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# LIFE CYCLE ASSESSMENT IN HISTORIC BUILDINGS: A BIBLIOMETRIC EXPLORATION OF GLOBAL RESEARCH TRENDS

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**Abstract**: Efforts to mitigate the environmental impact of the construction sector increasingly rely on analytical tools aligned with sustainability principles. Among these, Life Cycle Assessment (LCA) plays a critical role by quantitatively evaluating the environmental effects of buildings across all life stages, thereby informing design and decision-making processes. However, existing literature predominantly focuses on LCA applications in new constructions, while historic buildings—often recognized as cultural heritage assets—remain underrepresented in this context. This study systematically investigates global academic trends in LCA applications within historic buildings through bibliometric analysis. 310 publications indexed in the Web of Science Core Collection between 2001 and 2025 were examined, based on the keywords "historic building" and "life cycle assessment." Bibliometric tools such as VOSviewer and the Bibliometrix R package were employed to visualize keyword co-occurrence, source coupling, and author collaboration networks. Thematic classification was conducted semi-automatically using high-frequency keywords. Findings reveal that topics such as energy efficiency, carbon emissions, adaptive reuse, and sustainable restoration dominate the literature, whereas significant research gaps persist in areas like social sustainability, traditional material data, and policy support. The study aims to contribute to interdisciplinary scholarship by promoting scientifically grounded evaluations of the environmental performance of historic buildings and advancing sustainable conservation strategies.

**Keywords**: Life cycle assessment (LCA), Historic buildings, Sustainable conservation, Bibliometric analysis, Cultural heritage, Environmental impact.

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## 1. INTRODUCTION

The construction sector stands out as one of the areas with the highest environmental impact worldwide in terms of greenhouse gas emissions, energy consumption, and natural resource use (Potrč Obrecht et al., 2020; Dsilva et al., 2023). Therefore, the quantitative evaluation of buildings' environmental performance in line with sustainability principles is of great importance for both design and conservation processes. In this context, Life Cycle Assessment (LCA) is widely employed as a scientific method that enables a comprehensive analysis of the environmental impacts generated across all life stages of a building—from raw material acquisition to end-of-life disposal (Bjørn et al., 2018; van der Giesen et al., 2020).

In recent years, LCA has increasingly served as an effective decision-support tool, particularly in areas such as material selection, energy-efficient design, and the development of circular economy strategies. It also plays significant roles in promoting sustainable design, supporting certification processes, and informing policymaking (Najjar et al., 2019; Marsh et al., 2023; Kumar et al., 2025). However, common applications of this method tend to focus primarily on new construction projects, while heritage buildings of cultural significance remain relatively underrepresented in the literature (Franzoni et al., 2020; Mahmad et al., 2024).

Yet, interventions such as the restoration, adaptive reuse, and maintenance of historic buildings have considerable environmental implications due to their high embodied carbon content and extended service lives (Hu & Świerzawskib, 2024). Compared to demolition and reconstruction scenarios, conservation-oriented strategies often demonstrate lower environmental impact levels within the scope of LCA, thereby highlighting the need for hybrid models that simultaneously address both cultural and environmental sustainability goals (Karoglou et al., 2019; Endo & Takamura, 2021). Nonetheless, the lack of data on traditional construction materials, the difficulty of quantifying cultural values, and the absence of standardized methods currently limit the scope of such analyses (Bonoli & Franzoni, 2019; Fnais et al., 2022).

Against this backdrop, a systematic examination of the existing academic literature on the life cycle assessment of historic buildings is required. The primary aim of this study is to analyze relevant academic publications indexed in the Web of Science (WoS) database between 2001 and 2025 using bibliometric analysis methods, in order to identify research trends, thematic clusters, and methodological orientations in the field. The study employs visual and quantitative analytical techniques such as keyword co-occurrence mapping, source citation networks, and Sustainable Development Goal (SDG) matching (Donthu et al., 2021). In doing so, it seeks not only to reveal the current focal areas in the literature but also to identify themes that have not yet been sufficiently explored.

Within the scope of this study, the following objectives were pursued:

- To identify the key concepts and themes highlighted in the literature on historic buildings within the context of LCA,
- To determine the research areas that have received the most attention as well as those that have been neglected,
- To classify the methods, datasets, and assessment tools employed,
- To identify research gaps that could contribute to sustainable conservation strategies,
- To provide guiding recommendations for future scholarly research.

In this regard, the study offers a scientific basis for conservation strategies that address both environmental and cultural sustainability, while simultaneously creating a strategic literature map for policymakers, researchers, and practitioners in the field of life cycle assessment.

## 2. CONCEPTUAL BACKGROUND

LCA is a scientific, quantitative method for evaluating the environmental impacts of products, services, or systems throughout their life cycle—from raw material extraction to final disposal. It is widely applied across sectors to enhance sustainability, compare alternatives, and support decision-making (Bjørn et al., 2018; van der Giesen et al., 2020). By taking a holistic view of all life stages, LCA uses scientific methods and data to quantitatively reveal environmental impacts.

A key feature of LCA is its "cradle-to-grave" scope, covering raw material extraction, production, use, and end-of-life disposal. This comprehensive, science-based approach evaluates impacts using quantitative data. Figure 1 shows the main processes of LCA and their cyclical progression.

By addressing multiple environmental aspects—such as carbon footprint, resource use, and pollution—LCA supports both retrospective (ex-post) and forward-looking (ex-ante) analyses (Bjørn et al., 2018; Buyle et al., 2019; van der Giesen et al., 2020).

As a decision-support tool, LCA helps compare alternatives and identify "hotspots" at the product, process, and system levels, guiding improvements toward sustainability goals (Bjørn et al., 2018; Christensen et al., 2020; Potrč Obrecht et al., 2020). It is used not only in the private sector but also in environmental certification, regulatory compliance, and public policy development (Batal, 2019; Christensen et al., 2020). With applications in waste management, wastewater treatment, construction, technology, and policy-making, LCA has become essential for assessing environmental impacts and supporting multi-sectoral sustainability efforts.

LCA is a key tool for assessing and reducing the environmental impacts of the construction sector, which significantly contributes to global emissions and resource use. It guides sustainable design, material selection, and policy development. Early-stage integration allows architects and engineers to compare alternatives, identify environmental "hotspots," and make data-driven choices, especially when combined with tools like BIM (Potrč Obrecht et al., 2020; Kumar et al., 2025).

Applications in projects, such as a Dubai case achieving a 26% reduction in embodied carbon, show its potential (Dsilva et al., 2023). LCA supports green certifications like BREEAM and LEED, drives the preparation of EPDs, and promotes circular economy practices (Marsh et al., 2023). Hybrid LCA methods offer broader results but face transparency and standardization challenges (Bakindi et al., 2025). Improving data quality and addressing uncertainties is critical for reliable outcomes (Resch et al., 2021). Overall, LCA is indispensable for minimizing the environmental footprint of the built environment and advancing sustainability goals.

### 2.2. Types and Focus Areas of LCA

Key life cycle–based frameworks for assessing sustainability include Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (sLCA), and Life Cycle Sustainability Assessment (LCSA). Each focuses on a different sustainability dimension: LCA on environmental impacts, LCC on economic costs, and sLCA on social effects such as working conditions and stakeholder impacts (Sala et al., 2013; Guinée, 2016; Nubi et al., 2024; Konaré et al., 2023; Furness et al., 2021; Przytuła & Burchart, 2024; Schau et al., 2012; Venkatesh, 2018).

While these methods can be applied separately, LCSA integrates all three to provide a comprehensive assessment of environmental, economic, and social performance (Sala et al., 2013; Guinée, 2016; Nubi et al., 2024; Konaré et al., 2023; Furness et al., 2021; Przytuła & Burchart, 2024; Schau et al., 2012; Hu et al., 2013). Table 1 summarizes their main focus areas.

**Table 1.** Types and differences of LCA derivatives (Created by the author)

| Framework | Main Focus | Dimension Assessed | Integration Level |
|---|---|---|---|
| LCA | Environmental | Environmental impacts | Single |
| LCC | Economic | Costs | Single |
| sLCA | Social | Social impacts | Single |
| LCSA | Holistic | All three (Econ, Env, Soc) | Integrated |

LCA is increasingly used to assess and reduce the environmental impacts of historic buildings, guiding sustainable restoration, adaptive reuse, and maintenance strategies. It enables comparison of operational and embodied impacts across restoration methods, helping identify solutions with the lowest footprint (Bonoli & Franzoni, 2019; Franzoni et al., 2020; Endo & Takamura, 2021).

Adaptive reuse projects generally show significantly lower environmental impacts than demolition and new construction, highlighting the importance of reuse in heritage conservation (Hu & Świerzawskib, 2024). LCA is particularly valuable for embodied carbon assessments in maintenance and repair, where intervention durability and end-of-life scenarios are critical (Franzoni et al., 2020; Mahmad et al., 2024).

Challenges include limited data on traditional materials, difficulty balancing cultural preservation with environmental goals, and lack of standardized methods and policy support (Bonoli & Franzoni, 2019; Karoglou et al., 2019; Franzoni et al., 2020; Endo & Takamura, 2021; Fnais et al., 2022; Hu & Świerzawskib, 2024; Mahmad et al., 2024). Overall, LCA supports informed decision-making in heritage interventions, but its effectiveness depends on better material data, stronger integration with cultural priorities, and improved policy frameworks.

## 3. MATERIAL AND METHOD

This study adopts a bibliometric analysis approach to examine the development and research trends of academic publications on LCA in historic buildings. As a multidisciplinary research field, LCA has broad applications spanning both architectural and engineering domains. However, this diversity has resulted in a scattered and rapidly evolving body of literature. In this context, bibliometric analysis is chosen as a suitable and comprehensive method to systematically map the accumulated knowledge, identify existing research clusters, and reveal potential gaps in the field.

Bibliometric analysis enables the quantitative evaluation of scientific publications on a given topic. This method offers an effective framework for tracking the evolution of literature over time, visualizing relationships among subject areas, and uncovering academic collaborations (Donthu et al., 2021). Additionally, it holds value for interpreting the field's development and providing strategic guidance for future research.

Accordingly, a search was conducted in the Web of Science (WoS) Core Collection database using the keywords ("historical" OR "historic" OR "renovation") AND ("life cycle assessment" OR "LCA"). The retrieved publications were limited to the categories of construction technologies, green and sustainable technologies, environmental engineering, and civil engineering. The search resulted in 310 English-language academic articles; book chapters, conference proceedings, abstracts, and other document types were excluded from the analysis.

The dataset underwent a two-stage analysis process. In the first stage, publications were examined according to the following criteria:

- Publication trends over the years.

In the second stage, the analyzed data were visualized using VOSviewer software, and the following bibliometric relationships were evaluated:

- Keyword co-occurrence analysis,
- Bibliographic coupling (co-citation) analysis.

Through these analyses, the thematic distribution of LCA research in historic buildings, academic collaborations, and leading researchers in the field were revealed, aiming to provide a comprehensive mapping of the domain.

The distribution of publications by year indicates a marked increase in academic interest in LCA related to historic buildings, particularly after 2015. While the number of publications was quite limited between 2001 and 2011, it rapidly rose from 2019 onwards, peaking at 46 publications in 2024 (Figure 1). This growth reflects the increasing importance of the LCA approach within sustainability and heritage conservation fields. The lower count for 2025 may be due to the year not being complete at the time of data collection.

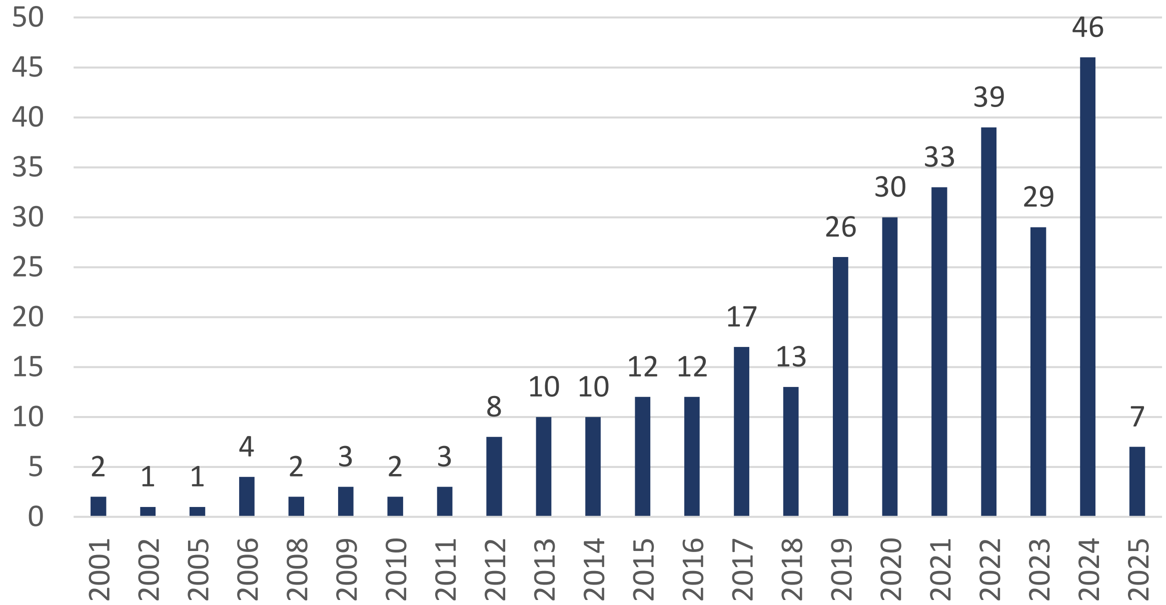


**Figure 1.** Publication distribution by year

The co-occurrence network of keywords in LCA publications on historic buildings from 2001 to 2025 reveals the main research trends and thematic clusters in the literature. Constructed using VOSviewer software, the term "life cycle assessment" occupies a central position in the network, with a high number of connections indicating that it constitutes a core conceptual node in the field. Variations in the term's spelling appear as separate nodes within the network, reflecting the terminological diversity present in the discipline (Figure 2).

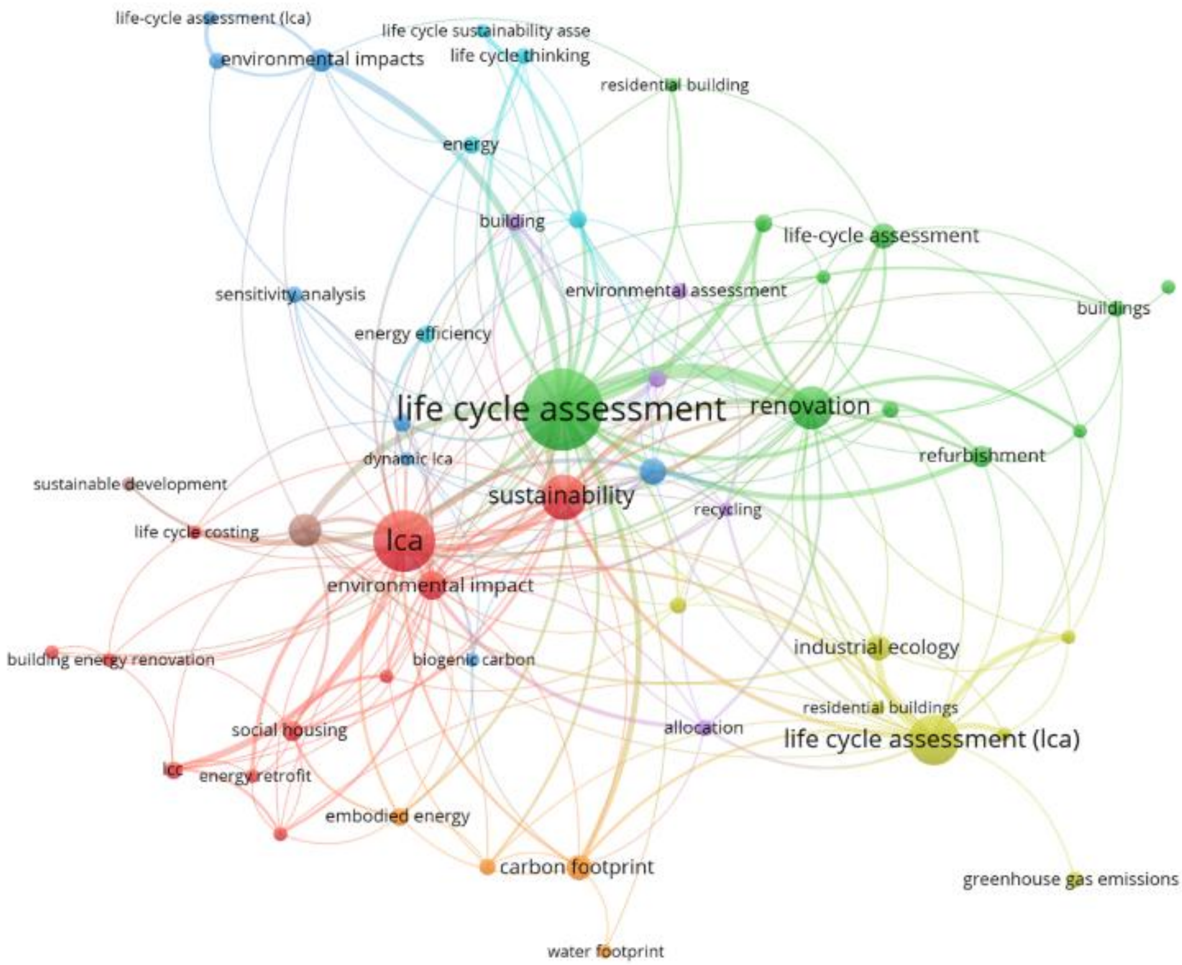


**Figure 2.** Keyword co-occurrence network of publications

The keywords located at the center of the network are the most frequently used terms and those most strongly connected to other concepts. The colors represent distinct clusters, each grouping keywords that are more closely related within themselves. Specifically:

- The green cluster includes terms such as life cycle assessment, renovation, building, and refurbishment, representing LCA studies primarily focused on building renovation and rehabilitation processes.
- The red cluster comprises keywords like LCA, environmental impact, life cycle costing, sustainable development, and energy retrofit, encompassing studies centered on environmental impacts and cost analyses.
- The yellow cluster contains concepts such as carbon footprint, industrial ecology, and greenhouse gas emissions, reflecting research focused on carbon footprint and industrial processes.
- The blue cluster includes environmental impacts, sensitivity analysis, and energy efficiency, representing more analytical and performance-measurement-based studies.

The connecting lines in the network indicate the frequency with which two keywords are used together. As the thickness of the lines increases, so does the co-occurrence intensity of the two terms in the literature. Additionally, the size of the nodes represents the usage frequency of each keyword. For example, the term life cycle assessment is depicted by the largest node, highlighting it as the most frequently used keyword.

Overall, the findings reveal that the literature on life cycle assessment primarily concentrates around several key themes: building renovation and rehabilitation processes, environmental impact and cost analysis, sustainability and carbon footprint issues, as well as energy efficiency and performance evaluations. The concepts of life cycle assessment and sustainability form a common axis across all clusters, indicating the adoption of an interdisciplinary approach.

The cluster and density network of co-cited references based on publications in the field of LCA for historic buildings between 2001 and 2025 illustrates the usage patterns of sources frequently cited together (Figure 3). This visualization, generated using VOSviewer software, highlights the sources that are often co-cited within the literature.

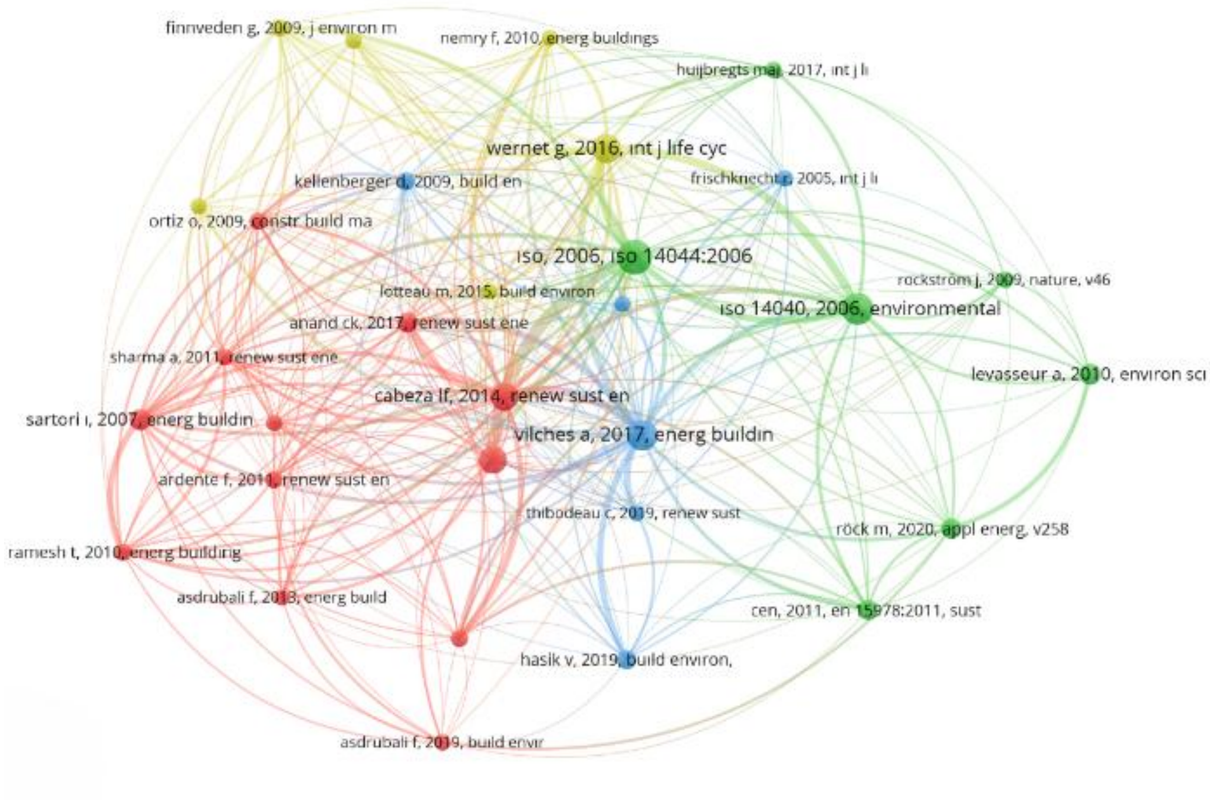


**Figure 3.** Clustering and density of co-cited references in publications

The resulting co-citation network illustrates that the literature on life cycle analysis of historic buildings is shaped by diverse interdisciplinary approaches. The clusters in the visualization represent different knowledge domains based on both environmental impact assessment methodologies and sustainability practices at the building scale:

- The red cluster includes sources focusing primarily on building-scale energy efficiency, renovation, and sustainability strategies. Authors such as Cabeza et al. (2014) and Vilches et al. (2017) stand out in this cluster with studies assessing the performance of existing building stocks and proposing improvement measures. This cluster is particularly valuable for research on energy retrofitting and adaptive reuse potential of historic buildings.
- The green cluster encompasses the theoretical foundations of LCA alongside standardized environmental assessment frameworks. References such as ISO 14040:2006, ISO 14044:2006, and Rockström et al. (2009) provide the methodological framework enabling the evaluation of historic buildings' environmental performance according to universal criteria.
- The blue cluster highlights applied aspects of life cycle analysis, consisting of

publications featuring detailed comparative studies of building materials. Works by Hasik (2019) and Cen (2011) are frequently cited in material-based comparative analyses, such as those contrasting reinforced concrete with traditional historic building materials.

- The yellow cluster reflects methodological literature addressing more theoretical, conceptual, and scope-defining aspects of LCA. Authors like Finnveden et al. (2009) are especially important in ensuring methodological coherence in LCA scenarios applied to historic building adaptive reuse or preservation processes.

The strong interconnections among all these clusters indicate that LCA functions not only as a technical analytical tool but also as an interdisciplinary evaluation framework. In the processes of preservation, adaptation, and sustainable transformation of historic buildings, the LCA approach offers a holistic perspective that simultaneously considers both environmental and cultural sustainability.

## 4. RESULTS AND EVALUATION

This bibliometric analysis examined the thematic orientation, geographic distribution, and core source clusters of scientific publications on Life Cycle Assessment (LCA) in historic buildings.

Findings show a notable rise in academic interest after 2015, with rapid growth after 2019. The number of publications reached 46 in 2024, underscoring the growing importance of evaluating historic buildings within the sustainability context.

Italy and the United States lead in publication output, followed by China, Spain, Belgium, and France. This reflects Europe's strong heritage conservation tradition and the increasing sustainability-driven construction activities in the US and China.

Keyword co-occurrence analysis identifies four main research axes: (i) building renovation and rehabilitation, (ii) environmental impact and cost analysis, (iii) carbon footprint and emission management, and (iv) energy efficiency and performance measurement. The consistent linkage between "Life Cycle Assessment" and "sustainability" across clusters highlights the interdisciplinary and multifaceted nature of the field.

The co-citation network reveals four major literature clusters: energy efficiency and sustainable building performance, environmental assessment methodologies, material-based comparative applications, and conceptual LCA approaches. Dense interconnections among sources indicate a maturing body of literature with emerging standard references.

## 5. DISCUSSION AND CONCLUSIONS

This study systematically reviewed academic literature on Life Cycle Assessment (LCA) in historic buildings, identifying current trends, thematic focuses, and development potentials. Findings show that LCA is increasingly applied beyond new construction to guide sustainable restoration, adaptive reuse, and maintenance of historic structures.

Bibliometric analysis reveals a sharp rise in studies in recent years, concentrated mainly in Europe and in countries such as the United States with large building stocks. Keyword and source analyses indicate a strong emphasis on technical aspects—environmental impacts, energy efficiency, and carbon footprint—while social sustainability and the quantification of cultural values remain underexplored.

Methodological and data-related challenges hinder full integration of LCA in historic contexts. Key issues include the lack of specific data on traditional materials, difficulty translating cultural priorities into quantitative models, and limited policy support. These gaps restrict the ability to balance heritage conservation with sustainability goals.

To achieve a more holistic sustainability approach, future LCA applications in historic buildings must incorporate environmental, social, and economic dimensions. Strengthening interdisciplinary collaboration and enhancing data integration through digital tools will be critical to advancing sustainable preservation of the historic environment.

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The authors have no conflicts of interest to declare.

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