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ORIGINAL ARTICLE

Revealing the concept of sustainability in life cycle assessment

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Abstract – Life cycle analysis is essential in promoting improvements to mitigate climate change. Climate change impacts can be reduced through mitigation of greenhouse gases and increasing adaptation to the changes to be expected across all sectors. This article aims to examine and characterize the current application of the Life Cycle Sustainability Assessment (LCSA). This study is focusing on a systematic review and bibliometric analysis highlighting the concept of sustainability in Life Cycle Assessment (LCA). Firstly, three types of LCA are presented based on the selected publications that can underpin the different existing trends. This systematic literature review also aimed to examine the LCSA-related publications and introduce the main findings or highlight changes. Secondly, research was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. Then, using bibliometric tools, the evolution of the literature and the relationship between the different types of LCSA are discussed. Bibliometric analyses were considered based on the Scopus database and the exported dataset for systematic analyses. The co-authorships, co-occurrences, keywords, and co-citations were analyzed using the VOSviewer software for the period of 2010 and 2022. The results underpinned that the LCSA model can contribute to fostering the way toward a sustainable and climate-oriented transition. Literature analysis has clearly confirmed that LCA research with a sustainability focus is on an evolutionary trajectory. Most of the surveyed LCSA literature is related to environmental sciences (40%), followed by energetics (21%) and social sciences (20%) in almost equal proportions. The economic dimension of sustainability is under-represented in LCSA studies. The LCSA studies described numerous indicators which can contribute to monitoring the three dimensions of sustainable development.

Keywords – sustainability, life cycle sustainability assessment, LCSA, systematic review, PRISMA protocol

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INTRODUCTION

Sustainability can be assessed in several methods. One of the increasingly used tools in environmental management is Life Cycle Analysis (LCA) which has become a dominant tool for scientific analyses and an essential method for transmission sustainability to use knowledge to promote the business sector and governmental decision-making (Li et al., 2018). The Life Cycle Assessment analyses the environmental aspects of a product throughout its life cycle (Muralikrishna and Manickam, 2017). LCA is standardized by ISO 14040 series (2006), which includes all the objectives, tools, and procedures used in LCA to assess specific environmental factors and impacts, that may be associated with individual products. This international standard lays the principles and framework for preparing LCA studies and assessment reports and includes requirements. There has been a significant increase in interest in using LCA to an expectation that this method could provide a definitive answer to environmental problems (Kerekes and Kindler, 1997). There are several methodologies for assessing the environmental impact of biomass, including environmental LCA (Szlávik and Szép, 2018). However, the LCA does cover only the environmental dimension of sustainability. In this sense, Life Cycle Sustainability Assessment (LCSA) framework is intended to cover all three sustainability dimensions (economic, social, and environmental). Due to its transdisciplinary nature, it could be an effective tool for measuring sectoral sustainability evaluation. The first framework for LCSA was developed by Klöpffer and Renner (2008). Their framework is based on the following three pillars: Life Cycle Assessment (LCA), Life Cycle Cost (LCC), and Social Life Cycle Assessment (S-LCA):

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA} \qquad (1)$$

Klöpffer's initial approach has evolved into the LCSA guidelines of the UNEP and the SETAC (2011) Life Cycle Initiative, which includes instructions for conducting LCSA studies and presents them in case studies. Ciroth et al. (2011) present how the above three pillars can be combined to achieve a comprehensive LCSA. The study provides an initial guide to LCSA, incorporating UNEP/SETAC and ISO 14040 standards (Ciroth et al., 2011).

However, the methodology of LCSA is under discussion in the literature (Hannouf and Assefa, 2018; Ferrari et al., 2019; Alejandrino et al., 2021; Fauzi et al., 2019; Silva et al., 2019; Costa et al., 2019). Fauzi et al. (2019) identified a research gap in defining the relationship between the three methods (LCA, LCC, and S-LCA). Ferrari et al. (2019) conducted an LCSA assessment for ceramic tiles in Italy and applied the LCSA framework to separate pillars. In the analysis by Costa et al. (2019), most LCSA studies come from the United States (U.S.) and Germany. Alejandrino et al. (2021) addressed different applications of LCSA methodologies under a systematic review. Most of the studies reviewed used process-based methods. However, new approaches have also been used, such as input-output-based and self-developed methods (Hall, 2019; Corona and San Miguel, 2019). Corona and San Miguel (2019) set up a self-developed LCSA framework that provides more flexibility in setting targets.

Researchers (Hannouf et al., 2022; Wulf et al., 2018) recognized the interest in the field of LCSA, and connections were established between SDG and LCSA. Hall (2019) examines the economic pillar of LCSA. Bhyan et al. (2022) made a bibliometric analysis between 2000 and 2020 to assess sustainability using an LCA in residential buildings. Stamford (2020) identified the advantages and disadvantages of LCSA and illustrated the application of LCSA in the energy sector through two case studies. Visenti et al. (2020) conducted a literature review to explore the use of LCSA from 2008-2019. China had the highest number of publications, and the sustainability indicators used in the reviewed studies showed a wide diversity. Soust-Verdaguer et al. (2023) assessed the sustainability of buildings through a case study in which they developed an LCSA-based tool, the BIM3LCA structure tool, to support the selection process under the building construction. The BIM (Building Information Modelling)-based LCSA was implemented according to ISO 21931-1:2022 framework (ISO, 2022).

LCSA helps companies and governments to achieve their goals for sustainable development. The LCSA is an essential tool for companies to evaluate the impacts of their activities from a life cycle viewpoint (Martínez-Blanco et al., 2014). Dantas and Soares (2022) presented a systematic literature review on the application of LCSA in the energy sector and concluded that the energy sector operates as a platform for LCSA.

MATERIALS AND METHODS

1. Objectives

Through a systematic review, the research aims to identify the LCSA case studies and applications of different methodologies in the Scopus database. The research was carried out to address the main scope of LCSA studies and perform a bibliometric and systematic review.

2. Selection criteria

The research is a systematic literature review and preliminary, descriptive bibliographic research to identify and analyse research on LCSA to increase knowledge in the field. Systematic reviews have increasingly become the focus of LCA research (Wafa et al., 2022).

A systematic review is essential for academic studies in preparing academic papers (Shi and Li, 2019; Mecha et al., 2022). Its main advantage is to provide reliable information and be methodologically transparent (Tranfield et al., 2003). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009) were used for the literature review. We used the Scopus electronic scientific database search engines. The PRISMA includes a checklist and a flowchart, which are necessary to produce a transparent literature review (Liberati et al., 2009; Buzási and Csizovszky, 2023).

The systematic review aims to map the LCSA publications for 2010-2022 and present the main research findings or highlight changes. The research was conducted using the PRISMA protocol methodology for a comprehensive review. As a first step, we conducted a preliminary search for previous systematic literature analysis related to the LCSA to support the validity of our research. The research was conducted in the Scopus database, ensuring scientific quality. The following three keyword combinations were used to search by title, abstract, and keywords: "Life Cycle Sustainability Assessment", "Life Cycle Sustainability Analysis", and "LCSA". Publications written in English were included in the database. In the first round, 192 articles were found along the three search combinations. All data were imported into a CSV file. Within the topic, we precisely defined which cases we excluded from the articles we examined so that we only included articles relevant to our research question.

A total of 59 articles were eliminated based on the following selection criteria: (1) only research articles and review articles were included in the sample (excluded n = 41); (2) research areas are engineering and environmental science (excluded n = 17); the publications year were limited to 2010-2022 (excluded n = 1). In the end, 130 relevant articles remained in the sample. The process along the exclusion criteria is illustrated in Figure 1. The following inclusion and exclusion criteria were considered.

Inclusion criteria:
1. Title.
2. Abstract.
3. Full text.

Exclusion criteria:
1. Book, Book series, Conference proceeding.
2. Non-English articles.
3. Year before 2010.

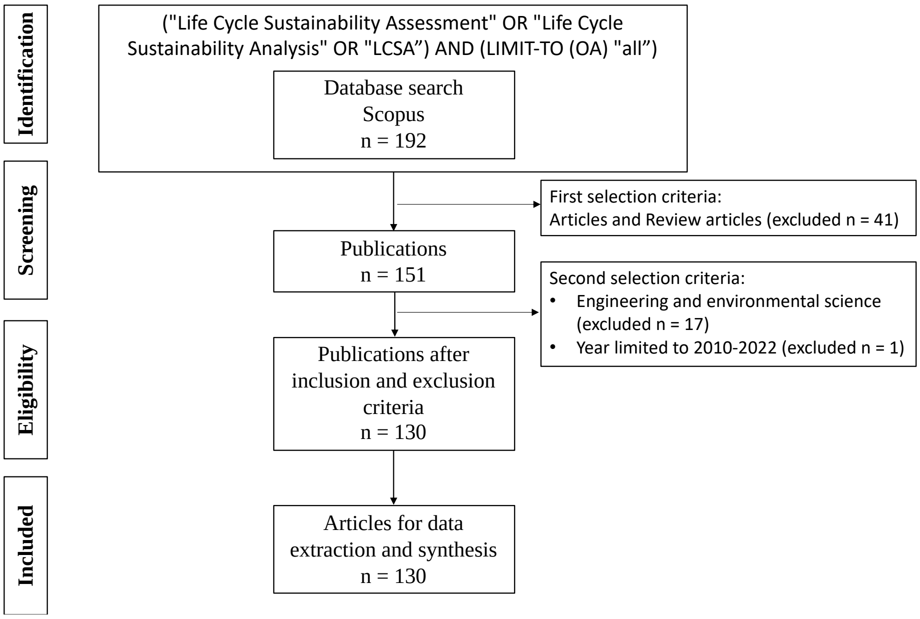

Figure 1. Flow chart of the systematic review based on the PRISMA protocol methodology (Moher et al., 2009).

3. Bibliometric and systematic analysis

The bibliometric and systematic analysis dataset has been selected according to the criteria of VOSviewer software that could be used for data analysis. VOSviewer can handle bibliographic data files from Scopus, Web of Science, or another scientific database. Scopus contains the most abstracts and literature citations reviewed by multidisciplinary fields. Therefore, a comprehensive review of the LCSA literature and the internet literature analyses was carried out using Scopus database search engines and PRISMA methodology (Figure 1).

Bibliometric analyses can provide a broad overview of the research area, especially if a large literature sample is to be processed. Indicators were initially created, and more precise methods were developed, such as bibliometric analysis. Network visualization can be performed using different software tools. Such software can be used to create other networks, which can be used to explore the various structural elements used for the database. The systematic review covers a chosen topic for a given period and presents the main research findings or highlights the changes. The method is used through a meta-analysis of new conclusions on a given topic (Mack, 2016). We conducted preliminary research on LCSA-related issues that have previously been the subject of systematic literature analysis to support the validity of our study.

The bibliometric research was carried out through the VOSviewer program, also used by van Eck and Waltman, 2014; Torok and Sipos, 2022; Micu et al., 2022; Wafa et al., 2022. The CSV file type was used for analysis, which was then used to build the visualization maps. Maps were prepared for three types of bibliometric analysis between 2010 and 2022: co-authorship, co-occurrence (keywords: all, authors, and index keywords), and citation (cited reference, cited sources, and cited), and the CVS file was exported from the Scopus database.

RESULTS

1. General results

The methodological framework for LCSA has been introduced by Kloepffer (2007), based on three separate LCA. The initial approach evolved into the United Nations Environment Program and the Society of Environmental Toxicology and Chemistry LCSA guidelines (UNEP/SETAC, 2011).

The first publication shown in Scopus research on life cycle sustainability assessment appears in 2010, titled "Towards life cycle sustainability assessment" (Finkbeiner et al., 2010) and "Ecodesign - Carbon Footprint - Life Cycle Assessment - Life Cycle Sustainability Analysis. A Flexible Framework for a Continuum of Tools" (Heijungs, 2010). Both articles use Kloepffer's approach. Based on the literature review, the number of publications on LCSA shows increased in the last 12 years (Figure 2).

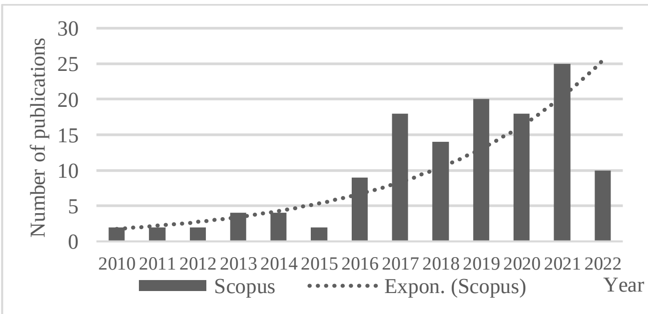

Figure 2. Number of research articles on LCSA by year

The most prominent year was 2021, with 25 related articles. LCSA publications have shown an increasing trend in eight years. The growth rate of LCSA publications was expected due to the global sustainability agreements, climate action, and due to the performance of the scientific communities.

2. Bibliometric analyses of LCSA

2.1. Co-authorship analysis

To identify research related to LCSA, the authors examined 130 open-access articles in the Scopus database. The exported dataset was visualized using VOSviewer software to explore the scientific relationship (Figure 3).

The visualization map was created from bibliographic data. The co-authored dates were based on the CSV dataset. The co-authorship type of review was analyzed with a full counting method. A maximum of 25 authors per document and a minimum of two papers per author have been defined. Therefore, of the 425 authors, 73 met the thresholds, but some items are not connected. Thus, the co-authorship was calculated with 23 authors in three clusters, and the total link strength was 136. The size of the sphere in the visual map indicates the number of articles. A larger sphere indicates the highest amount of co-authorship of publications by authors (Figure 3). The sphere's color presents the year of publication: yellow indicates a relatively new topic, and purple indicates an older issue. There is a robust network among the authors who have co-published an article.

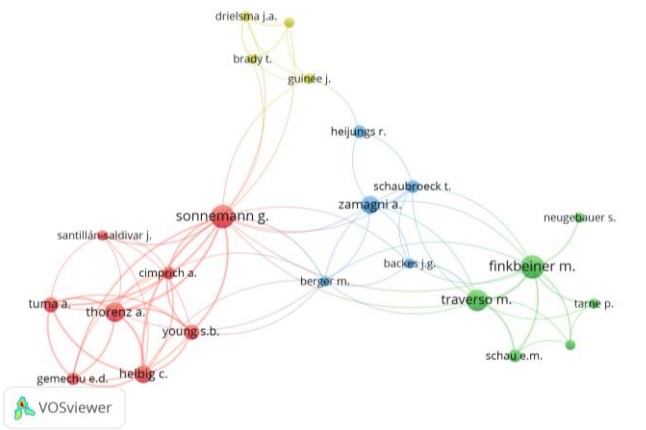

Figure 3. Co-authorship visual map (network visualization)

By running the research in the Web of Science database, we recognized a similarity in the number of duplicates, but we have found differences in the keywords. Sonnemann G. (Sonnemann et al., 2004; Sonnemann et al., 2015; Gemechu, 2015; Valdivia et al., 2021) has a strong publication network with 17 authors, eight publications, and 217 citations (total link strength: 37), followed by Finkbeiner M. (Finkbeiner et al., 2010; Finkbeiner 2011; Chang et al., 2017) with ten authors, eight publications and 713 citations. Traverso M. (Backes and Traverso, 2021; Valdivia et al., 2013; Martínez-Blanco et al., 2014; Tarne et al., 2017; Traverso et al., 2012a; Traveso et al., 2012b; Lehmann et al., 2013) contributes to the publication network with seven publications and 646 citations. Thorenz A. (Thorenz et al., 2018; Thorenz and Reller, 2011; Gemechu et al., 2015) and Helbig C. (Helbig et al., 2016a; Helbig et al., 2016b; Helbig et al., 2018) had 168 citations with the total link strength 24.

The research analyzed the links between 46 countries. A minimum of two documents and four citations per country were considered. After the thresholds were set, the co-authorship relationships with other countries were identified.

The countries with the strongest links were selected. So, finally, 23 countries were selected and grouped into two thematic clusters by VOSviewer. The largest red cluster contains 137 documents. The most significant countries are Germany, the United Kingdom, Sweden, France, the Netherlands, the U.S., Italy, Spain, Brazil, Canada, Denmark, South Korea, Turkey, and China (Figure 4).

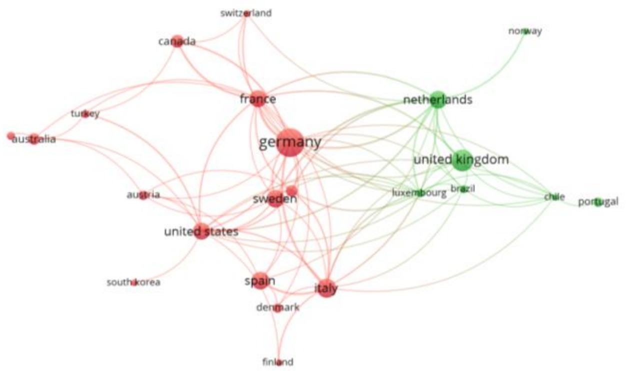

Figure 4. Country visual map

Germany is the strongest country on the map with 33 articles and 1220 citations (the total link strength: 31). The United Kingdom is the second country with 19 articles and 820 citations, followed by Italy with 15 documents and 542 citations. 13-13 papers come from Netherlands and Sweden. The color on the visual map shows the research area, and the thickness of the lines and the size of the spheres illustrate the level of country collaboration. Europe published the most (38%) LCSA studies in the past twelve years (Figure 5).

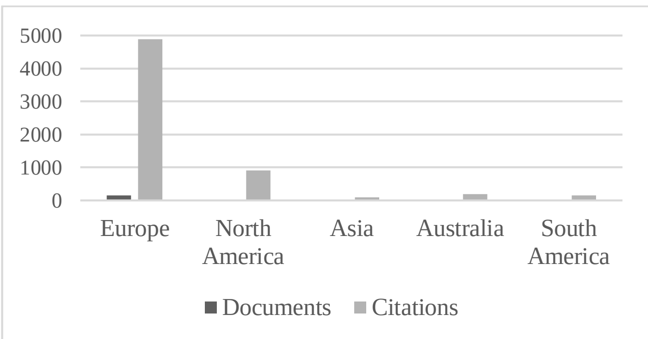

Figure 5. Map of articles contribution by continents

2.2. Co-occurrence analysis

Keywords concisely and accurately present the document's content, and the primary task of automatic keyword retrieval is to determine a set of these concepts from the document's content. VOSviewer was used for a co-occurrence type of bibliometric analysis.

The database was exported from Scopus (as a CVS file), and the author keywords were analyzed with a full counting method. Figure 6 illustrates the "author keyword" map for the Life Cycle Sustainability Analysis literature, with the minimum number of occurrences of keywords being three. Consequently, 32 out of 451 keywords meet the threshold. For the 32 keywords, we analyzed the strength of co-occurrence relationships with other keywords.

Keywords with the same color are more often used together, and clusters of research topics can be identified. The largest spheres represent the majority of keyword co-occurrences, and the smallest present the lowest number. The ten most highlighted keywords were life cycle sustainability assessment (34 occurrences), life cycle assessment (28 occurrences), sustainability (18 occurrences), LCSA (16 occurrences), sustainability assessment (16 occurrences), life cycle assessment (LCA) (13 occurrences), industrial ecology (13 occurrences), life cycle sustainability assessment (LCSA) (13 occurrences), life cycle costing (12 occurrences), life cycle sustainability analyses (7 occurrences).

LCSA literature is grouped into six thematic clusters with 125 links, and the total link strength is 242. The biggest red cluster (7 items) is an assessment-related cluster ("life cycle assessment", "multi-criteria decision analyses", "life cycle costing"). Therefore, these are directly related to decision-making processes. The dark blue thematic cluster (6 items) contains keywords concerning sustainability ("sustain-ability", "life cycle sustainability analyses", "sustainability manufacturing", and "carbon footprint"). The green cluster (6 items) presents the keywords regarding life cycle analyses. The yellow cluster (5 items) focuses on industrial aspects ("industrial ecology", "resources", and "supply risk"). The purple cluster (4 items) is concerned with life cycle assessment. Finally, the light blue thematic cluster (4 items) connects to the use of secondary raw materials ("circular economy", "waste management", "resource recovery").

2.3. Co-citation

The cited document was analyzed by VOSviewer software to create a visual map based on bibliographic data. Data was read from a bibliographic database-supported file type (Scopus). The minimum number of citations of a document was 4 of 130, and 98 papers met the threshold. For each of the 98 papers, the number of citation links was calculated. The documents with the minimum total link strength were selected, so we ended up with 87 documents visualized on the map (Figure 7). The 87 items were sorted into 17 clusters with 244 links.

The most co-cited document was Finkbeiner et al. (2010), with 453 citations and 33 links to other documents. Halog and Manik (2011) had 187 citations and 13 links. Atilgan and Azapagic (2016) had 144 citations and ten links. Onat et al. (2017) had 130 citations and 21 links. Iacovidou et al. (2017) have 124 citations and only one link. Zamagni et al. (2013) had 122 citations, and Zamagni A. (2012) had 121 citations and 20 links. Stamford and Azapagic (2014) had 115 citations and nine links. The documents listed are the most cited articles and authors in the field of LCSA.

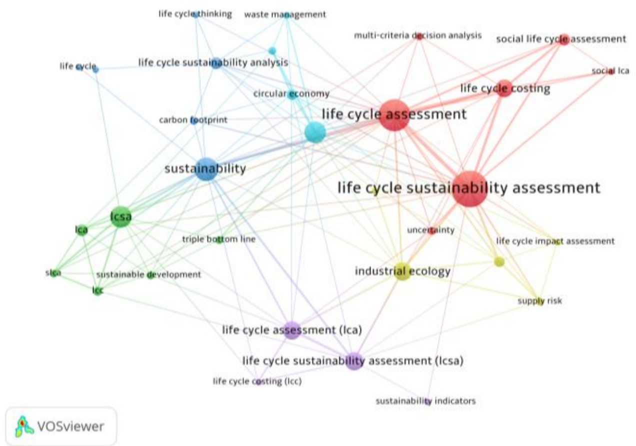

Figure 6. Authors' keyword density visual map

The co-cited sources were also analyzed with VOSviewer software. The thresholds were chosen, with the minimum number of citations of a source was eight. Ninety-six meet the thresholds from the assessed 3752 sources. The total link strength was zero in one case, so it was removed from the sources. Note that when the database was being developed, it was not yet realized that the data exported from the Scopus database were not coherent. The bibliographic data for some articles were divergent, and VOSviewer software could not handle the corrected data in the exported file. Therefore, we have yet to visualize the co-cited sources because the data would provide inaccurate and misleading information.

The co-citation sources analysis sorted the 95 publications into 8 clusters. Links were 1665, and the total strength of the link was 64.609. The "int. j. life cycle assess" (The International Journal of Life Cycle Assessment) published the highest number of publications on the topic of LCSA, citations were 815, and the total strength of the link was 23.843. Followed by the "j. clean. prod " (Journal of Cleaner Production), which had 427 citations (total strength of the link: 16.793), and "Sustainability" had 351 citations and 13.620 total link strength. The "j. int. ecol" (Journal of Industrial Ecology) had 235 citations (total strength of the link: 9988), and "energy policy" had 83 citations (total strength of the link: 3154).

2.4. Thematic areas

An overview of the thematic areas indicates that the LCSA publications are characterized by a multidisciplinary approach, as shown in Fig. 8. The application of LCSA has been mainly in the field of environmental sciences (40%), followed by energy (21%), and social science (20%). Several studies have used a comprehensive approach to LCSA in engineering (13%), business, management, accounting (4%), and computer science (2%).

Considering the different thematic areas of LCSA-related studies, the cognitive aspects of sustainability can be interpreted in almost all cases, which may influence practical implementation and should be addressed in future research directions (Majerova, 2022; Filina-Dawidowicz, 2022).

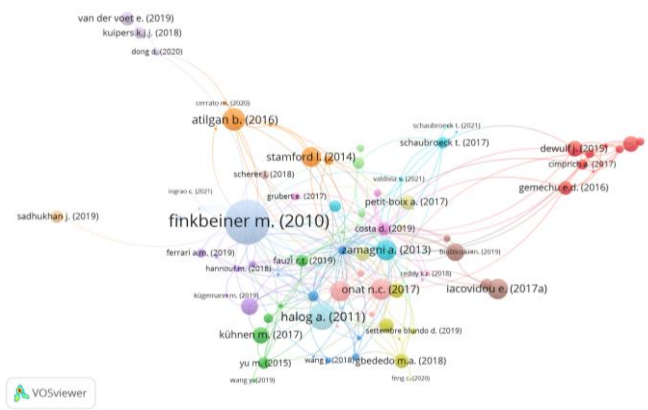

Figure 7. Visual map of the co-cited documents

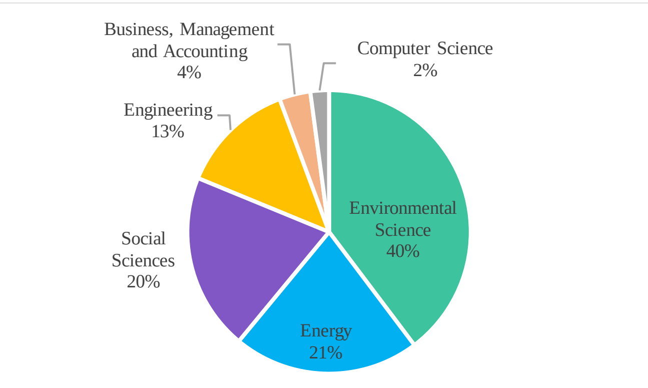

Figure 8. The main thematic areas of the bibliographic analyses

Conclusion

The methodology of LCSA is still evolving (Ferrari et al., 2019; Guinee et al., 2011; Alejandrino et al., 2021). A systematic review is a common approach to analyzing and visualizing bibliographic articles. The research on four visual maps demonstrates co-authorship, co-occurrence, and co-citation. In this regard, 23 authors published an article on the topic of "Life Cycle Sustainability Assessment", "Life Cycle Sustainability Analysis", or "LCSA". Sonnemann G. and Finkbeiner M. have the highest number of publications (8 documents each), followed by Traverso, who contributes to the publication network with seven articles and 646 citations. Germany is the strongest country on the visual map, with 33 documents and 1220 citations. Europe published 38% of the publications (148 articles) in the past twelve years and provided the highest number of sources.

VOSviewer was used for a co-occurrence type of bibliometric analysis. According to the studies, the total was 451 for all keywords, and 32 met the threshold. The most frequently used keyword was "life cycle sustainability assessment", which appeared 34 times, and the total link strength was 45. The keyword "Life cycle assessment" was mentioned 28 times, and the overall link strength was 54.

According to the co-citation analysis, 87 articles were selected in 17 clusters with 244 links. The most cited document was Finkbeiner et al. (2010), with 453 citations and 33 links to other documents. In terms of journals, The International Journal of Life Cycle Assessment published the highest number of publications on the topic of LCSA, with citations were 815 and 23.843 total link strength. An overview of the thematic areas reveals that LCSA studies require a multidisciplinary approach.

The application of LCSA has been mainly used in the field of environmental sciences (40%), energy (21%), and social science (20%). As LCSA research develops, further sectoral analyses and evaluations of practical implementations can be expected to appear in the literature, focusing on the effectiveness of challenge-based solutions. It will likely lead to an improved design process, as well as generating LCSA results that are reliable and can be replicated.

The added value of the research lies in providing scientists with an overview of the applications of LCSA, presenting authors, countries, and specific research that provides a basis for other researchers to research on similar topics, and helping practitioners to apply LCSA in practice by examining the case studies that have been identified in this research. Moreover, the sectoral analysis helps to identify which sectors have LCA gaps and where further improvements can be made. The publications identified also provide several indicators useful for professionals in practice, e.g., how to produce sustainable products with a combination of the three techniques of LCA, LCC, and SLCA. This enables triple bottom-line decision-making on the three dimensions of sustainable development.

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