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LIFE CYCLE ASSESSMENT OF CEMENTITIOUS MIXTURES FOR 3D CONCRETE PRINTING: A BIBLIOMETRIC REVIEW

AVALIAÇÃO DO CICLO DE VIDA DE MISTURAS CIMENTÍCIAS PARA IMPRESSÃO 3D DE CONCRETO: UMA REVISÃO BIBLIOMÉTRICA

EVALUACIÓN DEL CICLO DE VIDA DE MEZCLAS CEMENTICIAS PARA LA IMPRESIÓN 3D DE HORMIGÓN: UNA REVISIÓN BIBLIOMÉTRICA

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ABSTRACT

Life Cycle Assessment (LCA) has become one of the main approaches for evaluating the environmental performance of 3D concrete printing (3DCP). Although previous review studies have synthesized the application of LCA to 3DCP, the scientific development of this research field has received little attention from a bibliometric perspective. This study examines the scientific literature on LCA applied to cementitious mixtures for 3DCP through a bibliometric analysis of publications indexed in the Scopus and Web of Science databases. The analyses were performed using RStudio with the Bibliometrix package. Scientific production, publication sources, countries, collaboration networks, influential publications, keyword co-occurrence, and trend topics were examined. The results show that most publications on this topic have been published in recent years and are concentrated in a limited number of journals and countries, with China leading both scientific production and international collaboration. Keyword analyses indicate a growing interest in sustainable cementitious materials suitable for printing, especially those incorporating supplementary cementitious materials, such as fly ash and calcined clay, together with engineering performance and sustainable construction. The findings provide a bibliometric perspective on the scientific development of LCA applied to 3D concrete printing, complementing existing review studies by identifying publication patterns, collaboration networks, and emerging research topics.

KEYWORDS: *Life cycle assessment. 3D concrete printing. Bibliometric analysis. Cementitious materials. Sustainable construction.*

RESUMO

A Avaliação do Ciclo de Vida (ACV) tornou-se uma das principais abordagens para avaliar o desempenho ambiental da impressão 3D de concreto (3DCP). Embora estudos de revisão anteriores tenham sintetizado a aplicação da ACV à 3DCP, o desenvolvimento científico dessa área de pesquisa recebeu pouca atenção sob uma perspectiva bibliométrica. Este estudo examina a literatura científica sobre ACV aplicada a misturas cimentícias para 3DCP por meio de uma análise bibliométrica de publicações indexadas nas bases de dados Scopus e Web of Science. As análises foram realizadas por meio do RStudio com o pacote Bibliometrix. Foram examinados a produção científica, as fontes de publicação, os países, as redes de colaboração, as publicações influentes, a coocorrência de palavras-chave e os tópicos de tendência. Os resultados mostram que a maioria das publicações sobre o tema foi publicada nos últimos anos e está concentrada em um número limitado de periódicos e países, com a China liderando tanto a produção científica quanto a colaboração internacional.

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As análises de palavras-chave indicam um interesse crescente em materiais cimentícios sustentáveis adequados para impressão, especialmente aqueles que incorporam materiais cimentícios suplementares, como cinzas volantes e argila calcinada, juntamente ao desempenho de engenharia e à construção sustentável. As conclusões oferecem uma perspectiva bibliométrica sobre o desenvolvimento científico da ACV aplicada à impressão 3D de concreto, complementando os estudos de revisão existentes ao identificar padrões de publicação, redes de colaboração e temas de pesquisa emergentes.

PALAVRAS-CHAVE: Avaliação do Ciclo de Vida. Impressão 3D de concreto. Análise bibliométrica. Materiais cimentícios. Construção sustentável.

RESUMEN
La Evaluación del Ciclo de Vida (ECV) se ha convertido en uno de los principales enfoques para evaluar el desempeño ambiental de la impresión 3D de hormigón (3DCP). Aunque estudios de revisión anteriores han sintetizado la aplicación de la ECV a la 3DCP, el desarrollo científico de esta área de investigación ha recibido poca atención desde una perspectiva bibliométrica. Este estudio examina la literatura científica sobre la ECV aplicada a mezclas cementicias para 3DCP mediante un análisis bibliométrico de publicaciones indexadas en las bases de datos Scopus y Web of Science. Los análisis se realizaron mediante RStudio con el paquete Bibliometrix. Se examinaron la producción científica, las fuentes de publicación, los países, las redes de colaboración, las publicaciones influyentes, la coocurrencia de palabras clave y los temas de tendencia. Los resultados muestran que la mayoría de las publicaciones sobre el tema se publicaron en los últimos años y se concentran en un número limitado de revistas y países, con China liderando tanto la producción científica como la colaboración internacional. Los análisis de palabras clave indican un interés creciente en materiales cementicios sostenibles adecuados para la impresión, especialmente aquellos que incorporan materiales cementicios suplementarios, como cenizas volantes y arcilla calcinada, junto con el desempeño de ingeniería y la construcción sostenible. Las conclusiones ofrecen una perspectiva bibliométrica sobre el desarrollo científico de la ECV aplicada a la impresión 3D de hormigón, complementando los estudios de revisión existentes al identificar patrones de publicación, redes de colaboración y temas de investigación emergentes.

PALABRAS CLAVE: *Evaluación del Ciclo de Vida. Impresión 3D de concreto. Análisis bibliométrico. Materiales cementicios. Construcción sostenible.*

1. INTRODUCTION

The construction industry plays a fundamental role in economic development but is also recognized as one of the largest consumers of natural resources and one of the major contributors to global greenhouse gas emissions. According to the United Nations Environment Programme (UNEP, 2025), the buildings and construction sector accounts for approximately 34% of global CO_2 emissions and consumes around 32% of the world's energy (Marandi; Shirzad, 2025; Moreira; Rego, 2020). A substantial share of these impacts is associated with Portland cement, the most widely used construction material worldwide. Although the cement industry has advanced toward decarbonization, it still emits approximately 2.4 Gt of CO_2 annually, and manufacturing one tonne of clinker releases about 0.87 t of CO_2 (IEA, 2026; Marandi; Shirzad, 2025). In response to global decarbonization targets, research has increasingly focused on technologies that reduce the

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environmental footprint of construction materials and processes while maintaining engineering performance.

Among these approaches, three-dimensional concrete printing (3DCP) has emerged as a promising alternative to conventional construction (De Schutter *et al*., 2018; Heidarnezhad; Zhang, 2022; Perrot *et al.,* 2018; Zhang *et al.,* 2019). By depositing cementitious materials layer by layer without formwork, the technology offers greater design freedom and the potential to reduce material waste, labor demand, and construction time (Girskas; Kligys, 2025). As a result, research on printable cementitious materials has grown considerably over the last decade, encompassing mixture design, rheological behavior, buildability, mechanical performance, durability, and structural applications (Mechtcherine *et al.,* 2020; Perrot *et al*., 2018; Rahman *et al*., 2024).

The environmental performance of 3DCP depends not only on the printing process but also on decisions related to material selection and life cycle management (Buswell *et al*., 2018; Khan *et al.,* 2021). Variables such as clinker content, supplementary cementitious materials, transportation, energy demand, service life, and end-of-life scenarios directly influence the environmental impacts of printed elements. Consequently, Life Cycle Assessment (LCA), standardized by ISO 14040 and ISO 14044, is widely used to quantify these impacts and compare the environmental performance of cementitious mixtures developed for additive manufacturing (ISO 14040, 2006; ISO 14044, 2006; Pomponi; Moncaster, 2018; Tinoco *et al.,* 2025). Although recent review articles have summarized the main technical advances in this area (Jones; Li, 2023; Mir *et al*., 2022; Sambucci *et al*., 2023), the scientific development of this research field has received limited attention from a bibliometric perspective. Consequently, publication trends, collaboration networks, leading contributors, thematic evolution, and emerging research topics have received limited attention from a bibliometric perspective.

This study presents a bibliometric analysis of the scientific literature on LCA applied to cementitious mixtures for 3D concrete printing. Publication trends, scientific collaboration, and thematic evolution were analyzed to characterize the development of research in this field and identify emerging research themes.

2. METHODOLOGY

2.1. Study design

A bibliometric review was conducted to investigate the scientific literature on Life Cycle Assessment (LCA) applied to cementitious mixtures for three-dimensional concrete printing (3DCP). The study examined the evolution of scientific production, the main publication sources, the most influential authors, countries, and collaboration networks, as well as the thematic

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development of the field. The results were used to provide an overview of the current research landscape and to identify existing gaps and future research opportunities.

2.2. Databases

The bibliographic search was performed in the Scopus and Web of Science Core Collection databases. These databases were selected because they provide broad coverage of peer-reviewed scientific literature and standardized bibliographic information suitable for bibliometric studies (Mongeon; Paul-Hus, 2016). Their combined use increases the retrieval of relevant publications while reducing database-specific coverage limitations. In addition, both databases allow data export in formats compatible with the Bibliometrix package, facilitating data integration and subsequent bibliometric analyses.

2.3. Search strategy

The bibliographic search was conducted in the Scopus and Web of Science Core Collection databases in June 2026. Equivalent search strategies were applied in both databases, adapting the search fields according to the indexing system of each platform. The search included scientific articles published between 2016 and 2026 and combined terms related to three-dimensional concrete printing and LCA using the Boolean operators AND and OR.

The search strategy adopted in Scopus was:

TITLE-ABS-KEY (("3D concrete printing" OR "3D printed concrete" OR "3DCP" OR "construction 3D printing" OR "concrete printing") AND ("life cycle assessment" OR "life cycle analysis" OR "life cycle impact assessment" OR "environmental impact assessment" OR "LCA"))

The search strategy adopted in Web of Science was:

("3D concrete printing" OR "3D printed concrete" OR "3DCP" OR "concrete printing" OR "construction 3D printing" OR "additive manufacturing of concrete" OR "additive manufacturing of cementitious materials" OR "3D printed cementitious materials" OR "additive manufacturing of mortar") AND ("life cycle assessment" OR "life cycle analysis" OR "life cycle impact assessment" OR "environmental impact assessment" OR "LCA")

After the searches were conducted, the records retrieved from each database were exported in their respective compatible formats: “CSV” for Scopus and “plain text” for Web of Science. Subsequently, the files were imported into the RStudio environment, where the metadata were merged and subjected to automatic duplicate record removal using the Bibliometrix package.

2.4 Inclusion and exclusion criteria

Initially, the search strategy retrieved 113 documents from the Scopus database and 75 from Web of Science. Subsequently, filters regarding research areas were applied, as some of the

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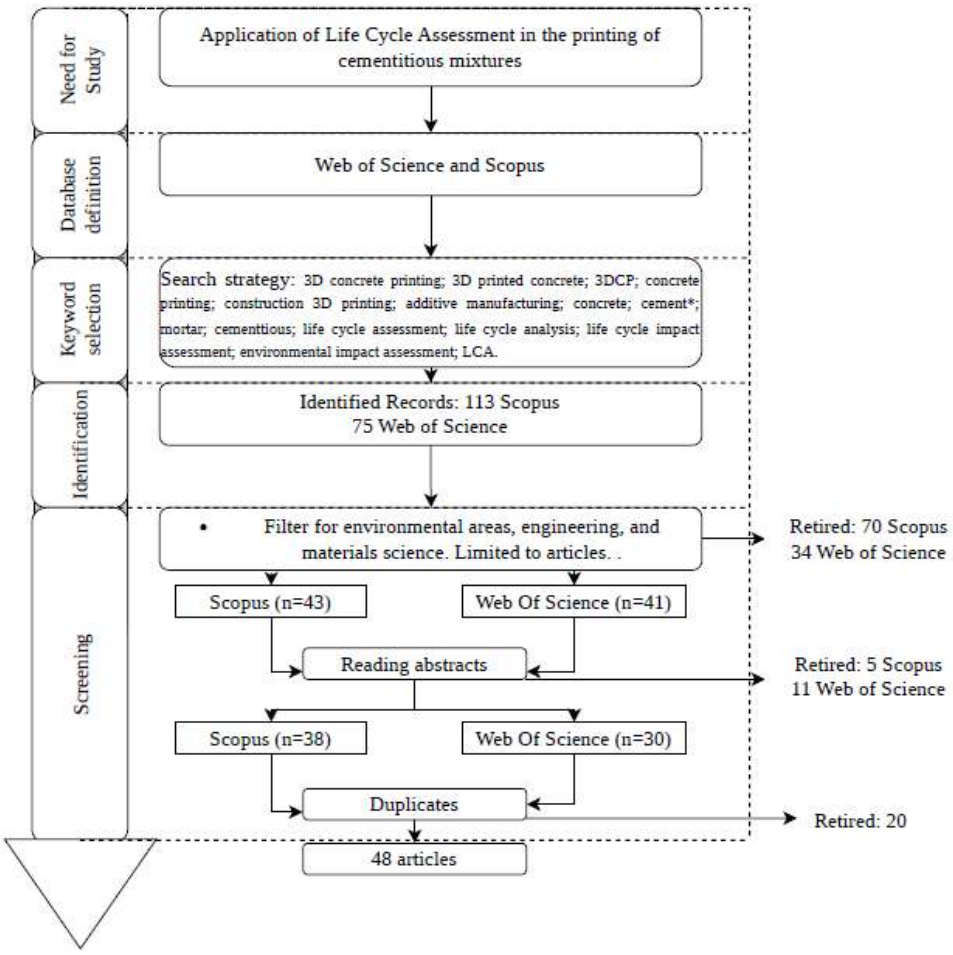
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retrieved records fell outside the scope of this study, including publications that did not address the application of Life Cycle Assessment to 3D concrete printing. Thus, the search was restricted to the fields of Engineering, Environmental Sciences, and Materials Science, and limited to the document type "article." Following the application of these criteria, 70 records from Scopus and 34 from Web of Science were excluded.

After this stage, 43 articles from Scopus and 41 from the Web of Science remained. Subsequently, the abstracts of all studies were screened to assess their relevance to the research topic. Studies that did not address LCA or any other type of environmental assessment were excluded, resulting in the removal of five articles from Scopus and eleven from the Web of Science.

The remaining records were exported and imported into the RStudio environment, where the Bibliometrix package was used to integrate the databases and identify duplicates. At this stage, 20 duplicate documents were removed, resulting in a final sample of 48 articles, which served as the basis for the bibliometric analyses, as shown in Figure 1.

Figure 1. Flowchart of the process for identifying, selecting, and including documents for the bibliometric analysis



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2.5. Bibliometric indicators

The bibliometric analysis employed both descriptive bibliometric indicators and network analysis techniques. Descriptive indicators assessed annual scientific output, publication sources, contributing countries, and influential publications. Network analysis examined collaboration networks, keyword co-occurrence, thematic mapping, and emerging research trends.

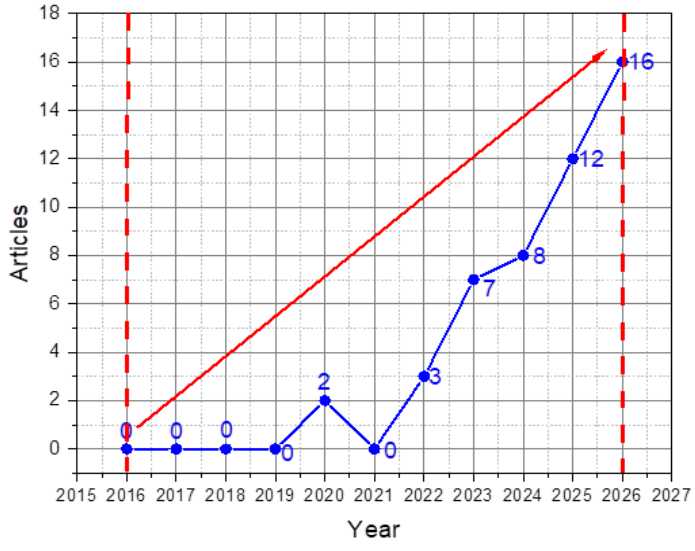
3. RESULTS AND DISCUSSION

3.1. Evolution of scientific production

Scientific publications on LCA applied to 3D concrete printing remained scarce until 2021, with the first study identified in 2020, followed by a rapid increase in scientific output from 2022 onward (Figure 2). No studies were identified between 2016 and 2019 or in 2021, indicating that the application of LCA to 3D concrete printing remained largely unexplored during the analyzed period.

From 2022 onward, scientific production increased steadily, with the number of publications rising from 3 in 2022 to 7, 8, 12, and 16 in 2023, 2024, 2025, and 2026, respectively. Together, these studies accounted for approximately 96% of all documents retrieved during the study period. This growth coincides with the increasing emphasis on decarbonizing the construction sector and reducing the carbon footprint of cement-based materials and construction systems (Nayak; Nayaka, 2026; Ahmed *et al.,* 2026*;* Caroscio *et al.,* 2026). At the same time, international initiatives such as the European Green Deal (2019) and the GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete (2021) reinforced the importance of quantifying the environmental impacts of emerging construction materials and technologies, contributing to the growing adoption of LCA in construction research.

Figure 2. Annual evolution of publications retrieved between 2016 and 2026



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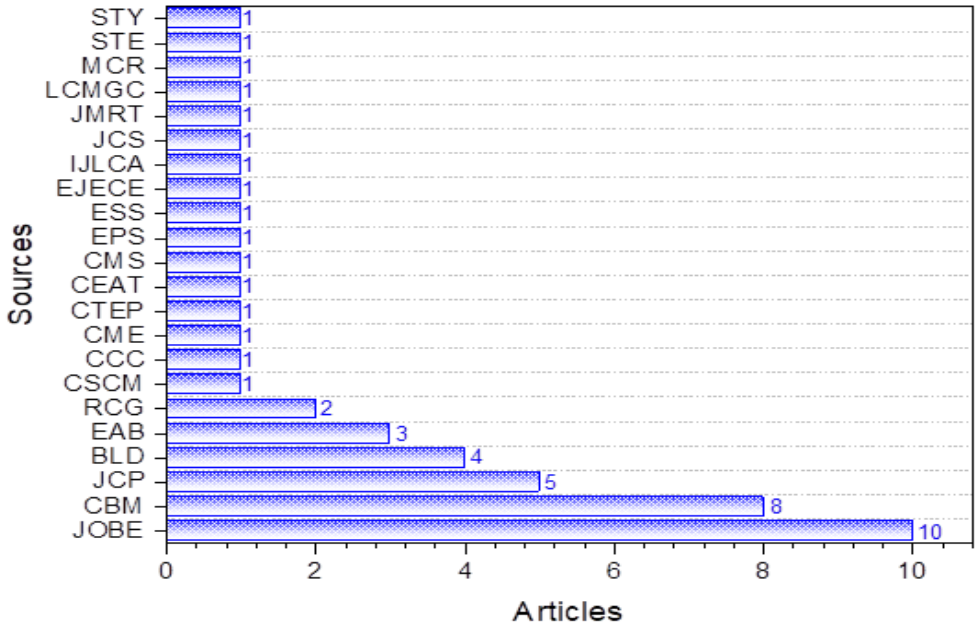
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3.2. Most productive journals

The distribution of publications across journals reveals a clear concentration of studies in a few specialized journals (Figure 3). *Journal of Building Engineering* published the highest number of studies on LCA applied to 3D concrete printing, with 10 publications, followed by *Construction and Building Materials*, with 8. Together, these journals account for approximately 38% of the scientific production identified. *Journal of Cleaner Production* and *Buildings* contributed 5 and 4 publications, respectively, while the remaining studies were published among other journals.

The concentration of approximately 60% of the publications in only four journals indicates that the dissemination of knowledge on LCA applied to 3D concrete printing still occurs predominantly through a limited number of specialized journals. This result also makes it possible to identify the journals that have concentrated the publication of research related to this topic.

Figure 3. Distribution of publications by journal



*JOBE – *Journal of building engineering,* CBM- *Construction and building materials,* JCP-*Journal of cleaner production,* BLD – *Buildings;* EAB- *Energy and buildings;* RCG – *Recycling;* CSCM – *Case studies in construction materials;* CCC- *Cement and concrete composites;* CME – *Chemosphere;* CTEP – *Clean technologies and environmental policy;* CEAT- *Cleaner engineering and technology;* CMS – *Cleaner materials;* EPS- *Engineering proceedings;* ESS- *Engineering structures;* EJECE - *European journal of environmental and civil engineering;* IJLCA- *International journal of life cycle assessment;* JCS - *Journal of composites science;* JMRT- *Journal of materials research and technology;* LCMGC- *Low-carbon materials and green construction;* MCR- *Magazine of concrete research;* STE- *Science of the total environment;* STY- *Sustainability.*

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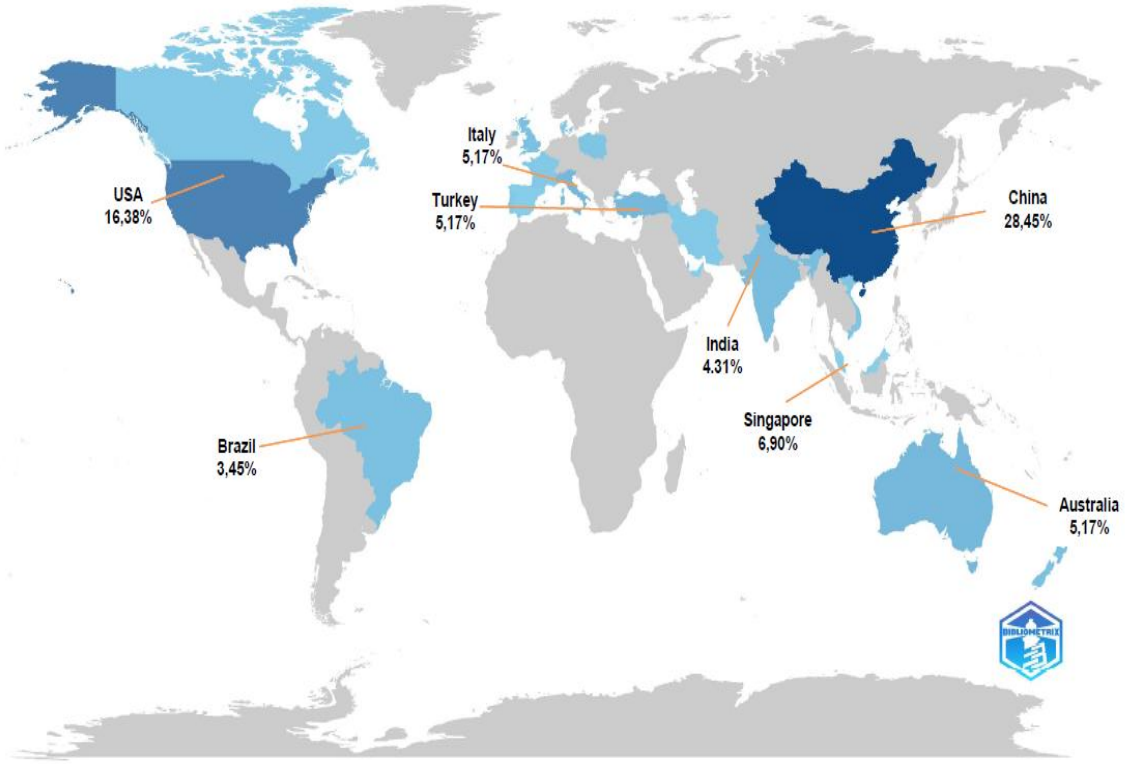
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3.3. Most productive countries

The geographical distribution of scientific production (Figure 4) shows that China accounts for 28.45% of the publications on LCA applied to 3D concrete printing, followed by the United States with 16.38%. A second group comprises Singapore (6.90%) and Australia, Italy, and Türkiye, each accounting for 5.17% of the publications. India and Brazil contribute 4.31% and 3.45%, respectively.

The participation of countries from Asia, North America, Europe, Oceania, and South America demonstrates that research on LCA applied to 3D concrete printing has been conducted across diverse geographical contexts. The concentration of publications in a limited number of countries, particularly China and the United States, also highlights the leading role of these countries in consolidating the research field and will be further examined through the international collaboration network analysis presented in the following section.

Figure 4. Scientific output by country



3.4. International collaboration among countries

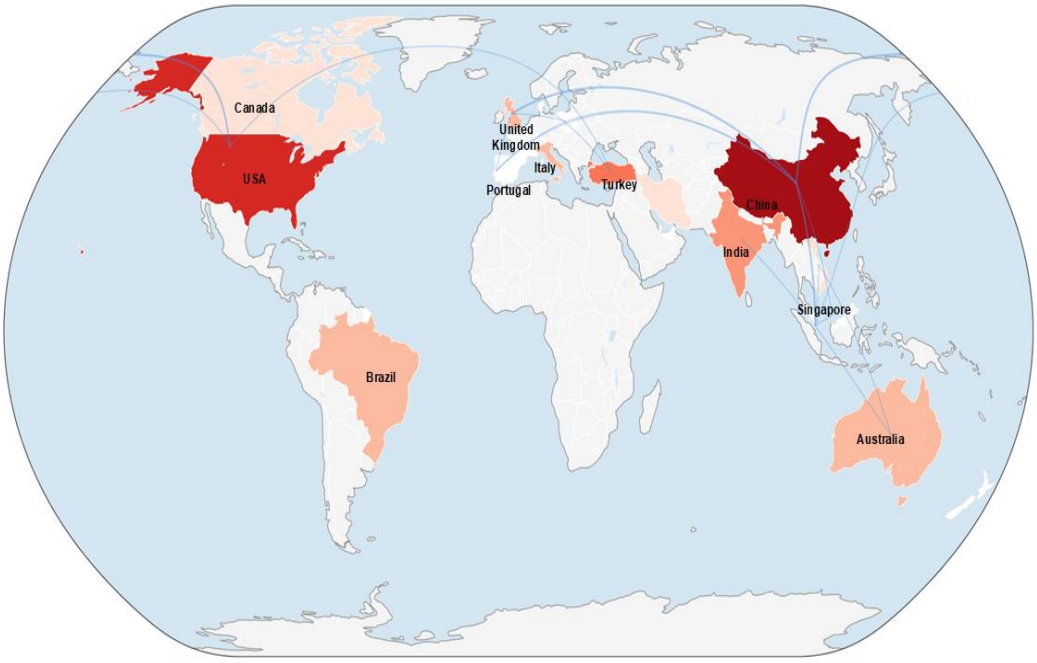
Figure 5 shows the international collaboration network among countries. China occupies the central position in the network and presents the largest number of collaborative links, with the strongest connections observed with the United States, the United Kingdom, and Singapore.

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Additional collaborations are identified among other countries, including Australia and India, Australia and Vietnam, Poland and Portugal, the United Kingdom and Portugal, Singapore and Malaysia, and the USA and Turkey, although these collaborations are less frequent.

Figure 5. Countries' Collaboration World Map



The collaboration network agrees with the scientific production presented in Figure 4, where China accounted for the largest number of publications. Countries with higher scientific output also tend to occupy more central positions in the collaboration network. Despite international partnerships across Asia, Europe, North America, and Oceania, most links occurred only once, indicating that international collaboration remains relatively dispersed in this research field.

3.5. Most influential publications

The citation analysis identified Weng *et al.* (2020) as the most influential publication on LCA applied to 3D concrete printing, with 229 citations, followed by Mohammad *et al*. (2020) and Liu et al. (2022), with 123 and 64 citations, respectively (Table 1). The considerable difference in citation counts between the first-ranked article and the remaining publications indicates that the study by Weng et al. has become one of the principal references for environmental assessment in this research field.

Beyond comparative environmental assessments, the most cited publications address different printable materials, including geopolymers, industrial wastes, porous concrete, and earth-based systems, illustrating the diversity of applications investigated within this research field.

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Table 1. Most cited articles worldwide on the topic

Rank	Author/Title	Quotes	Periodical
1	(Weng *et al*., 2020) Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach.	229	Journal of cleaner production
2	(Mohammad et al., 2020) 3D concrete printing sustainability: a comparative life cycle assessment of four construction method scenarios.	123	Buildings
3	(Liu *et al*., 2022) A comparative study on environmental performance of 3d printing and conventional casting of concrete products with industrial wastes.	64	Chemosphere
4	(Curth *et al*., 2024) 3D printing earth: local, circular material processing, fabrication methods, and life cycle assessment.	46	Construction and building materials
5	(Mir *et al.,* 2022) Life cycle assessment of construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing.	39	Cleaner engineering and technology
6	(Sambucci *et al.,* 2023) Life cycle assessment (LCA) of 3d concrete printing and casting processes for cementitious materials incorporating ground waste tire rubber.	33	Recycling
7	(Jones; Li, 2023) Life cycle assessment of ultra-tall wind turbine towers comparing concrete additive manufacturing to conventional manufacturing.	32	Journal of cleaner production
8	(Gislason *et al*., 2022) Porous 3d printed concrete beams show an environmental promise: a cradle-to-grave comparative life cycle assessment.	29	Clean technologies and environmental policy
8	(Roux *et al*., 2023) Life cycle assessment of a concrete 3d printing process.	29	International journal of life cycle assessment
9	(Bianchi *et al*., 2024) Life cycle assessment of building envelopes manufactured through different 3d printing technologies.	28	Journal of cleaner production
10	(Zhang et al., 2023) Environmental profile of 3d concrete printing technology in desert areas via life cycle assessment.	27	Journal of cleaner production

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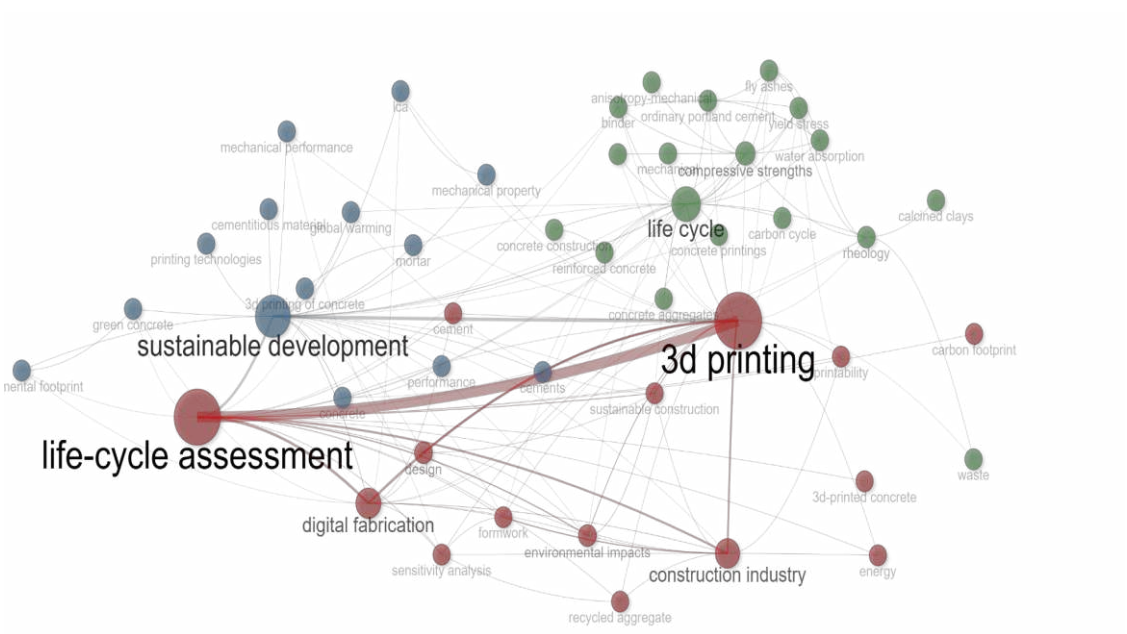
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All of the most influential publications were published between 2020 and 2024, corresponding to the period in which scientific output on this topic began to expand (Figure 2). The highest citation counts were associated with the earliest publications, reflecting the longer period available for citation accumulation. At the same time, the concentration of the most influential studies within a relatively short publication period indicates that the intellectual foundation of research on LCA applied to 3D concrete printing has been established only in recent years.

3.6 Keyword co-occurrence network

The keyword co-occurrence network (Figure 6) illustrates how frequently keywords appear together in the same publications, allowing the identification of the main research themes and their relationships within the field. The descriptors life cycle assessment and 3D printing occupy the central positions in the network. Since both terms were included in the search strategy, the discussion focuses on the remaining keywords, which characterize the thematic structure of the retrieved literature.

Figure 6. Keyword co-occurrence network of the study



Three thematic clusters can be identified. The red cluster is associated with environmental assessment and construction processes, the green cluster with cementitious materials and mixture design, and the blue cluster with sustainable construction and additive manufacturing. Among the remaining descriptors, the prominence of fly ash and calcined clay indicates that these supplementary cementitious materials have received considerable attention as partial substitutes for Portland cement or clinker in printable mixtures. Their association with terms related to carbon

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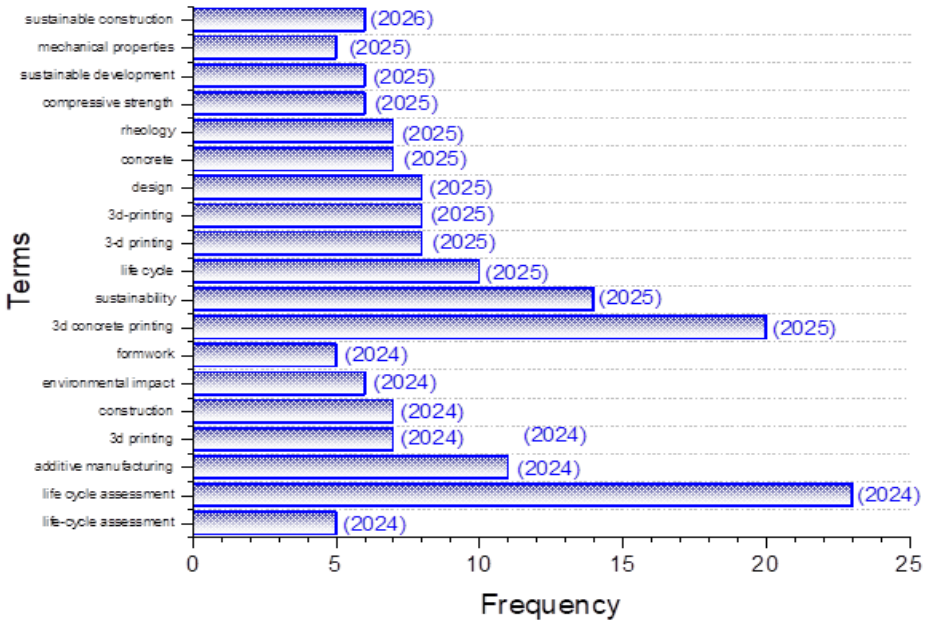
footprint, compressive strength and rheology suggests that recent studies have sought to reduce the environmental impacts associated with binder production while simultaneously satisfying the performance requirements of 3D concrete printing.

3.7. Trend Topics

The temporal evolution of keywords (Figure 7) illustrates how the research focus has changed over the analyzed period. As discussed in the previous section, the central position of life cycle assessment and 3D concrete printing is influenced by the search strategy adopted in this study. Therefore, the temporal evolution of the remaining keywords is emphasized, as it better reflects changes in the research topics over the analyzed period.

The trend topics are concentrated between 2024 and 2026, consistent with the increase in scientific production observed in Figure 2. Early trend topics are mainly related to environmental assessment and additive manufacturing, whereas more recent topics include descriptors associated with engineering performance (rheology, compressive strength and mechanical properties) and sustainable construction. The appearance of sustainable development and sustainable construction among the most recent terms suggests that sustainability has become an increasingly recurrent theme in studies on 3DCP.

Figure 7. Temporal evolution of the most frequent research topics



3.8. Research gaps and future perspectives

The analysis of the studies shows that the literature has primarily focused on comparing 3D concrete printing with conventional construction methods in order to quantify the environmental benefits resulting from the elimination of formwork, the reduction in material consumption, and the

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increase in productivity. However, important research gaps remain, particularly regarding studies that simultaneously integrate environmental, functional, and economic performance, as well as those adopting a full life cycle (cradle-to-grave) approach. In addition, aspects such as accounting for concrete recarbonation throughout the life cycle, the use of primary inventories obtained at laboratory or industrial scale, and the development of cementitious mixtures aimed at reducing the carbon footprint of 3D concrete printing remain underexplored in the literature.

Research has primarily focused on Portland cement-based mixtures, geopolymers, fly ash, and ground granulated blast-furnace slag. This suggests opportunities to investigate a broader range of alternative binders and locally available materials for printable cementitious mixtures. The results also indicate that future studies could expand the scope of environmental assessment by considering impact categories beyond carbon emissions and strengthening international collaboration. Such efforts may contribute to the development of more sustainable printable cementitious materials adapted to different regional contexts.

4. CONCLUSIONS

This study presented a bibliometric analysis of the scientific literature on LCA applied to cementitious mixtures for 3DCP. The analysis provides an overview of the evolution of this research field and identifies its main research trends. Based on the bibliometric analysis, the following conclusions can be drawn:

- Research on LCA applied to 3DCP is concentrated in recent years. The Journal of Building Engineering and Construction and Building Materials were the leading publication venues, while China accounted for the highest scientific output and occupied the central position in the international collaboration network.
- The most influential publications were published between 2020 and 2024, with emphasis on the environmental assessment of 3DCP and the development of alternative cementitious materials.
- Keyword co-occurrence and trend topic analyses highlight the increasing interest in sustainable printable cementitious mixtures, particularly those incorporating fly ash and calcined clay.
- Important research gaps remain regarding the development of low-impact cementitious materials and the adoption of comprehensive sustainability assessments integrating environmental, economic, and functional criteria.

The findings provide a bibliometric reference for future studies on Life Cycle Assessment applied to 3D concrete printing.

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