualisation of highly cited authors in LCA publications (1992–2022).

Table 4. Top 20 most productive authors in LCA publications (2019–2022).

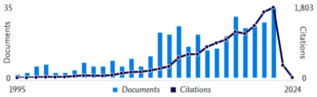
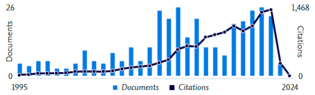
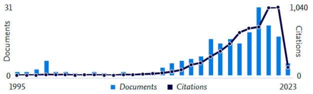
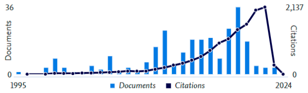
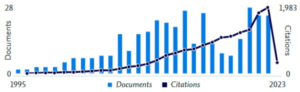
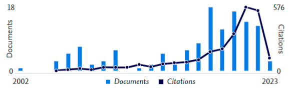
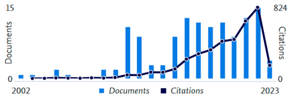
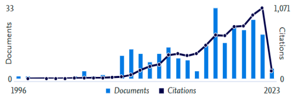
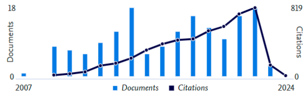
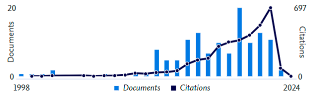
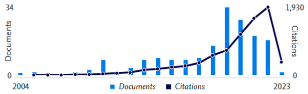
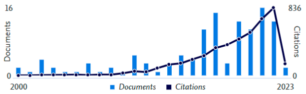
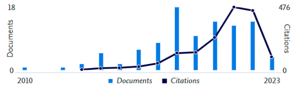
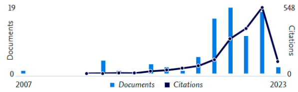
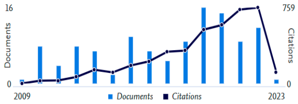
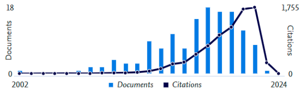
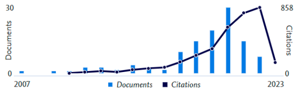
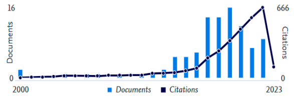
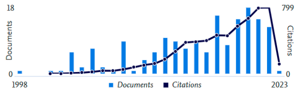
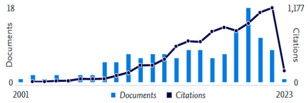
Author Name	TP	Institution	Country	h-Index	Documents and Citations Trend (A Graphical Summary Showcasing an Author's Yearly Publications Alongside Their Cumulative Citations).
Moreira, M.T.	68	University of Santiago De Compostela	Spain	65	
Feijoo, G.	57	University of Santiago De Compostela	Spain	65	
Finkbeiner, M.	50	Technical University of Berlin	Germany	44	
Azapagic, A.	48	University of Manchester	England	62	
Dewulf, J.	41	Ghent University	Belgium	63	
Aldaco, R.	38	Universidad de Cantabria	Spain	28	
Hong, J.	38	Shandong University	China	35	

Table 4. *Cont.*

Author Name	TP	Institution	Country	h-Index	Documents and Citations Trend (A Graphical Summary Showcasing an Author's Yearly Publications Alongside Their Cumulative Citations).
Gheewala, S.H.	36	King Mongkuts Univ Technol Thonburi	Thailand	50	
González-García, S.	36	Universidade de Santiago de Compostela	Spain	44	
Freire, F.	35	Universidade de Coimbra	Portugal	30	
Habert, G.	35	ETH Zurich	Switzerland	45	
Sonnemann, G.	35	Institut des Sciences Moléculaires	France	31	
Margallo, M.	34	Universidad de Cantabria	Spain	22	
Passer, A.	33	Graz University of Technology	Austria	17	
Iribarren, D.	32	Madrid Institute for Advanced Studies in Energy	Spain	40	
Sala, S.	32	European Commission Joint Research Centre	EU, Belgium	49	
Silvestre, J.D.	32	Universidade de Lisboa	Portugal	34	
Birkved, M.	31	University of Southern Denmark	Denmark	31	
Cellura, M.	31	University of Palermo	Italy	45	
Margni, M.	31	University of Applied Sciences Western Switzerland	Switzerland	45	

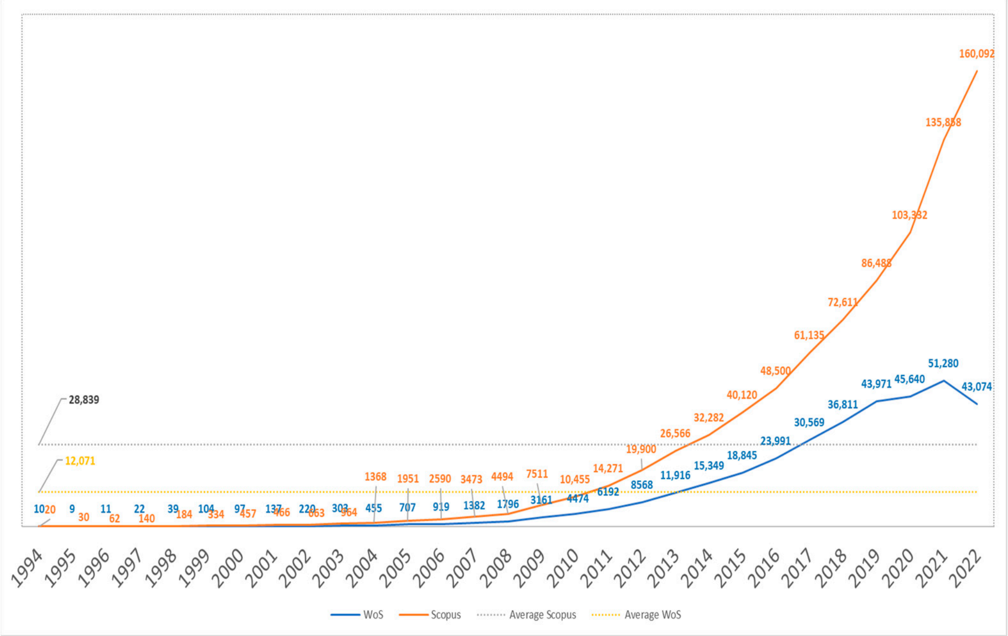


Figure 5. Total citation of LCA publications (1991–2022) in Web of Science and Scopus.

According to the TC/TP indicator for the period spanning 1999–2018, Jolliet, achieved the top ranking with an average of 72 citations per paper. Hauschild and Heijungs, from the University of Amsterdam, Netherlands followed closely behind [44]. For the period between 2019 and 2022, Sala, from the EU Commission Joint Centre attained the top ranking among the most productive authors, with Dewulf and Margni, following in second and third positions, respectively. Notably, most authors reached their maximum citation counts over the past 3 years, while the period from 2010 to 2022 exhibited the highest density of publications.

3.2.4. The Most Productive Countries/Territories

Since 2008, there has been a significant growth in LCA publications in both the United States and China. However, China has shown the most substantial growth rate since 2016 and is expected to surpass the US in the near future to become the most productive country in this area [44]. This broadly coincides with the conclusions drawn from various studies [90,91] regarding China's outstanding performance in terms of the quantity of indexed publications, particularly those indexed in SCI/SSCI. An overlay visualisation of co-authorship countries between 1992 and 2022 as presented in Figure 6 (The colour of a term indicates the average timeline of the total publications by country. The more prolific country and institute are based on the author's country affiliation), highlights the productivity of various countries in the LCA field. The USA, with 3263 publications (12.61%), is the most productive country, followed by China with 2262 publications (8.95%) and Italy with 2056 publications (6.93%). In terms of the TC indicator, the USA ranks first, followed by the UK, Italy, and China.

The present study illustrates a geographical map of regions exhibiting the highest LCA research output in the past 3 years, as depicted in Figure 7. Notably, China boasts a total production of 1669 publications, which constitutes 10.85% of the overall output, surpassing the United States with 1465 publications (9.52%), and closely followed by Italy with 1073 publications (6.99%). The term and geographical maps illustrated in Figures 7 and 8 demonstrate the worldwide distribution of the LCA concept. The results indicate that East Asian countries, including China, India, South Korea, and Japan, demonstrate the highest output, followed by North American, Western European, South American, Middle Eastern, and African countries. This trend suggests that the LCA concept has a global interest and finds applications across diverse regions.

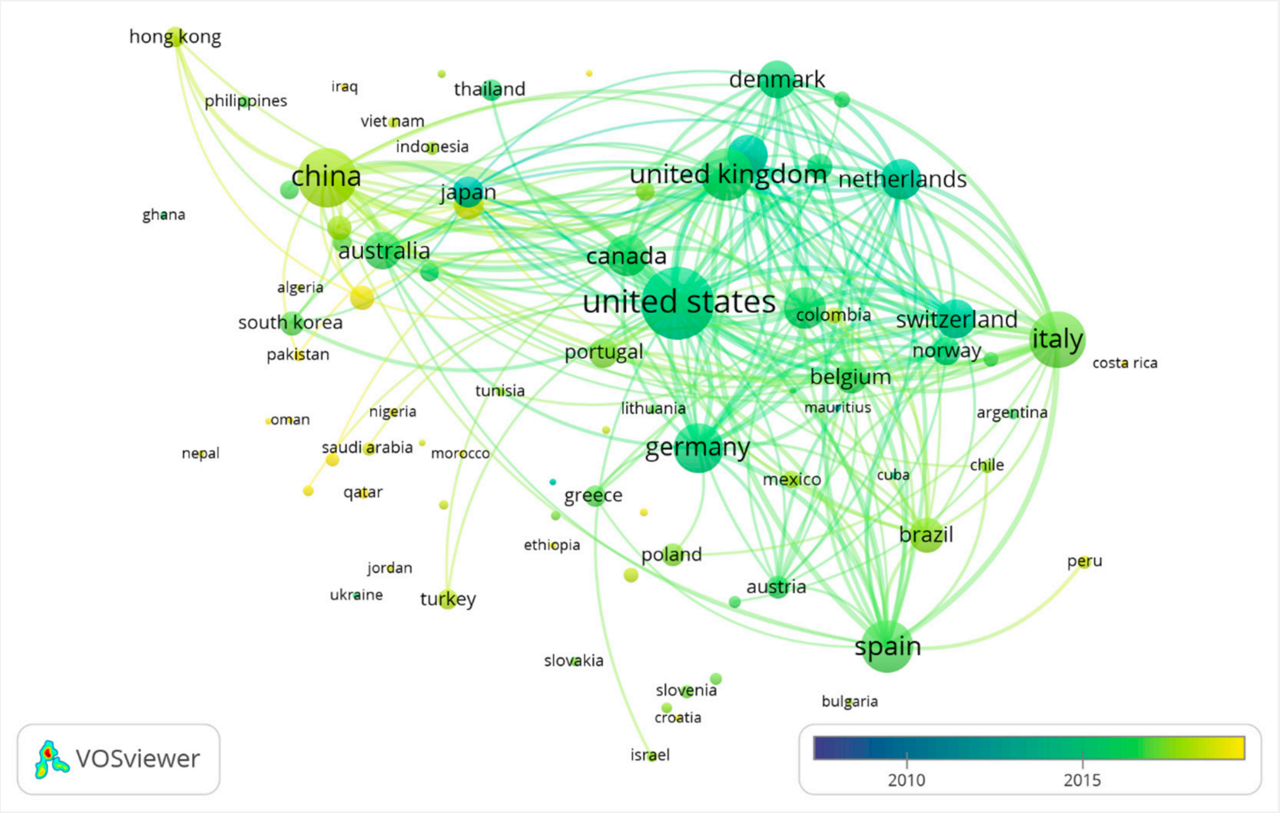


Figure 6. An overlay visualisation of co-authorship countries in LCA publications (1992–2022).

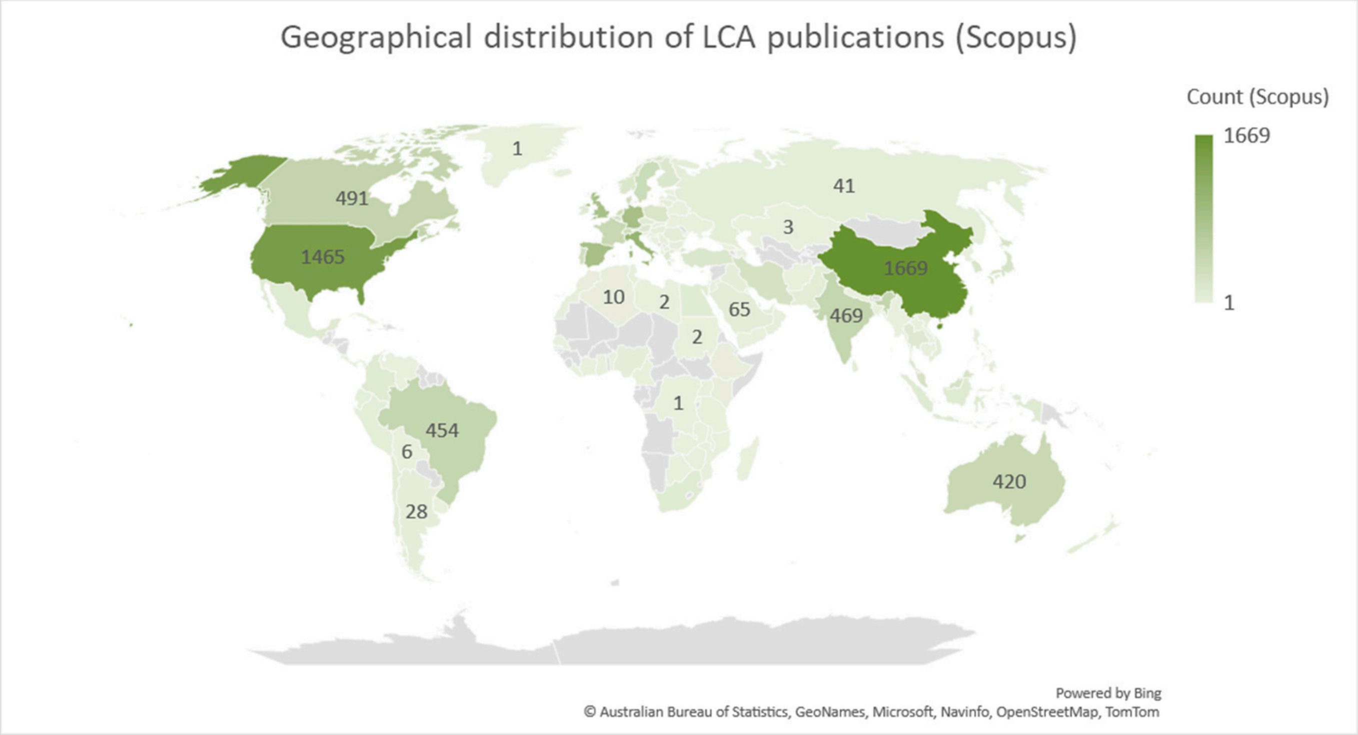


Figure 7. Geographical distribution of LCA publications for the period 2019–2022.

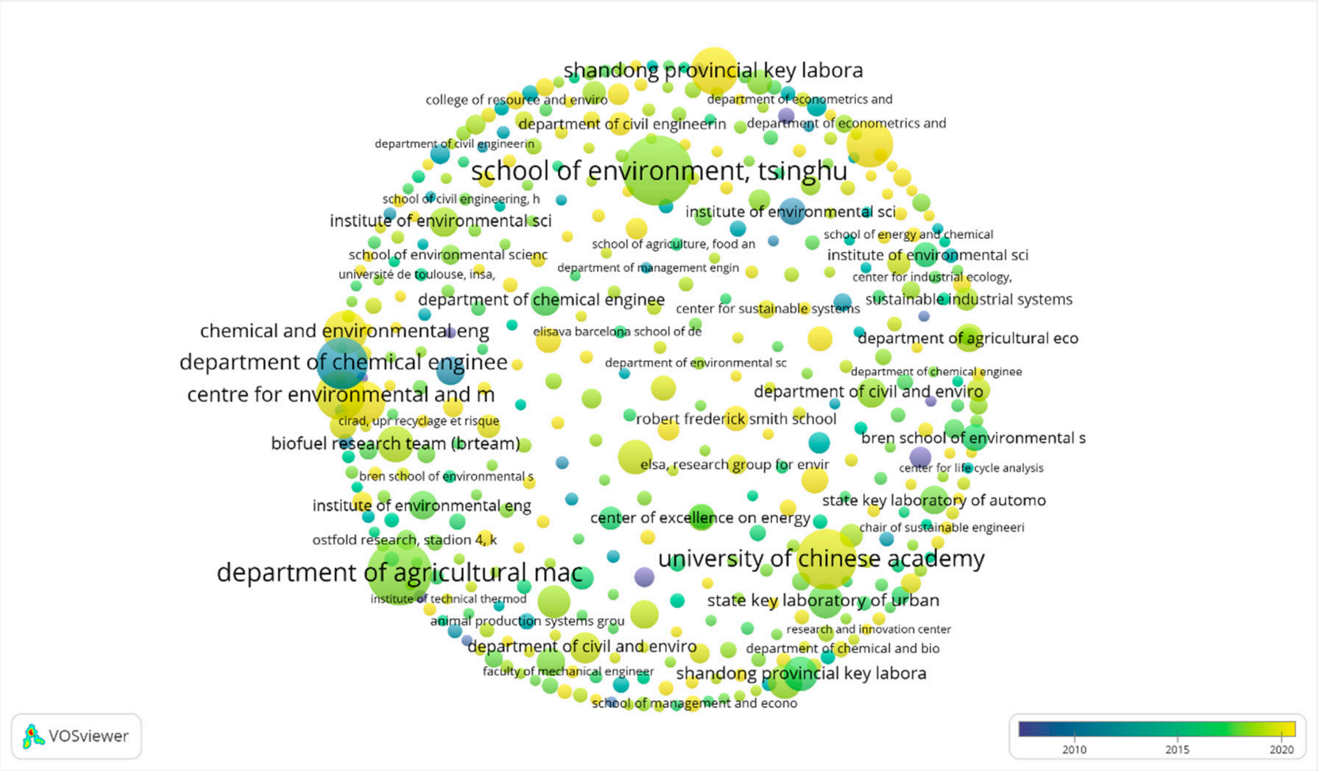


Figure 8. (The colour of a term signifies the average timeline of total citations by department, while the size of the nodes is determined by the total occurrences of citations.) An overlay visualisation depicting the total citations of LCA articles across institute departments from 1992 to 2022.

3.2.5. The More Productive Institutions and Departments

Numerous academic institutions from around the world are engaged in LCA-related research. Between 1999 and 2018, Technical University of Denmark ranks first. Notable institutions among the most productive institutes include the Technical University of Denmark, ETH-Zürich (Swiss Federal Institute of Technology in Zurich), University of California, Berkeley, Carnegie Mellon University, and the Norwegian University of Science and Technology, which all have a higher Average Citation Frequency of Article (ALCS), emphasising both quantity and quality of LCA-related research output [41,44].

Table 5 lists the 20 most productive institutions between 2019 and 2022, the ranking depends on the total productions, for the institutions with the same total production the ranking is determined by TC. The Chinese Ministry of Education and the Swiss Federal institutes of technology exceed Technical University of Denmark. The associated affiliations of China, Switzerland, Germany, France, and Belgium were found to dominate the 20 top productive institutions with more than two research institutes.

The present analysis encompasses departments within the most productive institutions in the field of LCA. Figure 8 displays a visualisation of departmental total citations from 1992 to 2022. It should be noted that some universities may have multiple active departments engaged in LCA research, such as the Technical University of Denmark, which includes the Department of Environmental Engineering, Department of Management Engineering, Department of Environment and Resources, and Department of Manufacturing Engineering and Management, as well as research groups and divisions within the same department, all with significant numbers of LCA-cited papers and indexed with different primary names that could affect their ranking in the term maps. It is noteworthy that the top three institutes published the highest number of articles in 2010, which has since decreased. This gap has been filled by other institutions, as evidenced by the increase in the total number of LCA-related publications, indicating that LCA has attracted attention from more institutions worldwide [43].

Table 5. More productive institutions in the field of LCA (2019–2022).

Rank 1–10				**10–20**			
Institution	**Count**	**%**	**Country**	**Institution**	**Count**	**%**	**Country**
Ministry of Education China	192	2.45	China	Universiteit Gent	89	1.14	Belgium
Technical University of Denmark	161	2.06	Denmark	University of Tehran	88	1.12	Iran
ETH Zürich	149	1.90	Switzerland	The Royal Institute of Technology KTH	86	1.10	Sweden
Chinese Academy of Sciences	137	1.75	China	Universidad de Santiago de Compostela	86	1.10	Spain
CNRS Centre National de la Recherche Scientifique	116	1.48	France	The University of Manchester	84	1.07	UK
Norges Teknisk-Naturvitenskapelige Universitet	108	1.38	Norway	University of Michigan, Ann Arbor	83	1.06	USA
Tsinghua University	107	1.37	China	Aalborg University	81	1.04	Denmark
Technische Universität Berlin	99	1.27	Germany	Universidade de Lisboa	81	1.04	Portugal
Politecnico di Milano	93	1.19	Italy	KU Leuven	78	1.00	Belgium
Chalmers University of Technology	91	1.16	Sweden	European Commission Joint Research Centre	78	1.00	EU Belgium

The Environmental Engineering Department of the Technical University of Denmark, the Institute of Environmental Engineering of ETH Zurich, and the Department of Chemical Engineering of the University of Santiago de Compostela are the most productive departments in terms of the number of LCA-related publications. On the other hand, the Department of Civil and Environmental Engineering at the School of Environment, Tsinghua University, the Department of Agricultural Machinery Engineering at the Faculty of Agricultural Engineering and Technology, University of Tehran, Iran, and the University of Chinese Academy of Science with other departments are emerging as the most promising departments in the LCA field.

3.2.6. Knowledge Diffusion and Cooperation Network

Authors de Souza and Barbastefano [39] showed a co-authorship social network formed by 2598 authors from 60 countries, 88% of co-authored articles, a mean of 1.87 authors per article; the LCA community forms a giant component which is still small, but which, nevertheless, might experience considerable growth in the near future. He and Yu [44] found that the cooperation intensity of the USA with Canada, China, Netherlands, England, and other countries is remarkably high. The USA is playing a key role in the LCA research, and China, Canada, UK, Netherlands, and Germany are most frequently cooperating with the USA. France and Germany have the closest cooperation with Switzerland, while the first partner country of Italy is Spain. The LCA co-authorship networks were concentrated in Europe and the USA, with limited representation in Africa, the Middle East, and Central Asia as illustrated in Figure 6.

The results of the survey conducted by Bjørn et al. [40], which gathered data from 25 global, regional, and local LCA networks observed that the global trend toward the formation of LCA networks appears to be on the rise, and this trend correlates with the number of LCA scientific publications published during the same time period.

The network visualisation presented in Figure 9 illustrates the co-authorship organisation within the LCA research field during the period spanning from 2019 to 2022. The visual depiction of the network reveals that China assumes a central position in LCA research cooperation by actively engaging with various institutions globally, and not just limited to a specific geographic location. Furthermore, it is worth noting that China maintains multiple affiliations, including those associated with academic and research institutions. Among the Asian countries, institutions engaged in academia are at the forefront of the LCA co-authorship network. While a majority of the LCA co-authorship is concentrated within academic institutions, the network also encompasses non-governmental institutions and research centres, albeit to a lesser extent.

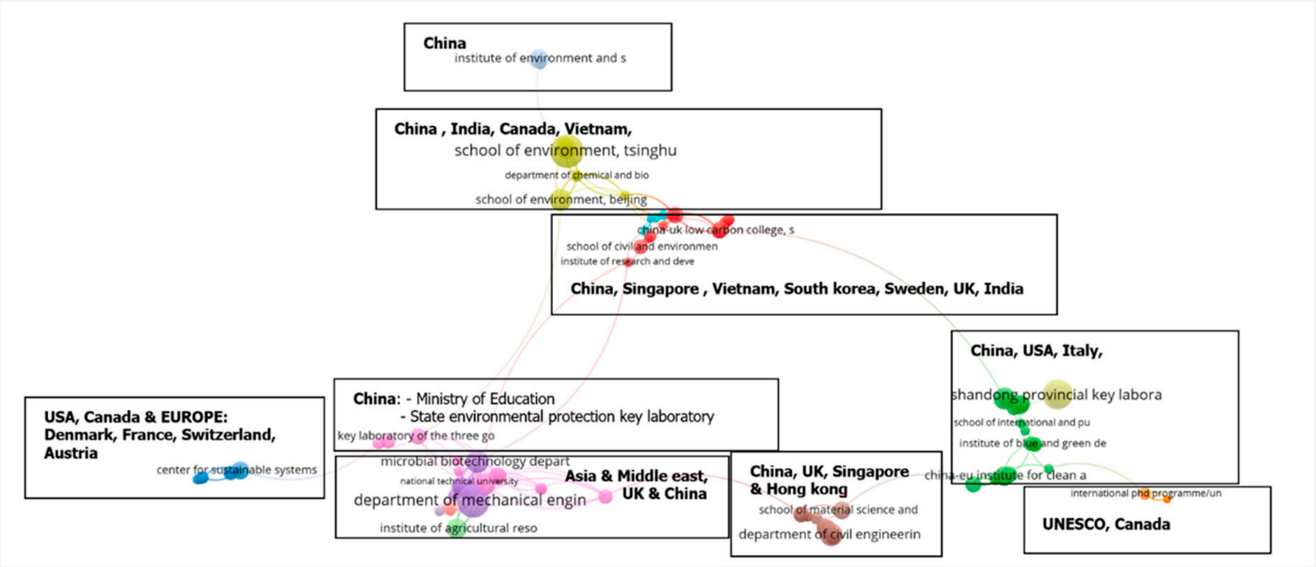


Figure 9. Network visualisation of co-authorship organisations in LCA publications (2019–2022).

3.2.7. Funding Agencies

This section focuses on evaluating the coverage of research funding information within LCA papers. Thorough care has been taken in collecting and interpreting the results, considering potential data quality issues and caveats associated with funding information in Scopus, highlighted in prior studies [92,93].

The provision of funding for academic research is a vital component in advancing a given field and generating new knowledge. In this regard, Figure 10 depicts the trajectory of LCA research funding by organisation, displaying the evolutionary pattern of funding agencies since 1991.

The exponential growth trend observed in this context has led to a marked increase of 1191% evolution in comparison to 2010 with 128% (APGR). The numbers of funded publications marked a rapid increase during the period from 2004 to 2010 and then exponential increase from 2010 to the present. National Natural Science Foundation of China has taken the lead, closely followed by the European Commission with the Horizon 2020 Framework Programme.

The significant rise in funding has facilitated the growth of research institutions, researchers, and collaborations, as demonstrated in Figures 6 and 9. Consequently, this has fostered a more dynamic and competitive LCA research environment, which has driven further research growth and publications, as illustrated in Figure 2.

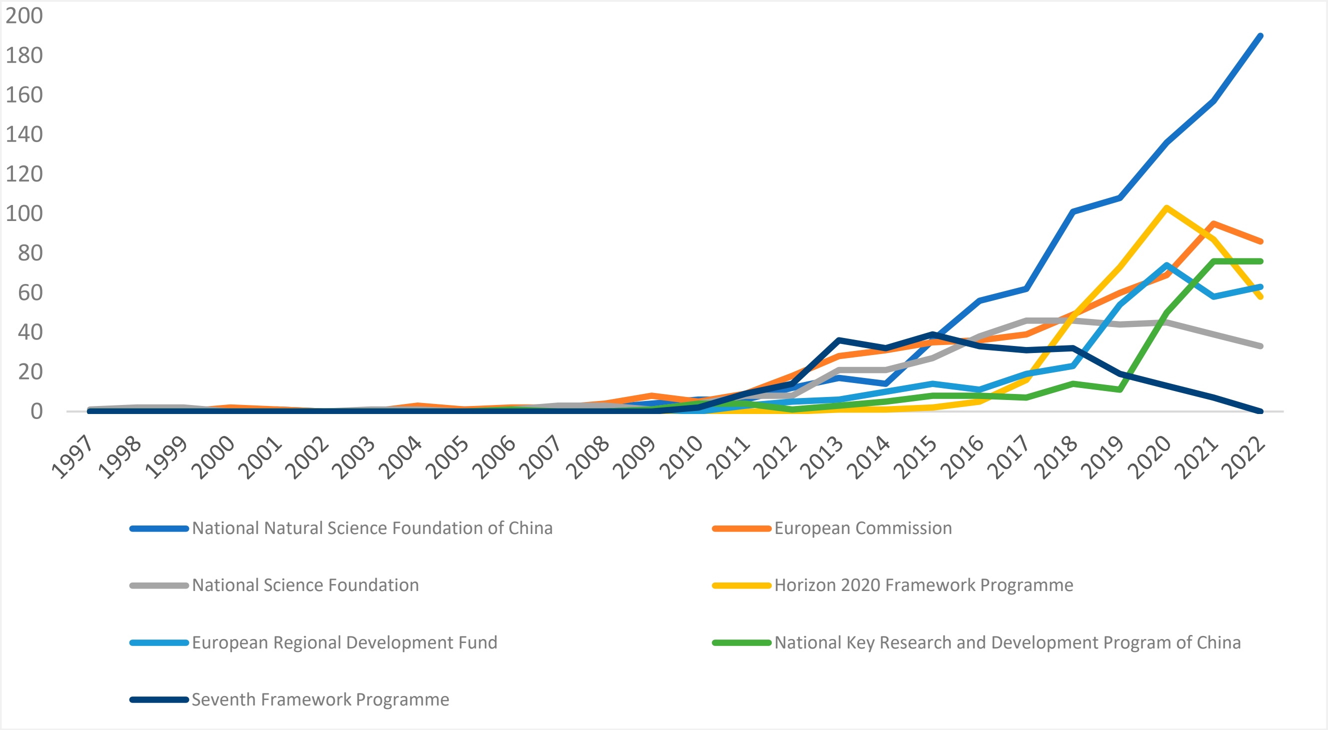


Figure 10. Evolution of LCA Funding by top funding sponsors (1991–2022).

The increase in research funding associated with LCA can be ascribed to multiple factors including regulatory, economic, and technological aspects, along with a burgeoning awareness of sustainability and environmental stewardship. The rising consciousness of environmental concerns, such as climate change, pollution, and depletion of natural resources, has intensified the emphasis on comprehending the impact of human activities on the environment.

Moreover, governments and regulatory bodies at the global level are increasingly mandating companies to conduct environmental impact assessments and adopt sustainable practices. Companies are recognising the importance of incorporating sustainability in their business operations to augment their Corporate Social Responsibility (CSR). Technological advancements, including remote sensing, data analytics, and artificial intelligence, have facilitated the acquisition, analysis, and interpretation of environmental data. Collaboration among scholars, industry experts, and government authorities has become more prevalent in recent times, resulting in escalated funding for LCA and environmental sustainability research, as stakeholders acknowledge the significance of joint efforts in addressing environmental challenges.

Table 6 shows the 20 top funding sponsors between 1992 and 2022. The associated affiliations and agencies of China were found to dominate the top sponsoring institutions representing more than 14% of indexed sponsored papers, notably National Natural Science Foundation of China (8%), Key Research and Development Program of China (3%), China Scholarship Council (2%), and Fundamental Research Funds for the Central Universities (1%). The European funding agencies ranked second representing more than 13% of indexed sponsored papers notably, European Commission (5%), Horizon 2020 Framework Programme (now is Horizon Europe) (3%), European Regional Development Fund (2%), and Seventh framework program (1%). Brazil represents more than 5% of indexed sponsored papers through Coordination for the Improvement of Higher Education Personnel (2%) and National Council for scientific and technological development (2%). The USA's National science foundation (3%) ranked in third position as LCA-related research funding sponsor. The Engineering and Physical Sciences Research Council (2%) and Natural

Sciences and Engineering Research Council of Canada (1%) are also among the top UK funding institutions.

Table 6. Top 20 funding sponsors for LCA publications (2019–2022).

Funding Sponsor	**Documents**	**Contribution**
National Natural Science Foundation of China	732	9.50
Horizon 2020 Framework Programme	397	5.15
European Commission	375	4.87
European Regional Development Fund	309	4.01
National Key Research and Development Program of China	258	3.35
National Science Foundation	239	3.10
Conselho Nacional de Desenvolvimento Científico e Tecnológico	191	2.48
Horizon 2020	188	2.44
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	187	2.43
Fundação para a Ciência e a Tecnologia	184	2.39
Engineering and Physical Sciences Research Council	143	1.86
Fundamental Research Funds for the Central Universities	139	1.80
US Department of Energy	139	1.80
Ministerio de Economía y Competitividad	135	1.75
Natural Sciences and Engineering Research Council of Canada	126	1.64
Bundesministerium für Bildung und Forschung	117	1.52
National Research Foundation of Korea	88	1.14
China Scholarship Council	82	1.06
Ministerio de Ciencia, Innovación y Universidades	79	1.03
National Institute of Food and Agriculture	72	0.93

Apart from the existing leading funding institutions, several organisations have emerged as significant contributors to LCA-related research funding. Notably, the US Department of Energy sponsored 184 publications, while the Ministry of Economy and Competitiveness of Spain sponsored 135 publications and the Federal Ministry of Education and Research of Germany sponsored 117 publications.

Figure 11 presents a visual representation of the network of co-funding sponsored organisations, which highlights the collaborative research efforts aimed at addressing global environmental challenges. These endeavours have the potential to promote interdisciplinary research, optimise resource utilisation, foster the development and implementation of global standards, and facilitate policy development. Given the pressing environmental concerns, such as climate change, biodiversity loss, and pollution, international research funding agencies recognise the importance of supporting coordinated efforts to mitigate these challenges. As environmental impact assessment is a multidisciplinary field, collaboration and co-funding are crucial to achieving optimal outcomes. By pooling resources, sharing knowledge and expertise, and promoting global standards, funding agencies can leverage their position to create a more sustainable future. Moreover, supporting evidence-based policy development through co-funding of research and collaborative efforts in environmental impact assessment can contribute to achieving this goal.

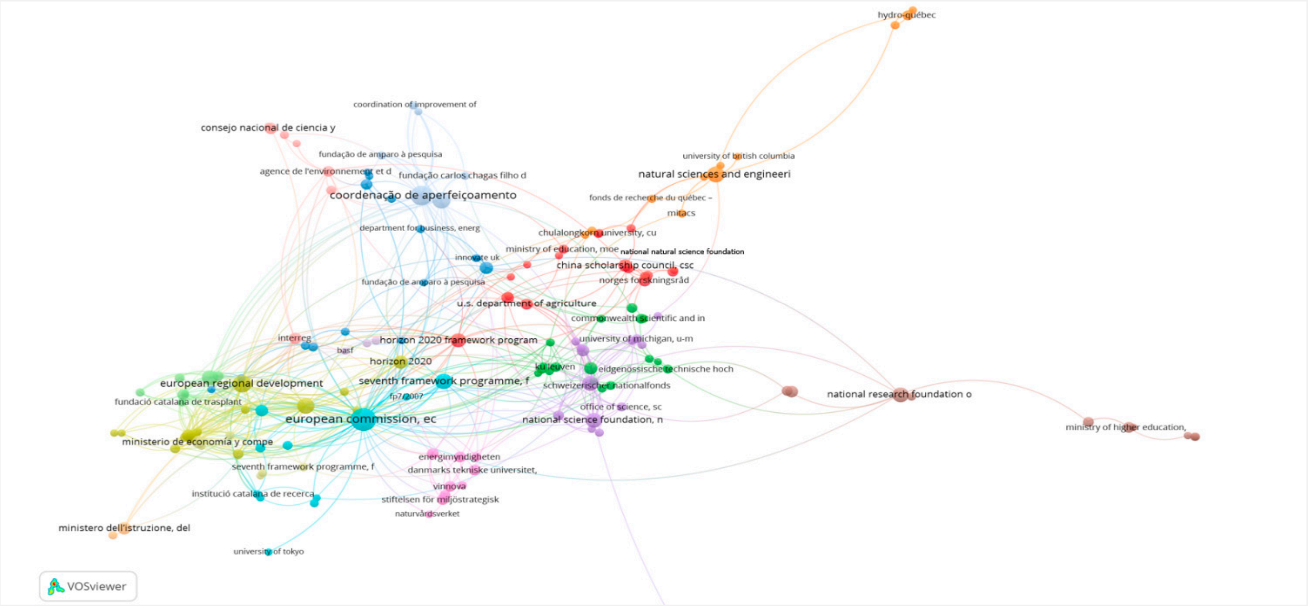


Figure 11. Network visualisation of co-funding organisations.

3.2.8. The Most Researched Areas

The collected publication data have been categorised into 27 subject areas indexed in Scopus. Table 7 illustrates that environmental science (27%), engineering (20%), energy (16%), and business, management, and accounting (7%) are the top subject areas in terms of the number of publications. The remaining subject areas, representing 29% of the total, are notably Social Sciences (4.5%), Chemical Engineering (3.6%), and Materials Sciences (3.4%). This observation indicates that LCA is a multidisciplinary field that encompasses a diverse range of research areas and subjects.

Table 7. Most productive subject areas in LCA publications (2019–2022).

Subject Area	Count	Percentage
Environmental Science	5004	27.27%
Engineering	3369	18.36%
Energy	3204	17.46%
Business, Management, and Accounting	1140	6.21%
Social Sciences	999	5.44%
Chemical Engineering	48	3.53%
Materials Science	86	3.19%
Agricultural and Biological Sciences	28	2.88%
Chemistry	40	2.40%
Computer Science	67	2.54%
Mathematics	71	2.02%
Economics, Econometrics, and Finance	307	1.67%
Earth and Planetary Sciences	85	2.10%
Physics and Astronomy	58	1.41%
Biochemistry, Genetics, and Molecular Biology	61	0.88%
Decision Sciences	12	0.61%

Table 7. *Cont.*

Subject Area	Count	Percentage
Medicine	49	0.81%
Multidisciplinary	6	0.36%
Arts and Humanities	0	0.11%
Immunology and Microbiology	8	0.15%
Pharmacology, Toxicology, and Pharmaceutics	3	0.18%
Veterinary	0	0.16%
Health Professions	4	0.13%
Nursing	7	0.09%
Neuroscience	2	0.01%
Psychology	2	0.01%

Figure 12 displays the temporal evolution of publications categorised by subject area, indicating an increase in the number of articles published in the top five subject categories during the period spanning from 1998 to 2009, followed by an exponential growth from 2009 to the present time. Engineering sciences were the primary research area during the 1992–2005 period, closely followed by environmental sciences, with environmental science becoming the leading research domain of LCA since 2015.

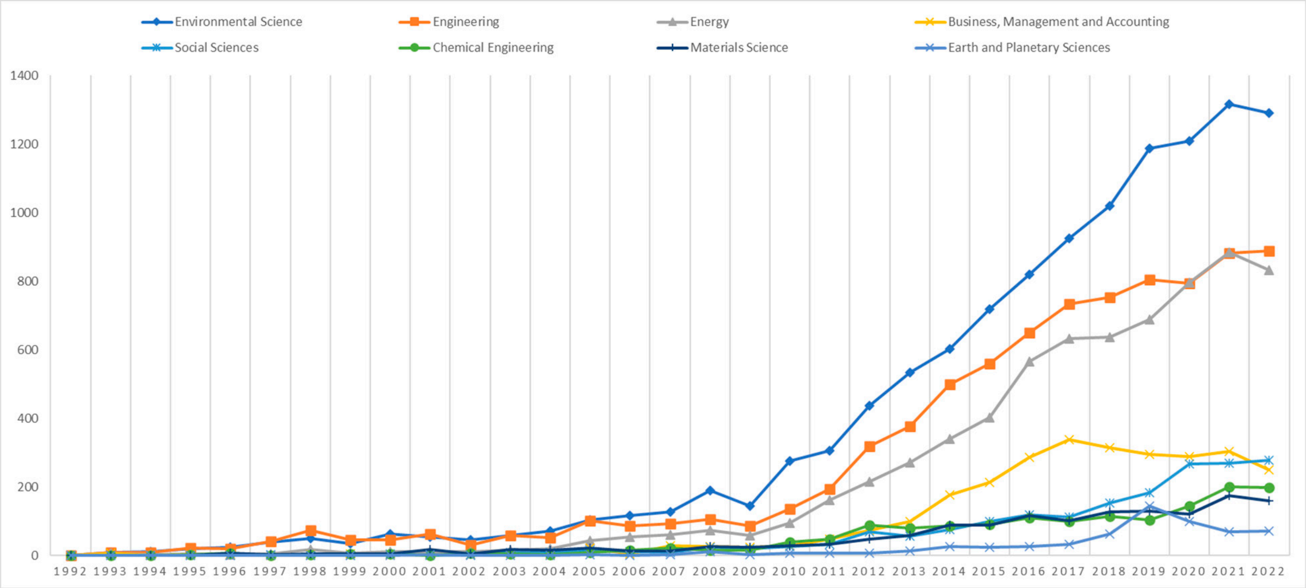


Figure 12. Evolution of LCA publications per subject area (1991–2022).

Notably, since 2010, two emerging research subjects, namely, social sciences and business management, have gained increasing attention, suggesting a heightened focus on the social aspects of LCA alongside its environmental dimensions. This has led to the emergence of Social Life Cycle Assessment (SLCA). Additionally, the integration of LCA into business management has become increasingly crucial over the last decade, enabling businesses to identify opportunities for improvement, manage their environmental impact more effectively, and provide stakeholders with transparent information regarding the sustainability of their products and services.

Through the application of bibliographic coupling of highly cited papers, the main subject areas of LCA research were classified into eight nodes that form high-density clusters, representing the intellectual base of LCA research environment. The identification of research fronts and corresponding intellectual bases allowed for an initial understanding of the intellectual structure of LCA research, which is further explored in Section 3.2.11. The network visualisation map in Figure 13 reveals the highly cited subject areas in LCA research, including the building sector [94,95], LCA methodology [96,97], LCA development [6,34], bioenergy [98], design and energy [99], biofuel [100,101], agriculture and food products [102], carbon footprint, and sustainability [103] as well as other fields such as materials [104,105].

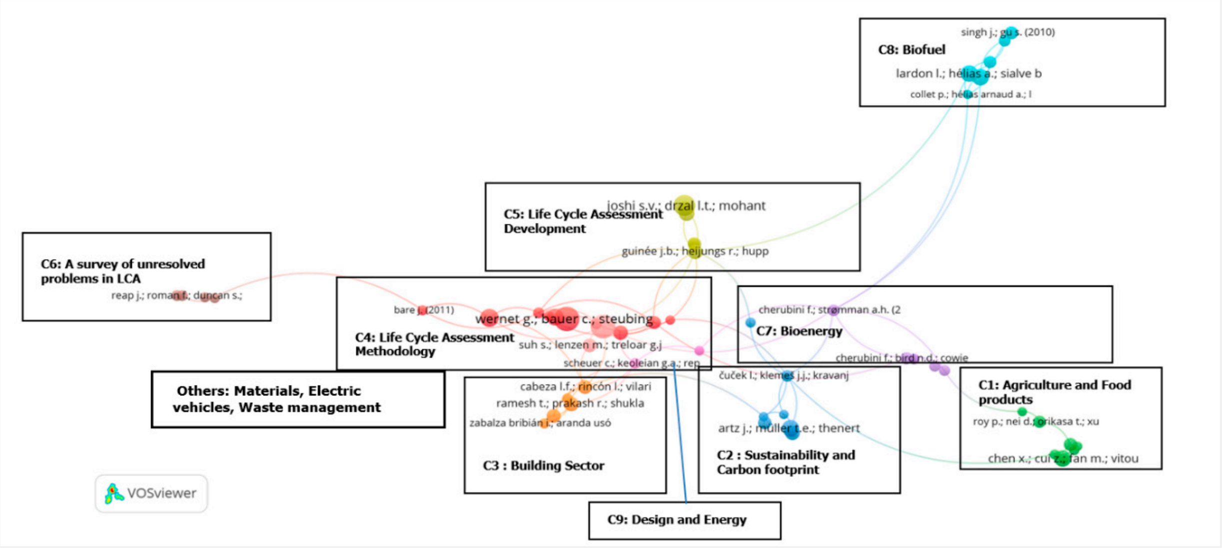


Figure 13. Bibliographic coupling of highly cited papers indicating the correlation between subject areas in LCA publications.

3.2.9. Analysis by Journals Source

According to Scopus, there are a total of 160 journals that have published LCA-related publications, covering a wide range of topics from engineering, science and technology, agriculture, materials science, economics, social sciences, etc. This indicates that the LCA field and approach have drawn significant interest and are widely applied across various academic disciplines.

Figure 1 depicts the evolution of LCA publications per year by source since 1991, while Table 8 lists the most influential journals between 2019 and 2022 including several bibliometric indicators, such as total publications, contribution, publisher, quartiles, and journal overall CiteScore. Among the most influential journals in terms of publication count are the Journal of Cleaner Production (JCP), International Journal of Life Cycle Assessment (IJLCA), Science of the Total Environment (JSTE), Resources, Conservation, and Recycling (RCR), Sustainability (Switzerland), Environmental Science Technology (EST), and Journal of Industrial Ecology. The number of articles published per source experienced a rapid increase between 1998 and 2009, followed by an exponential increase from 2009 to the present. IJLCA had the highest publication count between 1992 and 2013 but was surpassed by JCP and Sustainability (Switzerland) in 2020. Notably, several emerging journals have shown remarkable growth since 2010, including Energies, Resources Conservation and Recycling, Waste Management, Applied Energy, and Bioresource Technology.

Figure 14 highlights the most influential journals in terms of both citations and publication count since 1993. The citation count per source experienced a rapid increase between 1998 and 2009, followed by an exponential increase from 2009 to the present. IJLCA was the leading journal between 1992 and 2013 but was surpassed by JCP, EST, and STE in 2020.

Table 8. Top journals (2019–2022) for LCA publications.

Journal	Contribution	Publisher	Quartiles	CiteScore
Journal Of Cleaner Production	16.21%	Elsevier	Q1	15.8
Sustainability Switzerland	7.21%	MDPI	Q2	5
International Journal of Life Cycle Assessment	6.65%	Springer	Q1	8.4
Science Of the Total Environment	6.31%	Elsevier	Q1	14.1
Resources Conservation and Recycling	4.53%	Elsevier	Q1	17.9
Energies	3.60%	MDPI	Q2	5
Journal Of Environmental Management	2.07%	Elsevier	Q1	11.4
Journal Of Industrial Ecology	2.05%	Wiley-Blackwell	Q1	12
ACS Sustainable Chemistry and Engineering	1.89%	American Chemical Society	Q1	14.5
Renewable And Sustainable Energy Reviews	1.71%	Elsevier	Q1	28.5

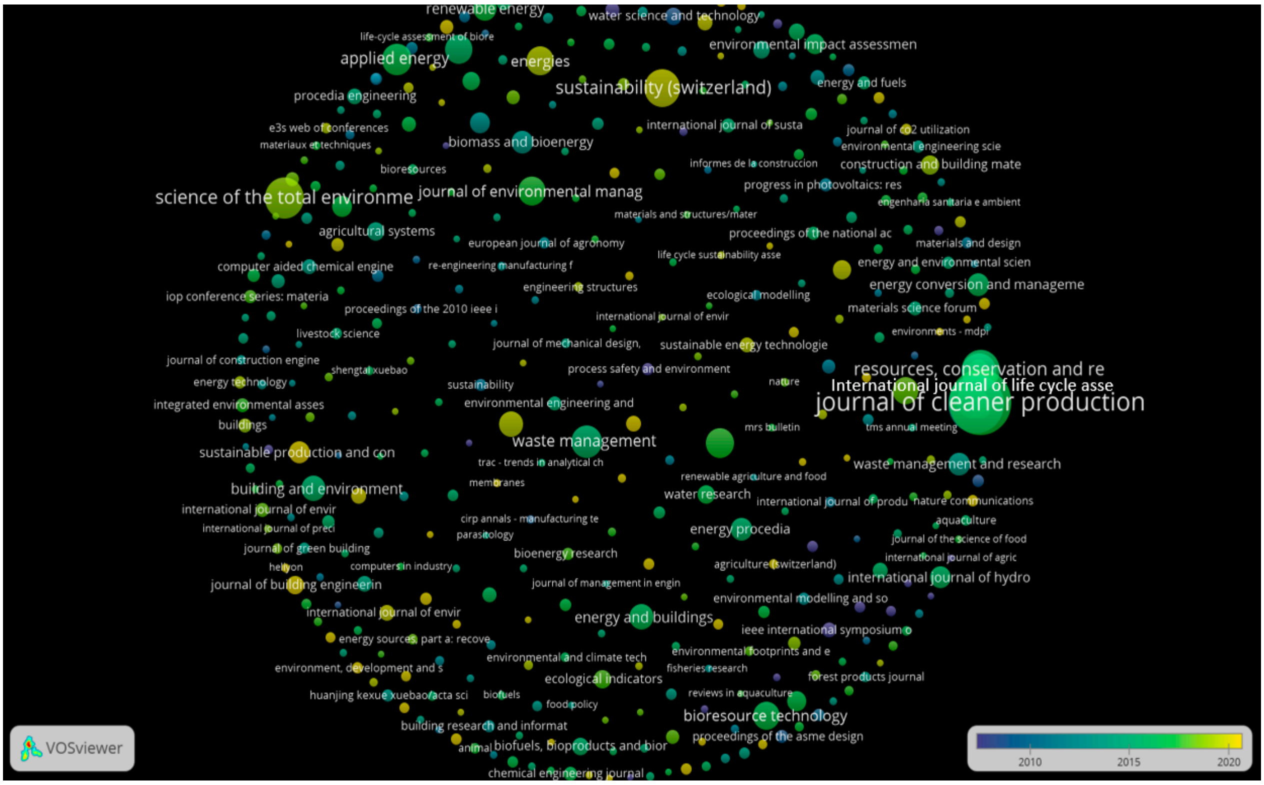


Figure 14. An overlay visualisation of total citations and productions for journals (1992–2022) in LCA publications.

The decline in publication count of the IJLCA can be attributed to the LCA field reaching a knowledge maturity and expanding to a wider range of applications. Furthermore, IJLCA currently focuses primarily on publishing research papers related to LCA methodology, tools, and applications that contribute new insights or extend the current state of knowledge in LCA.

Among the highest cited and production journals, the Applied Energy journal ranked first in terms of the TC/TP indicator, indicating its quality and relevance to the LCA field.

This was followed by the Journal of Environmental Management, Energy and Buildings, IJLCA, Bioresource Technology, and JCP.

3.2.10. Top Cited Articles

Table 9 delineates the attributes of articles, including the authors, years of the publication, total citations, journal titles, and keywords spanning from 1991 to 2022. Among these highly cited papers, Chong et al. [106] "Recent developments in photocatalytic water treatment technology: A review" garnered the most citations, totalling 3879, and briefly discussed the LCA involved in retrofitting the photocatalytic technology as an alternative waste treatment process. Wernet et al. [96] "The Eco invent database version 3 (part I): overview and methodology" ranked second and expounded on the methodological advancements of the Ecoinvent database version 3, one of the world's primary and widely used Life Cycle Inventory (LCI) databases. Finnveden et al. [16] "Recent developments in Life Cycle Assessment" provided a comprehensive review of methodological improvements and emerging issues in the field. Finally, Rebitzer et al. [107] "Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications" introduced the LCA framework and procedures for calculating emissions and resource consumption data in a Life Cycle Inventory (LCI). The observed upward trajectory in citation counts for the most frequently cited papers since their publication suggests their significance as reference papers in the field of LCA applications.

Table 9. Highly cited articles during 1991–2022.

Author and Year of Publication	**Total**	**Title**	**Journal**	**Keywords**
Chong, et al., (2010)	3879	Recent developments in photocatalytic water treatment technology: A review [106]	Water Research	TiO_2; Photocatalysis; Water treatment; Photocatalytic reactors; Kinetic modelling; Water qualities; Life cycle analysis; Mineralisation; Disinfection
Wernet et al., (2016)	2189	The Ecoinvent database version 3 (part I): Overview and methodology [96]	IJLCA	Ecoinvent version 3; Life Cycle Assessment (LCA); Life Cycle Inventory (LCI) database; Parametrisation; Regionalisation; System model
Finnveden et al., (2009)	2060	Recent developments in Life Cycle Assessment [16]	Journal of Environmental Management	Life Cycle Assessment (LCA) Strategic; Environmental Assessment; Risk assessment; LCC; Ecological footprint; Exergy analysis; Valuation; Weighting
Joshi et al., (2004)	1700	Are natural fibre composites environmentally superior to glass fibre reinforced composites? [104]	Composites Part A: Applied Science and Manufacturing	Natural fibres; A. Glass fibres
Binnemans et al., (2013)	1494	Recycling of rare earths: A critical review [19]	Journal Of Cleaner Production	Balance problem; Lanthanides; Rare earths; Recycling; Resource; Recovery; Urban mining
Mueller and Nowack (2008)	1476	Exposure modelling of engineered nanoparticles in the environment [108]	Environmental Science and Technology	Environmental Exposure; Nanoparticles

Table 9. *Cont.*

Author and Year of Publication	Total	Title	Journal	Keywords
Zhu et al., (2016)	1420	Sustainable polymers from renewable resources [109]	Nature	Catalysis; manufacturing; polymer; polymerisation; renewable resource; sustainability
Al-Salem et al., (2009)	1372	Recycling and recovery routes of Plastic Solid Waste (PSW): A review [110]	Waste Management	Municipal solid waste; plastic waste; polymer; recycling; sustainability; waste treatment
Rebitzer et al., (2004)	1300	Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications [107]	Environment international	Environmental impact; human activity; inventory; life cycle analysis; pollution effect; sustainable development
Vance et al., (2015)	1298	Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory [111]	Beilstein Journal of Nanotechnology	Consumer products; database; inventory; nanoinformatics; nanomaterials

Figure 15 presents an overlay visualisation illustrating the most frequently cited articles between 2019 and 2022. These articles are centred around five pivotal subject areas. Notably, energy, including clean energy technologies and energy storage technologies like vehicle battery storage [112,113], fuel cells [114], hydrogen production [115], and bioenergy, encompassing biofuels [116,117], are taking the forefront. The second significant subject area focuses on waste management and its associated technologies [118,119]. The third key domain is dedicated to the building sector, encompassing assessments of embodied greenhouse gases [120], green building [121], and materials like geopolymer concrete [122]. Decarbonisation technologies, notably carbon capture [123,124], constitute the fourth focal area. The fifth critical aspect pertains to composite materials, with a special emphasis on bio composites [125,126].

The outcomes presented in Table 9 and Figure 15 corroborate the research subject areas outlined in Section 3.2.8. Notably, highly cited papers align closely with the same top LCA subject areas. However, over the past 4 years, a novel sub-topic has emerged within highly cited papers. This new sub-topic delves into the environmental impact assessment of decarbonisation technologies. This underscores the pivotal role of LCA as a fundamental tool accompanying the development and evaluation of innovative technologies and strategies geared toward minimising environmental impacts.

Figure 16 displays a co-citation network visualisation of the top 100 cited papers in the field of LCA, which presents the most significant publications concerning LCA methodology. Notably, the key references in LCA are the methodology and development documents including the International Standards, which provide the fundamental principles and framework for conducting LCA, namely, the ISO 14040 series [1,127]. Other essential publications in this area include "The Eco invent database version 3 (part I): overview and methodology" by Wernet, Bauer [96], "The computational structure of life cycle assessment", "Recent developments in life cycle assessment" by Finnveden et al. [16], "International reference life cycle data system (ILCD) handbook—general guide for life cycle assessment—detailed guidance" by Joint Research Centre and Institute for Environment and Sustainability. [128], and "Emerging approaches, challenges and opportunities in life cycle assessment" by Hellweg and Canals [34].

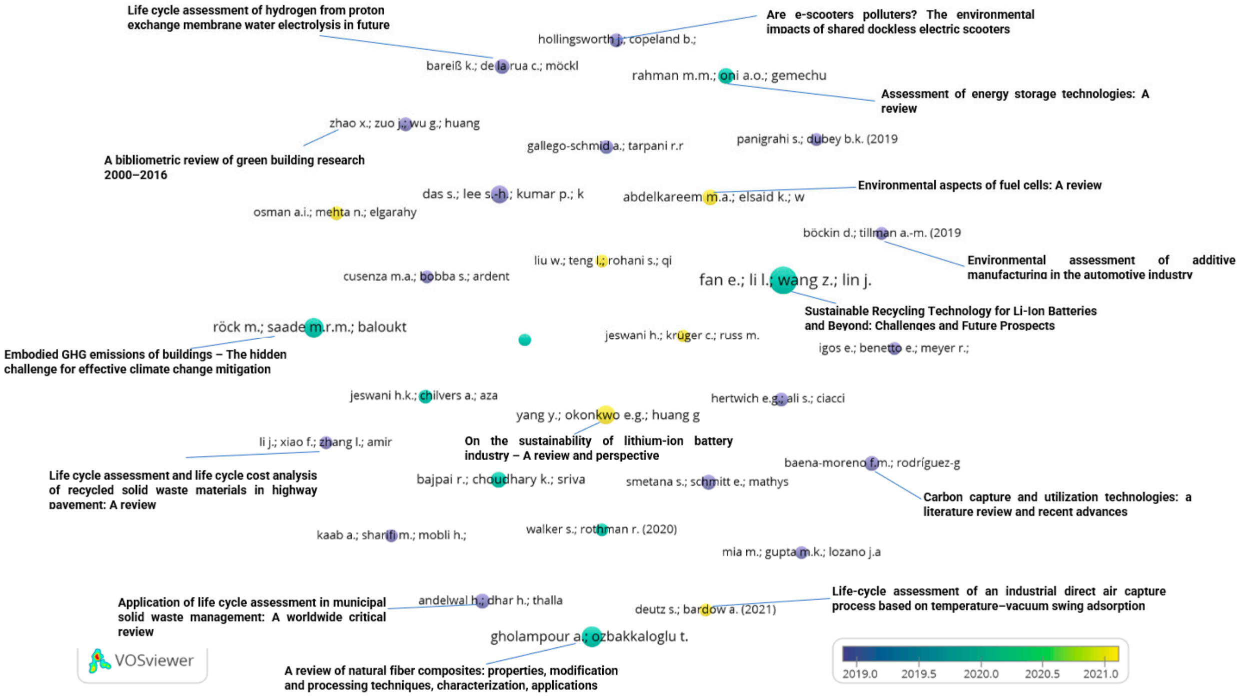


Figure 15. An overlay visualisation of highly cited articles (2019–2022) in LCA publications.

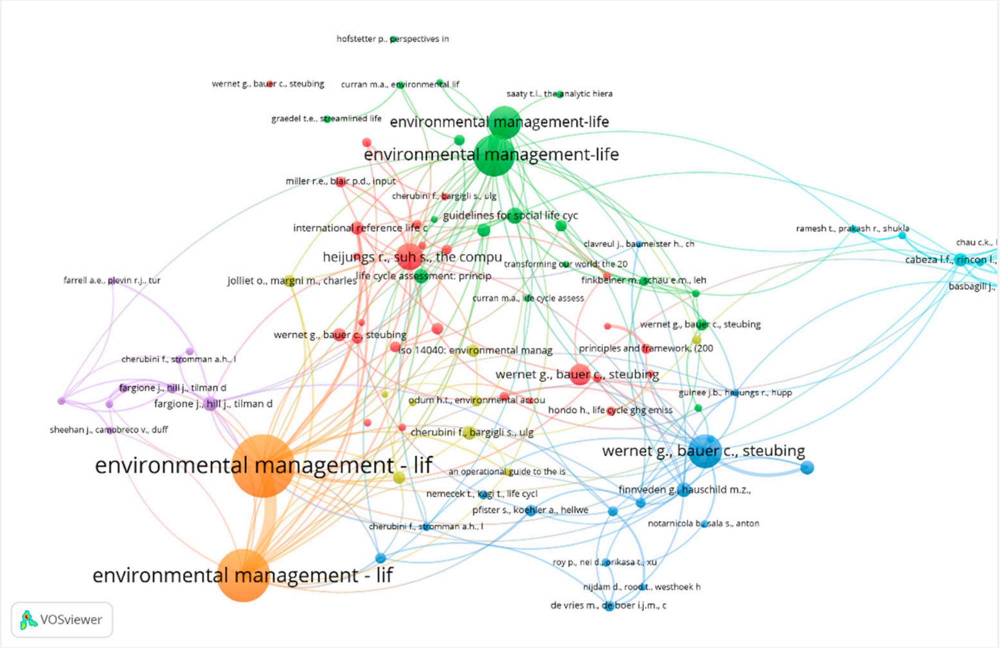


Figure 16. Co-citation network visualisation of top 100 cited papers in LCA publications.

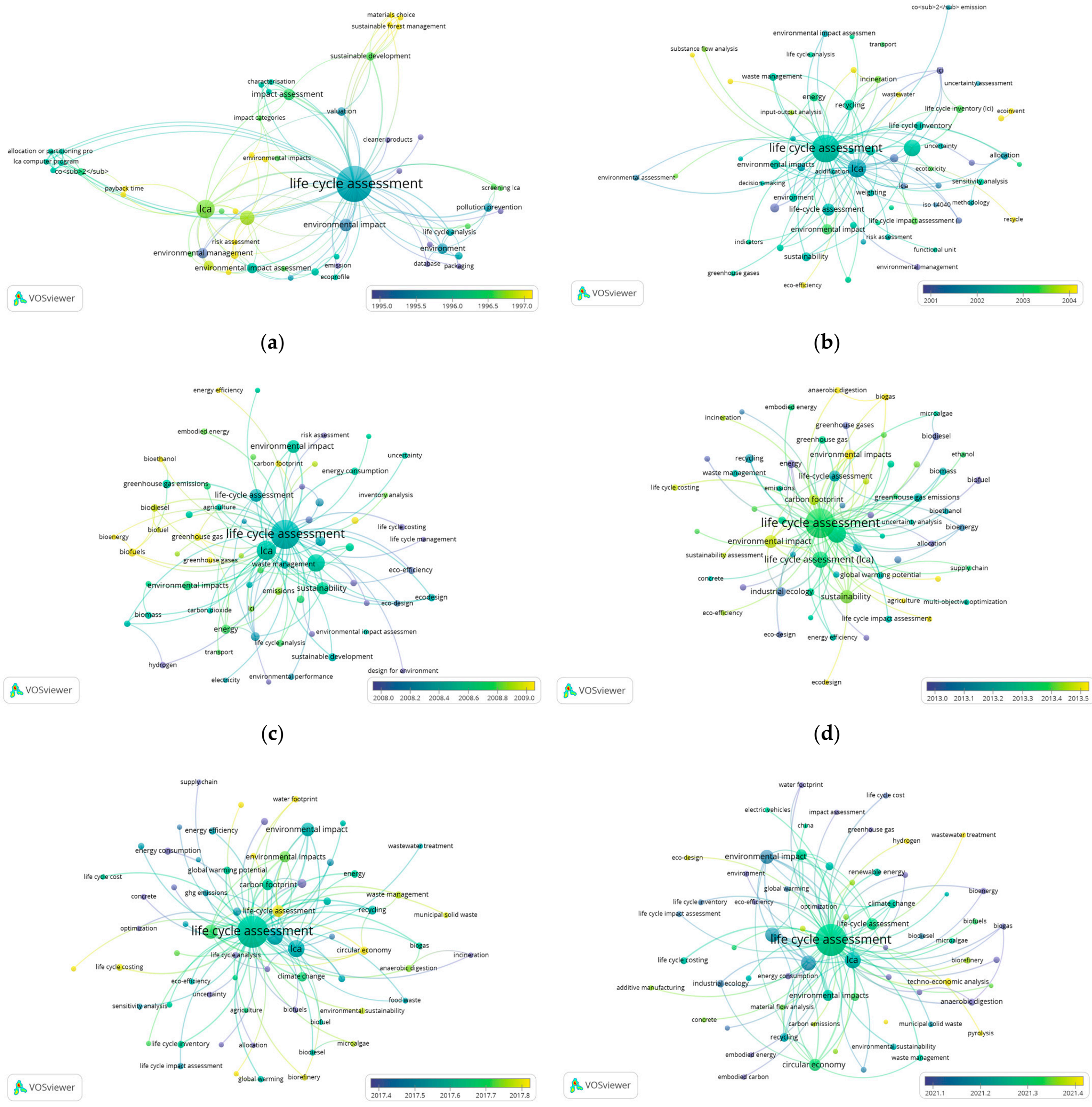
3.2.11. The Progression of Research Topics and Hotspots in the Field of LCA

Keywords co-occurrence analysis

The current study employs bibliometric data visualisation techniques to trace the evolution of research topics and focal areas in the field of LCA across six distinct time periods spanning from 1992 to 2022. Each period's commencement signifies a transition in the developmental timeline of LCA research, as detailed in Sections 1.1 and 3.2.11. These include milestone years like the standardisation years of 1997 and 2006, the pivotal year of 2010 that marks an increase in LCA research performance, and the integration of sustainability assessment. Another focal point year was 2015 which introduces SDGs, and the final period from 2019 (pre-pandemic) to 2022, characterised by the highest LCA publication output since 1991, contributing to 47% of all LCA publications.

This comprehensive analysis was achieved using a combination of subject clustering algorithms, visualisation techniques, knowledge map analysis, content analysis, and sample literature review. The thematic progression stems from an integrated examination of the network and frequency of co-occurring author keywords. This approach aids in capturing the evolving trends within the LCA-related domain and mapping the emergent thematic shifts.

For each of the six periods, the most prominent 40 author keywords were highlighted. Figure 17a–f visually represent keyword co-occurrence clustering networks. To effectively convey the themes of author keywords, distinct thresholds were employed based on their occurrence frequencies. The circle and font sizes denote the keyword frequency in the literature, while the distance between lines reflects the strength of connections between topics [74].



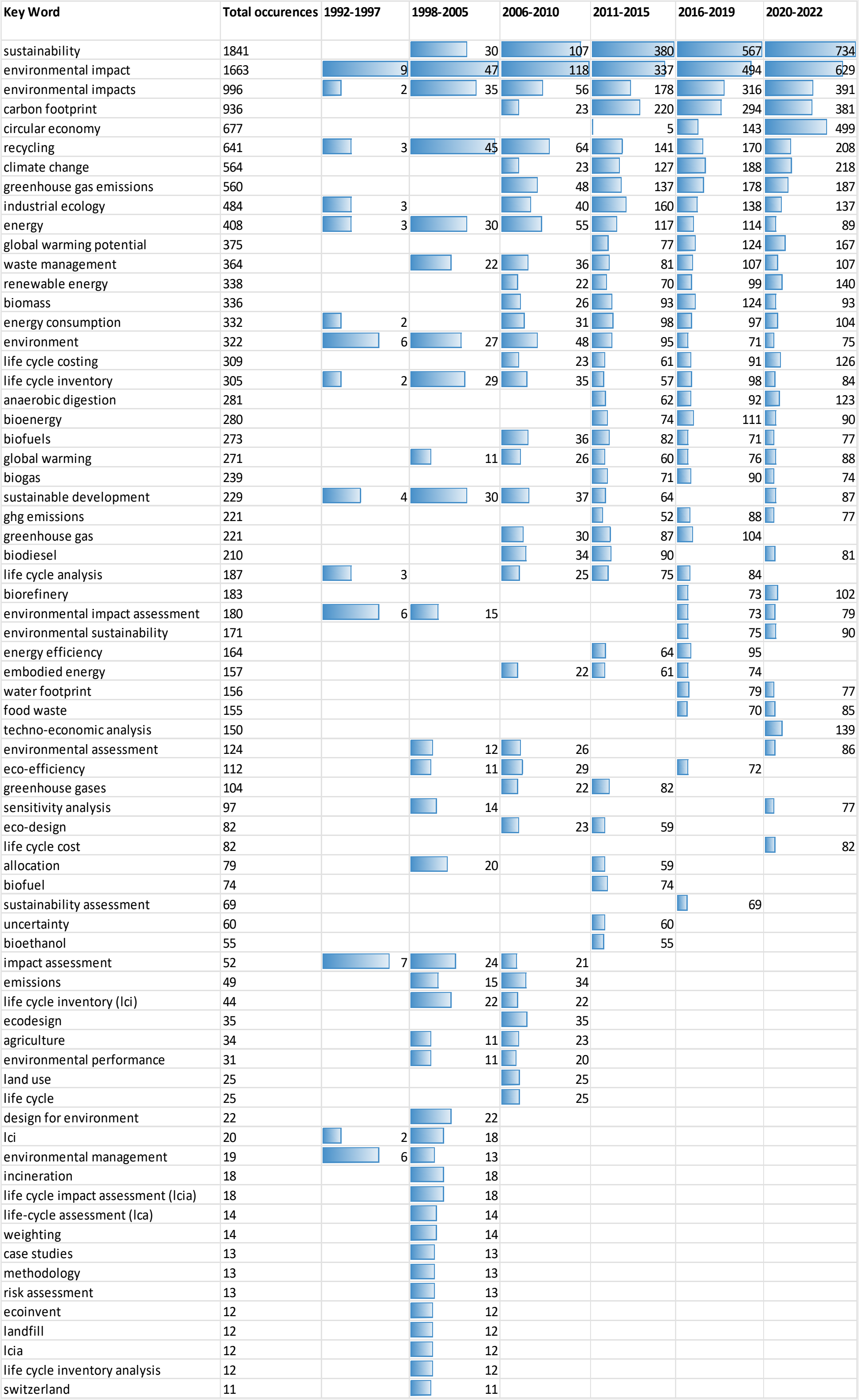
(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 17. Bibliometric co-occurrence analysis and overlay visualisation of life cycle assessment publication keywords. Periods: (**a**) 1992–1998; (**b**) 1997–2005; (**c**) 2006–2010; (**d**) 2011–2015; (**e**) 2016–2019; (**f**) 2020–2022.

These significant keywords have been concisely summarised in Figure 18, presenting the top 70 author keywords. This table can be interpreted both vertically and horizontally, facilitating comparisons and underscoring the evolution of LCA-related subjects across time.



Key Word	Total occurences	1992-1997	1998-2005	2006-2010	2011-2015	2016-2019	2020-2022
sustainability	1841		30	107	380	567	734
environmental impact	1663	9	47	118	337	494	629
environmental impacts	996	2	35	56	178	316	391
carbon footprint	936			23	220	294	381
circular economy	677				5	143	499
recycling	641	3	45	64	141	170	208
climate change	564			23	127	188	218
greenhouse gas emissions	560			48	137	178	187
industrial ecology	484	3		40	160	138	137
energy	408	3	30	55	117	114	89
global warming potential	375				77	124	167
waste management	364		22	36	81	107	107
renewable energy	338			22	70	99	140
biomass	336			26	93	124	93
energy consumption	332	2		31	98	97	104
environment	322	6	27	48	95	71	75
life cycle costing	309			23	61	91	126
life cycle inventory	305	2	29	35	57	98	84
anaerobic digestion	281				62	92	123
bioenergy	280				74	111	90
biofuels	273			36	82	71	77
global warming	271		11	26	60	76	88
biogas	239				71	90	74
sustainable development	229	4	30	37	64		87
ghg emissions	221				52	88	77
greenhouse gas	221			30	87	104	
biodiesel	210			34	90		81
life cycle analysis	187	3		25	75	84	
biorefinery	183					73	102
environmental impact assessment	180	6	15			73	79
environmental sustainability	171					75	90
energy efficiency	164				64	95	
embodied energy	157			22	61	74	
water footprint	156					79	77
food waste	155					70	85
techno-economic analysis	150						139
environmental assessment	124		12	26			86
eco-efficiency	112		11	29		72	
greenhouse gases	104			22	82		
sensitivity analysis	97		14				77
eco-design	82			23	59		
life cycle cost	82						82
allocation	79		20		59		
biofuel	74				74		
sustainability assessment	69					69	
uncertainty	60				60		
bioethanol	55				55		
impact assessment	52	7	24	21			
emissions	49		15	34			
life cycle inventory (lci)	44		22	22			
ecodesign	35			35			
agriculture	34		11	23			
environmental performance	31		11	20			
land use	25			25			
life cycle	25			25			
design for environment	22		22				
lci	20	2	18				
environmental management	19	6	13				
incineration	18		18				
life cycle impact assessment (lcia)	18		18				
life-cycle assessment (lca)	14		14				
weighting	14		14				
case studies	13		13				
methodology	13		13				
risk assessment	13		13				
ecoinvent	12		12				
landfill	12		12				
lcia	12		12				
life cycle inventory analysis	12		12				
switzerland	11		11				

Figure 18. Top 70 author -keywords over six distinct periods of LCA topical field timeline.

Period 1992–1997

The results showed that during the earliest period (1992–1997), LCA was in its nascent stage, and the research focused on developing LCA methodology, including the definition of goals, scope and functional unit, environmental impact categories, and the use of LCA-related terms and types (screening, streamlined LCA, and life cycle analysis). The study also highlighted the first LCA ISO standards version ISO 14040 which were based on SETAC established Code of Practice, with Type I environmental labelling and declaration standards (ISO 14020/22/23), in addition to case studies of waste and recycling, introduction of LCA software and databases, eco-efficiency, and environmental impact assessment methods. LCA was also used as a decision-making tool in various sectors, such as automotive, building, road transport, agricultural production, and the chemical industry. Other principal elements of LCA were also examined, including data quality indicators, allocation methods, inventory analysis, uncertainty and sensitivity analysis, characterisation (ethical and ideological valuation), and interpretation assessment.

Period 1998–2005

During the period from 1998 to 2005, the LCA field underwent significant growth and development. A major focus of research during this time was the issue of weighting, which involves combining environmental impacts into a single score or indicator for decision-making purposes. Various methods were explored, including relevance-based, damage-based, and cost-based weighting.

Numerous impact assessment methods were developed and applied in LCA studies, with the CML method being particularly noteworthy. Other popular methods included the Eco-Indicator 99 and IMPACT 2002+. The Ecoinvent database was also widely used for environmental inventory analysis.

There was increased emphasis on using LCA in product development, green innovation, and ecodesign, with particular attention to design for environment, design for sustainability, life cycle thinking, and optimisation. Researchers developed software tools and databases for LCA, and integrated LCA with other sustainability assessment tools.

Research also focused on integrating LCC and LCA and incorporating economic indicators such as the cost of environmental damage into LCA. Economic modelling techniques, including input-output analysis, were used to evaluate the environmental impacts of products and processes. Specific sectors and products, such as construction materials, vehicles, and electronic products, were studied in detail to assess the cost-effectiveness of different environmental strategies and product designs.

Period 2006–2010

During the period of 2006–2010, the field of LCA continued to advance and broaden its scope, with a focus on standardisation, product-specific studies, social LCA, sustainability metrics, and technology advancements. Significant areas of development included the application of LCA to emerging technologies, such as nanotechnology and biotechnology, and the incorporation of social impacts in LCA studies through Social Life Cycle Assessment (SLCA). The integration of social, economic, and environmental considerations into decision-making processes has become increasingly important, leading to the emergence of Life Cycle Sustainability Assessment (LCSA) as a novel approach. Meanwhile, impact assessment methods, such as ReCiPe and the ILCD, gained prominence.

The pressing global issue of climate change and the imperative to mitigate greenhouse gas emissions have engendered a heightened employment of LCA to evaluate the carbon footprint of products. The expansion of LCA beyond product-level assessments to include entire systems and supply chains was another notable trend, with the use of hybrid LCA becoming more common for system-level assessments. Attention was also given to uncertainty and sensitivity analysis, with several methods developed to address these issues.

Other research areas included the application of LCA to the food sector to examine the environmental impacts of different diets and production systems, as well as the use of LCA in policy-making and corporate sustainability reporting through Environmental Product Declarations (EPDs) and frameworks such as the Global Reporting Initiative (GRI). Additionally, the growing interest in renewable energy sources, such as solar and wind power, led to increased investment in these technologies to reduce reliance on fossil fuels and greenhouse gas emissions.

Period 2011–2015

During the period of 2011–2015, there was a growing awareness of the importance of reducing greenhouse gas emissions and addressing climate change, leading to increased interest in LCA and carbon foot printing as tools for measuring and reducing the environmental impact of products and services. This was reflected in LCA gaining recognition as a useful tool for policymaking, with the European Commission integrating LCA into its Product Environmental Footprint (PEF) initiative.

Additionally, new databases were developed and expanded (i.e., Ecoinvent), and there was a growing focus on social LCA, adoption by companies, and methodological advancements to improve accuracy. LCA also played a significant role in advancing the use of Anaerobic Digestion (AD) as a sustainable waste management strategy. The United Nations Environment Programme (UNEP) highlighted the potential of LCA to support the transition to a more sustainable economy.

Period 2016–2019

The period of 2016–2019 witnessed a growing focus on the intersection of LCA and circular economy, which resulted in the development of circular LCA frameworks and integration with other sustainability frameworks. LCA was increasingly used as a tool for assessing circular economy strategies, and businesses and governments adopted circular economy principles, contributing to the growing importance of LCA. During this period, there were also developments in sector specific LCA standards, social impact assessment, the use of big data and AI, and adoption by governments and policymakers, reflecting the continued importance of LCA as a tool for promoting sustainable practices across industries and sectors.

LCA is also valuable in the decarbonisation of industries and supply chains, helping to identify opportunities for emissions reduction and the most sustainable options for the future. Pyrolysis is a process that can be assessed using LCA to optimise its environmental performance and contribute to the transition toward a more sustainable, circular economy. Environmental Product Declarations (EPDs) and Product Category Rules (PCRs) were increasingly used during this period to provide transparent and verified information about the environmental impact of products, meeting the increasing demand for this information from consumers, businesses, and governments.

3.3. LCA Future Trends: Period 2020—Ongoing

In this study, future trends refer to the integration and analysis of densely cited and linked recent research articles (2018–2022), centred around common themes. These themes swiftly gain prominence as significant research fronts, thereby shaping upcoming research directions.

The identification and analysis of future trends draw from three sources: (1) Preceding sections' findings, particularly the evolution of LCA research areas and highly cited articles, (2) keyword co-occurrence analysis, specifically within the 2018–2022 timeframe, and (3) LCA topic clusters prominence indicator.

In addition to indicating the momentum and visibility of specific topics, this indicator will facilitate funding-centric analytics in the LCA research field. A correlation exists between the prominence (momentum) of a given topic and the funding per author within that domain. Generally, higher momentum corresponds to greater available funding per author for research on that topic [1]. Keyword co-occurrence analysis, depicted in Figure 17e,f, unveils five prominent LCA topic clusters, outlined with associated keywords in the corresponding Table 10. A cluster is a set of closely related nodes. Each node in a network is assigned to exactly one cluster [74].

Table 10. LCA keywords theme clustering: 2018–2022.

Cluster	Main Keywords	Theme
1	Circular economy—comparative LCA—Ecodesign—Sensitivity—Uncertainty analysis—Sustainability—Sustainable Development—	LCA methodology; Sustainable Development; Circular economy
2	Agriculture—Animal— Energy consumption—Fertilisers—Water—Toxicity—Land Use—Ozone depletion—Sustainability	Environmental Impact Assessment in Agricultural Systems
3	Biofuel—Biomass—Carbon footprint—Energy—Fossil fuels—GHG—Renewable energy—Sustainability	Energy and carbon emissions
4	Anaerobic digestion—incineration—landfill—municipal—solid waste—waste disposal—Economic aspect—Sustainability	Waste Management and Resource Utilisation
5	Bio-Based—Biopolymers—Circular economy—Composites—Plastic waste—Polymers—Textile—Waste Technology—Recycling—Polyethelene	Sustainable Materials and circular economy
Others: Agricultural wastes—Bioenergy—Biomass—Bioethanol—Techno Economic analysis—Feedstocks—Pyrolysis		

Scopus-based SciVal topic clusters emerge when the citation link strength between topics surpasses a threshold, which is outlined in Table 11. This dual perspective analysis reinforces the robustness and coherence of the study's findings.

Table 11. LCA SciVal topic clusters and prominence values.

Topic Cluster	2016	2017	2018	2019	2020	2021	2022
Life Cycle; Sustainable Development; Sustainability	98.28	98.23	98.55	98.79	97.91	97.76	97.8
Life Cycle Assessment; Photovoltaic System; Solar Collectors	98.74	98.72	98.97	99.07	98.91	99.09	99.07
Solid Waste Management; Life Cycle Assessment; Municipal Solid Waste; Circular economy	99.23	99.38	99.64	99.6	99.5	99.6	99.69
Biopolymer; Bioplastics; Biodegradable Plastics	83.06	89.8	93.02	93.4	92.65	96.94	96.76
Anaerobic Digestion; Biofuel; Life Cycle Assessment	98.28	98.23	98.55	98.79	97.91	97.76	97.8
Sustainability; Ecodesign; Cradle-To-Cradle cycle	95.13	96.95	97.42	95.26	94.6	95.93	94.64
Sustainability; United Nations Environment Program; Social Indicators; Life cycle sustainability assessment	93.75	93.76	97.6	97.45	95.19	95.78	97.22

Cluster 1: LCA methodology

Cluster (1) places a spotlight on LCA methodology as a guiding theme, with a strong emphasis on addressing uncertainties and conducting sensitivity analyses. This overarching theme encompasses a spectrum of interconnected subtopics, indicating the cluster's core focus on integrating LCA principles while enhancing reliability through sustainable approaches.

Although the research focus toward LCA methodology shows a diminishing trend, particularly nearing the end of 2005, recent developments have given rise to topics concentrating on uncertainty and sensitivity analysis [129–132]. These emerging areas reignite discussions on the fundamental challenges affecting LCA reliability. These challenges primarily stem from the lack of quantified uncertainties and data quality assessment in

LCA studies, further compounded by increasing system complexity and the pursuit of precision [26].

Recent areas of interest include dynamic LCA applications [133–135], as well as the integration of Artificial Intelligence (AI) and Machine Learning (ML) [31,136–138]. These evolving subjects underscore the growing complexity of systems and data, providing insights into temporal variations, leveraging large datasets, and utilising technological advancements. These areas emphasise the pressing need to enhance the precision and efficiency of LCA modelling techniques.

Cluster 1: Sustainable development and Sustainability

Since 1998, sustainability has consistently held its position as a predominant research focus and prevailing trend. LCA continues to play a crucial role in advancing sustainable practices across domains, serving as a metric to assess the environmental impact of emerging technologies. LCA has notably assessed environmental sustainability in batteries [112,113,139], waste treatment and recycling [140–142], and bio-based materials and energy [143–145]. A pertinent trend involves integrating LCA metrics with Sustainable Development Goals (SDGs) [146,147], and its use in holistic assessments of environmental impacts through Life Cycle Sustainable Assessment (LCSA) [148,149].

The prominence indicator values provide further insight into the consistent and robust research presence of this cluster. The prominence indicator (97.22) underscores the sustained importance and active exploration of sustainable development and sustainability within LCA research landscape.

Cluster 1: Circular economy

Commencing in 2011, circular economy has garnered heightened research attention, with a pronounced surge in research keywords since 2016, elevating it to a top three research fronts in LCA. Research trajectory underscores the use of LCA as a pivotal evaluative tool to gauge and enhance the thoroughness and transparency in the implementation of circular economy strategies [150,151]. This trend is particularly evident across varied applications, notably in building and design [152–154], as well as in addressing waste treatment and exploring end-of-life alternatives within the realm of bio-based products, materials, and energy [155–157].

Cluster 2: Agriculture

The dedicated theme of "Agriculture" has relatively decreased as a research focus within the realm of LCA since the conclusion of 2010. This shift is attributed to the evolution of agricultural research toward various subtopics, driven by concerns around sustainable food production, environmental impact, and resource management. Recent research directions primarily revolve around "Sustainable Intensification" and its environmental implications [158–160], particularly concerning urban agriculture [161–166]. Notably, some highly cited articles in agriculture pertain to organic agriculture [82,167,168], though it does not translate into a dominant research trend within this field.

Cluster 3: Energy and carbon emissions

The "Energy and Carbon Emissions" theme aligns closely with LCA, maintaining its status as pivotal research focuses and trends since 1998. This continued attention is attributed to the essential role of LCA in evaluating the comprehensive environmental impacts arising from energy source utilisation and associated emissions across the entire lifecycle. The research trajectory has evolved toward specific subtopics, with increasing exploration of renewable energy sources, low carbon footprint technologies, such as solar power, biomass utilisation, and hydrogen energy generation [169–172]. Additionally, a noteworthy emerging subtopic involves the evaluation of bioenergy, particularly when derived from waste materials [173–176]. The prominence indicator for the cluster "Life Cycle Assessment; Photovoltaic System; Solar Collectors" and "Anaerobic Digestion; Biofuel; Life Cycle Assessment" (99.07) reflect this dynamic focus, affirming the ongoing research enthusiasm in understanding the LCA of photovoltaic systems and biomass.

Cluster 4: Waste Management

Waste management and treatment technologies have consistently held focal positions in LCA research. LCA has continually evaluated the environmental impacts of diverse waste management approaches and technologies, aiding decision making by offering insights into environmental consequences and supporting the shift toward sustainable waste treatment practices. Notably, recycling, especially battery recycling technologies [112,113,177,178] remains a significant LCA research trend. Recent emphasis also lies on solid waste management, particularly plastics [110,141,179,180] and municipal solid waste [181–183]. Emerging trends encompass thermal decomposition via "pyrolysis" [184–186], biological processes such as "anaerobic digestion" [187,188], and microalgae-based approaches [189–191].

Cluster 5: Sustainable Materials and circular economy

This cluster emphasises the increasing focus on sustainable material choices in alignment with the circular economy framework. A growing research trend within this cluster centres around bio-based and geopolymer-based materials [192–196], indicating a significant surge in interest. The prominence indicator values for the cluster "Biopolymer; Bioplastics; Biodegradable Plastics" suggest its increasing importance and influence within LCA research landscape from 2016 to 2022 (83.06–96.76). Another noteworthy area of exploration is the selection of materials for additive manufacturing [147,197–199]. LCA research aims to assess the environmental impact of these materials and their potential to improve circular value chains.

4. Discussion and Conclusions

This study employs bibliometric analysis to examine three decades of LCA literature. Using the Scopus database as the data source, 9580 articles from the years 2018 to 2022 were selected to investigate the research landscape and key areas of interest within LCA. The study integrates analyses of LCA research progression, research fronts, and SciVal topic clusters' prominence percentiles to illuminate future development directions and create a comprehensive knowledge map. This approach aims to offer fresh perspective for LCA research.

a. Research Trends and Hotspots

The thematic analysis of LCA research trends revealed five prominent topic clusters:

(1) "Life Cycle; Sustainable Development; Sustainability" and "Sustainability; United Nations Environment Program; Social Indicators": This cluster indicates a growing focus on real-world applications to achieve global sustainability targets. (2) "Life Cycle Sustainability Assessment; Biopolymer; Bioplastics; Biodegradable Plastics": With mounting concerns about plastic pollution, LCA studies in this cluster are expected to expand to encompass various bio-based materials and their potential in different industries. (3) "Solid Waste Management; Life Cycle Assessment; Municipal Solid Waste; Circular Economy": This cluster suggests that future LCA research will delve into quantifying the benefits of recycling, upcycling, and waste-to-energy approaches. (4) "Life Cycle Assessment; Photovoltaic System; Solar Collectors" and "Anaerobic Digestion; Biofuel; Life Cycle Assessment": Anticipate more in-depth exploration of energy payback periods, carbon footprints, and environmental trade-offs associated with solar energy and bioenergy systems. (5) "Sustainability; Ecodesign; Cradle-To-Cradle Cycle": This expansion is likely to involve integrating LCA into early product development stages, promoting holistic and environmentally conscious design.

The trajectory points toward a broader application of LCA principles to address energy and design-related sustainability challenges, indicating a pivotal role for LCA research across various industries.

The definition of sustainability is moving toward a balance of Technical, Economic, Environmental, Social and Governance (TEESG) considerations.

b. Research Strength

The identified topic clusters showcase the interdisciplinary nature of LCA and sustainability research.

Quality Concerns and Collaboration

While the surge in LCA publications raises quality concerns, the rise in sponsored articles reflects a multifaceted research landscape influenced by regulations, economics, and environmental awareness. Collaboration among researchers, industry, and governments has intensified, leading to increased funding. The prominence of collaboration around research clusters signifies sustained growth in LCA research.

Global Engagement and Dynamic Journal Landscape

China's increasing contributions have propelled it past the United States in LCA research over the last 4 years, driven by diverse institutions and affiliations. The global co-authorship network involves academic, non-governmental, and research institutions, with East Asian countries significantly contributing. The journal landscape has evolved, with newer journals gaining prominence post-2010, indicating the changing face of LCA research.

c. Database Assessment

Comparing Scopus and WoS, Scopus covers a broader range of LCA-related publications, with differences primarily related to conferences and review papers. Retrieving data from the database is recommended within the research span between $N-1$ and $N + 1$. Standardised LCA author keywords, such as "life cycle assessment", should be used for improved indexing of LCA studies.

d. Limitations and Future Directions

This study's scope was confined to the Scopus database, potentially omitting valuable contributions from Chinese LCA literature present in other databases like CNKI. Future endeavours should expand to other Chinese databases, focusing on both the quantity and quality of their research output. Additionally, despite identifying main research topic clusters, a need remains for more detailed information on each topic's relation to LCA, warranting further investigation. Minor variations in outcomes due to normalisation approaches and parameter configurations in VOS viewer visualisation techniques may exist. However, this study's impartial findings provide a broader perspective on the progression of LCA research.

In conclusion, this study's bibliometric analysis sheds light on LCA research strength, progression, and trends. The identified clusters underscore the interdisciplinary nature of LCA research, with global collaboration and evolving journal landscapes driving its growth. Despite limitations, this study offers valuable insights into the trajectory of LCA research, contributing to the advancement of the field.

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